AAS 08-011

GENERIC DRAG FREE CONTROL SIMULATION – LESSONS LEARNED FROM GRAVITY PROBE B

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A generic drag-free simulator has been developed to aid in the design, on-orbit and post-mission data analysis phases of scientific satellite missions. Adaptable to missions as different in nature as Gaia (Global Astrometric Interferometer for Astrophysics) and STEP (Satellite Test of the Equivalence Principle), this simulator will provide necessary modeling capability to increasingly complex future missions. A complete mission software simulator including controls, full-body dynamics and comprehensive spacecraft environment disturbances has been established for Gravity Probe B (GP-B). Reproduction of the mission is being carried out to validate the simulator with actual flight data and refine the underlying models. The importance of this effort lies in the challenge to meet rising science requirements in the area of maximum disturbance rejection. Future missions such as Gaia, STEP, LISA (Laser Interferometer Space Antenna) and others require a minimum of 3 orders of magnitude improvement over the GP-B performance of 10^{-9} m/sec^2. While technology advancements will certainly be required to achieve these levels, it became increasingly clear to the scientists and engineers who delivered the GP-B results that the ability to monitor and adjust the coupling of spacecraft to subsystem controllers, at all stages of the mission is essential to optimizing mission results. We provide a look at the progress to date of this effort.

INTRODUCTION

GP-B was designed to test two predictions of Einstein's general theory of relativity by measuring the orientations of four high-precision gyroscopes relative to a distant guide star. While in theory a simple concept, the high accuracy required to achieve the mission goals imposed high performance demands on the measurement instrument. The resulting challenging realization led to technology spin-offs now benefitting future science missions that require a comparable or even lower bound on acceptable disturbances. For concept verification, a control software simulator has been established along with the mission development which could be combined with hardware in the loop to test attitude translation control (ATC) and the gyroscope suspension system for GP-B. With GP-B in orbit the simulator has also proven to be invaluable during the initial orbit check-out phase to aid in anomaly resolution, examples of which are given in [1].

The current simulation effort targets to provide a readily available tool for future science missions when addressing pre-flight scenario investigation, to ensure in-flight data quality and to aid in post-mission data reduction.

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THE GRAVITY PROBE B EXPERIENCE

The Gravity Probe B Relativity Mission was launched April 20, 2004 and completed September 28, 2005. It has been described as one of the most technically challenging science satellite missions ever flown by NASA. The experiment was proposed independently by Leonard Schiff and George Pugh shortly after the first successful satellites were delivered into space in the late 1950's and early 1960's. The experiment tests the geodetic and frame-dragging effects predicted by Einstein's General Relativity Theory, by measuring the precession of gyroscopes orbiting at 642 km around the Earth's poles. These two predictions, if valid, would result in a geodetic precession of 6614 milliarcseconds and a drift due to frame-dragging of 42 milliarcseconds after one year. To measure such small changes meant virtually complete elimination of classical torques that could contribute to the movement of the gyroscope spin axis, and an experimental instrument insulated sufficiently such that systematic variations in the data acquisition do not mask the relativistic effects. These extremely challenging requirements were impossible to achieve technologically at the time the experiment was proposed and the following six "near zeros" were identified as milestones toward achieving the necessary readiness.

Near Zero 1: Gyroscope Rotor Inhomogeneity. The difference in the geometric location of the rotor's mass center from its physical center can provide a lever arm that when acted on by the Earth's gravitational field will result in a torque. This placed a requirement on the manufacture of the GP-B rotors of having a "mass unbalance" of less than 300 nanometers. This requirement was operationally checked prior to gyroscope selection for flight. Once in orbit gyroscope performance has shown to be even better than estimated (see Table 1).

Table 1

Gyro #	1	2	3	4
Prelaunch estimate	18.8	14.5	16.8	13.5
On-orbit data	6.9	4.4	3.3	6.0

Near Zero 2: Drag-Free Control of the Spacecraft. Related to the first near zero requirement, the drag-free control is needed to reduce the force acting on the mass unbalance. The drag-free requirements for GP-B are broadly 1x10^{-9} m/sec^2 with a tighter requirement for 1x10^{-11} m/sec^2 in a narrow band centered at the roll frequency (13 mHz; 77.5 sec period) transverse to the direction of gyroscope spin.

Near Zero 3: Rotor Asphericity. Also a possible source of classical torques is the interaction between the gyroscope suspension system and the surface features of the gyroscope rotor. The gyroscope rotors are controlled to within one nanometer of the capacitive electrodes center using a capacitance bridge readout and electrostatic voltage, the gyroscope suspension system. The suspension voltages required are approximately 100 mV and can exert a torque on the rotor spin axis via imperfections in the rotor shape. This placed a manufacturing limit of 0.1 micrometers on the peak to valley difference which was successfully accomplished (see Figure 1).

