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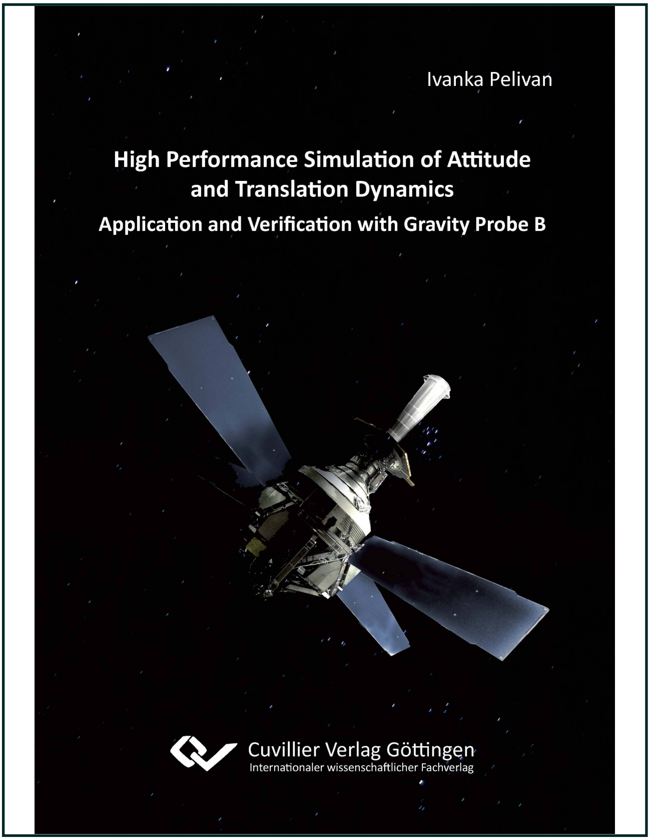
Application and Verification with Gravity Probe B



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High Performance Simulation of Attitude and Translation Dynamics

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1. Introduction

Space with its reduced environmental disturbances as compared to the conditions on Earth enables the execution of fundamental physics experiments that otherwise can not be carried out with the required precision. Gravity Probe B, the mission utilized for application and validation purposes, is one of many examples: Minuscule quantities of milliarcseconds/year in precession have to be measured to prove two predictions resulting from Einstein's General Theory of Relativity.

The formerly proposed STEP (Satellite Test of the Equivalence Principle) mission or the French MICROSCOPE (Micro-Satellite à Traînée Compensée pour l´Observation du Principe d´Equivalence) mission may serve as another example. The Equivalence Principle (EP) which constitutes the basis for Einstein's theory of general relativity can be tested on Earth with impressive precision already. Modern experiments using a torsion pendulum have found no violation of Equivalence for one part in 10^{13}. By means of the relative acceleration of two free-falling bodies in space, MICROSCOPE will test the Equivalence Principle at one part in 10^{15} and STEP was planned to advance this limit to one part in 10^{18}. The importance to achieve this accuracy is stated by several theories according to which the Equivalence may break down below 10^{-14}.

Other challenging science missions are Gaia (Global Astrometric Interferometer for Astrophysics) - an astronomy mission for measuring star positions and discovering extra-solar planets, LISA (Laser Interferometer Space Antenna) - a gravitational wave observatory, the past mission Gravity Probe B (GP-B) intended to test predictions of special and general relativity, and the current mission GOCE (Gravity field and steady-state Ocean Circulation Explorer) which measures Earth's gravity field with unprecedented accuracy. To guarantee the success of a mission, preliminary investigations are indispensable to predict the mission scenario, assess risks and estimate disturbances and error sources. With data processing for GP-B still on-going at the time of the start of this project, GP-B has been chosen as one of the baseline missions for testing of tools that enable and facilitate pre-launch and on-orbit investigative tasks.

Lessons learned from previous science missions such as GP-B and Hipparcos (High Precision Parallax Collecting Satellite), a precursor to Gaia, providing astrometric data on thousands of stars, have motivated research on a high-accuracy generic simulator. For validation purpose and knowledge enhancement regarding future science missions, a simulator adaptation is carried out to the Gravity Probe B mission.

1.1. Description of the Problem

The class of experimental science missions that is dealt with in this thesis has the following common conditions:

- They are scientifically and technically challenging because of an expected improvement of measurement accuracy by several orders of magnitude.
- The dynamics of the satellite is very closely linked to the scientific measurement instrument.
- The processing of the measurements needs a very long time with respect to the mission duration.

In the case of Gravity Probe B the measurements are taken for one year of mission lifetime and afterwards processed for considerably more than another year, far longer than planned, before the final scientific results are obtained. For the future mission Gaia it also will take several years after the end of the 5-year mission to process the measurements. To make sure that the measurements are not affected by undetectable errors which may disturb or even falsify the final result, a rapid processing of the first measurement data is necessary in order to identify the system behavior of the satellite and its parameters. In conjunction with a high-fidelity spacecraft dynamics simulator a thorough knowledge of the satellite, the instrument and its behavior can be gained. An extensive analysis of possible errors can be carried out before and during the mission to enhance the confidence in the experimental data.