Near Zero 4: Magnetic Field. In order to observe relativistic effects the gyroscope spin axis direction had to be monitored. It is not possible to mark the rotor for that purpose without violating the first and third near zero requirements. To measure the spin axis ori-

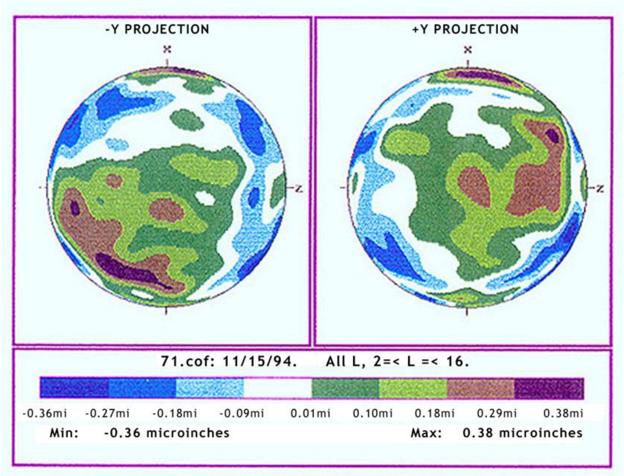


Figure 1 Gyroscope Surface Features

entation the London moment has been employed. The gyroscopes are coated with niobium, a superconducting metal. A spinning superconductor has a dipole magnetic moment (the London moment) perfectly aligned with its spin axis, exactly what was needed for the GP-B measurement. To implement this technique the magnetic field in the proximity of the rotor had to be smaller than the London moment.This was achieved using the Superconducting Lead Bag Technology developed for the program. The fields achieved were approximately 0.1 microgauss.

Near Zero 5: Ultra-Low Pressure. To ensure the proper use of the London moment as a reliable measurement the gyroscope spin speed had to be constant over the length of the mission. This was achieved by what is called the low temperature bake out and the associated use of a cryopump device. Once the gyroscopes were spun to their science spin speeds there was residual helium remaining in the vacuum can enclosing the science instrument. In the course of the mission this helium would eventually evaporate and act as a "spin-down" source by interacting with the gyroscope rotors. Table 2 shows that the bake out procedure dramatically improved the vacuum properties in the probe and exceeded the requirement with great margin.

Table 2 Gyroscope Spin-Down Rate On-Orbit (Years)

Gyroscope	Before bakeout	After bakeout
Gyro # 1	50	15,800
Gyro # 2	40	13,400
Gyro # 3	40	7,000
Gyro # 4	40	25,700

Near Zero 6: Rotor Charge. High energy particles that penetrate the spacecraft are a cause for rotor charging. It was necessary to maintain a charge level less than 15 mV throughout the mission. The technology developed to achieve this involves the use of UV light and gold plated bias electrodes placed in the gyroscope housing. Electrons were liberated from the rotor/electrode system by emitting UV light and biasing the electrode according to the polarity the charge was adjusted to.

Each of the near zero requirements were achieved over several years of development and performed to specification, and in most cases beyond, during the mission.

Lessons Learned

In the final report[2] produced for the Gravity Probe B mission a set of lessons learned and best practices were recommended for future missions involving the use of drag-free technology. It specifically suggests the use of a mission simulation that can reflect coupled spacecraft and payload dynamics to mirror the in situ performance of the integrated satellite. This is particularly important for missions such as LISA, GAIA, STEP and others where new key technologies are involved to meet disturbance requirements that exceed those of what is, at this point in time, the state of the art in low disturbance performance, GP-B.

In the execution of the GP-B mission it was noted that there was an unprecedented level of cooperation between engineers and scientists in achieving the final performance level of the science instrument. In reflecting on the challenges met, particular focus of the discussions was on the IOC (initial on-orbit calibration) phase of the mission. The IOC schedule was planned for over 18 months prior to launch. More than six segments of the schedule covering several weeks of operations were practiced using an Integrated Test Facility (ITF), combining flight-like hardware with software spacecraft simulators, operated from the flight mission operations center located at Stanford University to provide actual telemetry to engineers to build familiarity and experience under “test it as you fly it” conditions. The IOC schedule was to last 45 days and had 15 days of contingency for a total of 60 days. When the spacecraft entered its science data taking phase, however, 128 days had past.

Investigating the reasons for the prolonged IOC phase the review committee concluded that in spite of the engineering expertise available, and the time devoted to anticipation of anomalous events and the near perfect performance of each of the spacecraft and payload subsystems, what was lacking was the ability to adequately reproduce the coupled payload and spacecraft dynamics in an integrated simulation to efficiently address the challenges. The mission had made extensive use of simulators, both software and hardware alike, however the shortcoming was in failing to integrate them dynamically. Evidence of the importance in having dynamically coupled simulation including flight-like hardware in the loop was demonstrated in the post-launch upgrade made to the gyroscope suspension system/gyroscope simulator.