1.1.1. State of the Art

The basis of this work is the spacecraft simulator developed at ZARM, the Center of Applied Space Technology and Microgravity, University of Bremen, by [55], further on referred to as baseline simulator. The baseline simulator was originally developed for application to STEP employing drag-free technology. The concept of the drag-free satellite is described below. Due to the baseline simulator's target, it has also simply been named drag-free simulator.

One of the main targets for simulator application remains the drag-free concept. In order to guarantee a test environment low on disturbances within a satellite, the so-called "drag-free" control technique is utilized. The concept of the drag-free satellite has been proposed independently by M. Schwarzschild (1961), R.A. Ferrell, G.E. Pugh (1959), G.J.F. MacDonald, C.W. Sherwin (1962), and B.O. Lange (1961). Details about the control and use of drag-free satellites can be found in [36] and [37]. The first successfully flown satellite missions include TRIAD I and TIP II (see [28] for details on TRIAD), and Gravity Probe B has been operated successfully in its drag-free mode, the current status is displayed on the Gravity Probe B webpage, [60]. GOCE applies drag-free control in flight direction to stably remain in its low Earth orbit of 250km.

Drag-free control is used to eliminate or reduce disturbances within the satellite to a level that can be ignored in the following data processing. Ideally, the remaining accelerations on the experimental test masses are purely gravitational. However, not all disturbances can be compensated, especially the interaction between the satellite and the experiment through the measurement instrument is inherent. This complicates the satellite and test-mass dynamics considerably. To learn about the satellite behavior and thus be able to enhance mission performance, the simulation of the complete satellite system or system parts is commonly realized to some degree.

In addition to the baseline dynamics simulator, several environmental models exist for which a suitable interface has to be developed.

1.1.2. Objectives

In the proposed project, the main objective is to build a readily applicable, multi-purpose high-fidelity simulator for science missions for development and post-mission analysis based on already existing and newly developed models or model extensions. The recent mission Gravity Probe B has shown the necessity for ongoing simulator development post-mission launch. The IOC phase took 128 days instead of planned 60 days due to many events that required thorough investigation and instrument adjustment. With a post-launch update to the engineering simulator developed concurrently with GP-B control parameters for attitude translation control have been adjusted. Flight results have been incorporated into the simulation to enable anomaly resolution. It became obvious that a simulator validation has to include coupled dynamics to faithfully reflect mission behavior.

The objectives are to advance a generic high performance satellite dynamics simulator applicable to current (drag-free) science missions to aid in all mission stages:

- for consistency check with mission requirements
- to perform sensitivity and worst-case analysis
- for control design and verification
- test flight hardware and software interfaces
- for generation of data to test data reduction methods
- as diagnostic tool for post mission data analysis

The simulator needs to be assembled in a generic modular way in order to allow for adaptation to science missions as different in nature as STEP and Gaia that require a highly accurate model of satellite and experiment.

For validation purpose, model improvement and knowledge enhancement, the simulator modules are adapted to GP-B. Beyond the scope of this project the simulator is targeted to be adapted to Hipparcos for post-mission analysis and simulator verification and to be applied to STEP, MICROSCOPE and Gaia for performance simulations in preparation for the data reduction.

The baseline simulator's primary objectives are to provide a comprehensive simulation of the real system including science signal and error sources. The current goal deviates from the above for one aspect - in generalizing the simulator to be applicable to all kinds of missions, the science signal inclusion, as has been enabled for STEP and MICROSCOPE, cannot be enforced anymore. For the possibility to continue with STEP and MICROSCOPE, the additional heritage parameter and coding enabling the introduction of the presence of EP violation, has been kept for inclusion of science signal simulation.

By utilization of the simulator the a priori identification or estimation of all forces and torques acting on the satellite and the experimental test masses will be facilitated with the goal to predict the satellite mission to unexcelled accuracy. The simulator is meant to aid in design, test and verification for missions with a very high level of performance.

Applying the simulator to a specific mission for post-mission analysis is beneficial in various aspects. For post-mission analysis, the simulator can be applied twofold. Firstly, the data generated by the simulator can be used to test and verify scientific data analysis methods. In addition, with highly accurate attitude and orbit reconstruction the data reduction can be greatly improved as the position and attitude is given for the instant the science signal is recorded. In generating simulation data to test and verify methods of data analysis and offering the possibility to rapidly conduct mission scenario studies, the simulator can be used as integral part of the scientific data reduction process following mission end. The identification of possible disturbance components and error sources also aids in the subsequent processing of science data.