There are two modes to establish a drag-free environment.[3] In the unsuspended mode the proof mass is allowed to float freely and the satellite is commanded to follow the proof mass orbit. In the second (suspended) mode the proof mass is suspended and the drag-free system controls the spacecraft orbit such that suspension forces on the gyroscope are minimized. It was decided to operate the spacecraft vehicle in suspended drag-free mode after observing an unacceptable acceleration bias when using the baseline unsuspended mode that would have led to a slowly changing orbit of the spacecraft. This required modifications to the ATC parameters to meet the science requirements as those determined prior to launch for the suspended mode performed unsatisfactorily. It has proved to be most beneficial to modify the GSS/gyroscope simulator to include an ATC simulation creating a drag-free simulator to optimize the drag-free control parameters. This decision sought to leverage the extensive knowledge of the GSS/gyroscope dynamics gained during ground testing and subsequently validated with on-orbit data. The ATC model was designed and validated also using orbit data and integrated in a matter of weeks. The resulting simulator was used to produce modifications that exceeded the science mission requirements. After two iterations the drag-free controller was optimized for the final science configuration. The process was a success but valuable time had been lost.

To summarize, it is clear that Gravity Probe B's traditional use of its simulators prior to launch to deliver individual systems that met their requirements, to verify and validate its software and to train its operations team was very successful. While this was believed to be a requirement for a successful mission what was unexpected was that this was not sufficient.

Quoting from the Gravity Probe B Post Flight Analysis Final Report:

"Invest in high fidelity simulations. Hardware-in-the-loop simulators are critical to validate the overall effectiveness of a complicated scientific instrument and satellite system. Where the instrument cannot be operated on the ground, suitable high fidelity simulations with flight compatible interfaces must be developed. These simulators, however, must be vetted against flight data and updated once actual performance data is known. This is required to be able to resolve operational anomalies."

SIMULATOR DEVELOPMENT

With the GP-B mission completed in development and science phase and on-going data reduction activities a unique opportunity is given to comprehend the overall mission in a simulation environment. For the first time, flight data is available for an experimental setup where drag-free control has been applied in all degrees of freedom. Comparison with flight data is essential to establish a validated tool ready to aid future mission design where drag-free control is applied to provide an undisturbed environment for science measurements or else where close links between spacecraft and measurement instrument exist as is the case for GP-B.

The simulator development has undergone several stages. Based on [4] and [5] generic modules for spacecraft and experimental test-mass dynamics have been completed. Models for environmental disturbance calculation are developed and updated based on available data. Each of the generic moduls is described in detail through a documentation package including technical notes on underlying physics and a separate or attached user manual on how to apply the module. Mission-specific control modules have been developed alongside the overall mission design to test and verify control algorithms. The generic modules are mainly coded in Fortran and C/C++ and can be integrated into a Matlab/Simulink environment via S-function blocks. The mission-specific control modules are primarily developed in Matlab/Simulink. In the following, module and simulator development is briefly outlined. A more detailed description can be found e.g. in [5, 1].

Generic Simulator Modules

Currently, the dynamics core can handle a nine-body system in anticipation of application to STEP which up to date includes the largest number of experimental masses in a scientific satellite mission. This number however can be increased if required. The satellite and test mass dynamics are calculated w.r.t. the most natural or common frames, i.e. the satellite states are either represented in the Earth centered inertial (ECI) or in the body-fixed frame with its origin in the satellite center of mass (COM). For the test masses, computations are carried out w.r.t. the corresponding test mass body-fixed frames centered in their respective COMs, or corresponding housing frames. As driving force for the dynamics, special emphasis is given to the derivation of a most accurate Earth gravity model. Based on GRACE (Gravity Recovery and Climate Experiment) data, spherical harmonics are provided to 360th degree and order. On the availibility of new releases (see [6, 7]) the most up-to-date GRACE model is implemented. Gravitational influences due to the Sun, Moon and planets can be enabled. External disturbances due to atmospheric drag, solar radiation and magnetic fields are accounted for through parametric models and look-up tables generated in pre-processing utilizing finite element discretization of structural models. Element or volume forces are computed using standard model data[8,9,10] and enhancements[11,12] to account for characteristics not included elsewhere.

If the test masses are shielded from external disturbances by drag-free control the only other major disturbance source comes from satellite-gyroscope interaction through the measurement instrument. Simple spring-damper models including DC offsets are provided by the generic modules to approximate coupling interaction between the satellite and experiment. These can be replaced by external typically more advanced non-linear coupling algorithms or by calculated controller output. In case of GP-B the electrode force output from the gyroscope suspension system model is fed into the coupling link between spacecraft and gyroscope.