The foremost goal for the simulator application towards GP-B lies in validation and model enhancement. The attitude and orbit reconstruction of previous satellite missions like Hipparcos and Gravity Probe B helps to improve the simulator which then can be applied to future science missions with even higher fidelity. The choice of Gravity Probe B as baseline mission to test and validate the simulator is due to the fact that it is the first and main mission of the second generation of drag-free satellites. With GP-B for the first time, flight data is available for an experimental set-up where drag-free control has been applied in all degrees of freedom to provide an undisturbed environment for science measurements. In addition, for the first time acceleration measurements are combined with high accuracy attitude measurements. Gravity Probe B with its new technology serves as spin-off for other science missions like STEP.

Last but not least, a major focus is laid on applicability in terms of user-friendliness since collegues at ZARM and DLR (Deutsches Zentrum für Luft- und Raumfahrt, the German Aerospace Center) and test users have assessed the simulator application as complicated and discouraging at the current state.

1.1.3. Methods

The simulator will be developed in a generic modular way to allow for adaptation to science missions that are very different in nature but with the common ground that they require a precise model of satellite and experiment due to demanding accuracy and performance specifications. Existing spacecraft modules are improved and more sophisticated, accurate models are implemented. This refers to environment models such as gravitation, magnetic field, atmosphere, solar pressure etc. as well as models for the satellite itself and its sub-systems. Since for drag-free satellites measurements of accelerations on a very small scale are enabled, very small disturbances and misalignments can have a dramatic effect on the experimental results. It is therefore necessary to include models of any disturbances and misalignments possible.

A model refinement is carried out in view of preserving the generic applicability but also the options for model improvement with respect to the specific application are realized. The single modules need to be verified, therefore a mission-independent validation procedure has to be established. The test procedure shall cover baseline tests, that are typically simple in nature and aim at testing functionality and fulfillment of requirements in meeting expectations for simplified scenarios. The next verification step may comprise more complex tests for which analytical solutions can be derived like for simple dynamic systems. The validation against actual science data finally represents the ultimate test towards simulator reliability. The Gravity Probe B mission already provides the possibility to compare the simulation results to existing flight data.

1.1.4. Outline of the Thesis

Following this introduction, a short review is presented for models selected meeting the objectives outlined in section 1.1.2 above. In chapter 2 also, the final generic simulator is described, followed in chapter 3 by the major model improvements and enhancements that have been introduced within the scope of this work. In chapter 4 a mission overview for Gravity Probe B is given and in chapter 5 the adaptation to Gravity Probe B is carried out. In chapter 6 the validation of the simulator using science data from the GP-B mission is carried out as an essential step in achieving high-fidelity for a generic spacecraft simulator. Chapter 7 provides a summary and an outlook targeting future simulator additions and applications.

1.1.5. Contributions

The main contributions of this thesis lie in the following areas: 1) Complementing and advancing an existing spacecraft simulator [55] with respect to several aspects:

- General:
    - Research, assessment and selection of existing models from various sources.
    - Defining a general interface structure for all existing and future modules.
    - Building a common module for functions, parameters and variables used by various models.
    - Establishing the overall library, sub-library (categories) and module structures.
    - Establishing platform independency for Linux and Windows operating systems.
- Simulation Modules:
    - Major revision of the dynamics core module used in [55] and [62] and gravity field adding new features and functionalities.

  - Introduction of a mechanical reference frame to account for changes in center of mass. e.g. because of fuel consumption or moving masses.
  - New dynamics link implementation for inclusion of custom linear and nonlinear coupling interactions between satellite and test masses, also allowing the inclusion of internal test mass disturbances that counteract on the satellite.
  - Inclusion of alternative integration methods for the complex multi-body dynamics.
  - Incorporation of the Tsyganenko magnetic field model.
  - Inclusion of the Jacchia-Bowman 2008 empirical thermospheric density model.
  - Implementation of several mathematical operations.
  - Enhancing the transformation library by new generic functions.

- Preprocessing:
  - Calculation of a variable cross-section area and corresponding pressure point as preprocessing option.
  - Introduction of data preprocessing tools for Albedo and magnetic field.

- Testing:
  - Establishing an automated validation procedure for the dynamics core for baseline and more complex tests involving coupling scenarios which can be described analytically. Derivation of the analytical solutions.
  - Establishing an automated validation procedure for the gravity field, the magnetic field modules, the Jacchia-Bowman atmospheric model and several transformation and mathematical modules.

and 2) the first validation of the overall simulator with focus on the complete dynamics using science data is achieved considering

- the overall goal to provide a compound of high-fidelity models within a validated simulator readily applicable to complex science missions.

- to build the first complete software mission simulator for Gravity Probe B including all four gyroscopes, spacecraft environment, full dynamics and mission-specific control.

- the post-mission reconstruction for GP-B for validation purpose, model improvement and as platform to study for future science missions and to test parameter estimation methods.

- parameter estimation to match simulated and real data.