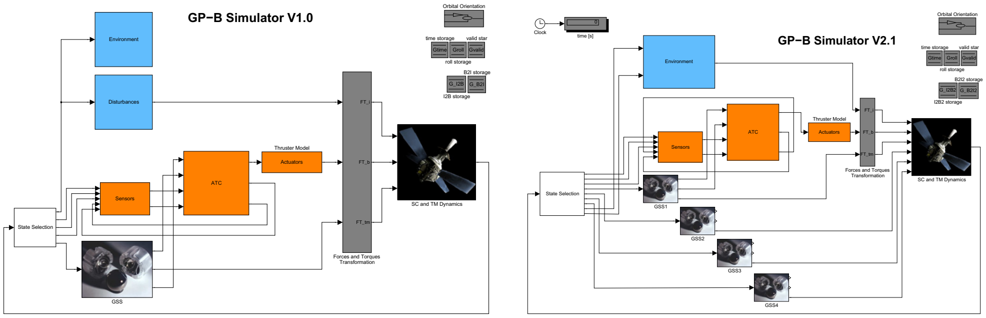
Mission-Specific Modules

The GSS model is part of the mission specific controls simulator developed concurrently with GP-B. It uses the difference in gyroscope and its housing reference position provided by the dynamics module to calculate suspension efforts. Control effort from the GSS is passed to the ATC to keep the spacecraft centered around the drag-free test mass. Attitude control uses sensor measurements from rate gyros, telescope and star tracker. The simulator model for ATC control uses the actual flight logic applied during the science phase of the mission. ATC force and torque commands are relayed to the actuator. The actuator model is comprised of 16 thrusters modeled as point forces to provide specific impulses. Converted into body forces and torques they are passed on to the dynamics model to update the satellite and gyroscope states.

For integration of the GP-B control modules with the generic simulator interfaces had to be established containing transformations from generic to mission-specific reference frames.

1-Gyro Simulator

The first mission simulator (shown in Figure 2(a)) has been assembled to match the original software version of the controls simulator for GP-B: a two-body system consisting of spacecraft and drag-free gyro. The controls simulator used Hill's equations to obtain satellite and gyroscope positions and velocities. For a cross-check the generic dynamics have been simplified to be comparable to the Hill's simulator and the idealized orbit conditions used to initialize the Hill's simulator have been adopted. The cross-check carried out in [5] shows the successful integration of the control modules into the overall simulator and especially confirms that the necessary transformations have been implemented correctly. At this point the simulator comprises a dynamically enhanced version of the engineering simulator developed along with GP-B. This engineering simulator can be executed with one or two gyros, one being a hardware gyro. The current modular structure of the generic simulator applied to GP-B also allows for module replacement with hardware in the loop.



(a) 1-Gyro Simulator (b) Complete 4-Gyro Simulator

Figure 2 Simulator Development.

4-Gyro Simulator

In the next step the simulator has been enhanced to account for all four gyros as shown in Figure 2(b). The disturbance module has been combined with the environmental module since it uses the environmental outputs to calculate external forces and torques on the satellite. In Figure 2(b) the first gyro is set as drag-free gyro feeding an ATC trigger pulse and the GSS control effort to the ATC. Every GSS module is set up such that every gyro can function as drag-free reference mass. In fact, during the mission the drag-free gyro has switched between gyro 1 and 3 a couple of times for several reasons.

With the 4-Gyro Simulator for the first time a complete dynamics and control simulator has been established for GP-B. For the following comparison to flight data the major part of the environmental influences has been disabled to keep the comparison simple. Simulator version 2.0, a preliminary version without environmental disturbances except gravitational, is used to verify dynamics with science data. This approach is justified as long as a comparison to nominal flight data i.e. where no disruptions due to external influences have been observed, is carried out. In this case, dynamics due to external disturbances other than gravitational are small enough to be neglected for the moment as we aim at dynamics module verification and not at mission reproduction.

SIMULATOR VERIFICATION

The major control modules have already been vetted with flight data available, see e.g. [1]. This part of the paper therefore focuses on validation of the dynamics core. In the following, two-orbit simulations are carried out with gyro 3 as drag-free proof mass and the results are compared to flight data spanning the same time period. Purely theoretical consideration leads to the conclusion that a gravity-gradient signal must appear eight times in the gyroscope data within a two-orbit time slot. It is also expected that gyro 1 shows the most pronounced gravity-gradient signal since it is farthest away from the drag-free gyro 3. This can be clearly seen in the topmost plots of Figures 3 and 4 where the body x-axis of the position vector for gyro 1 is displayed.

As a by-product and minor model improvement, verification with flight data revealed that adjustment was necessary for the modelled rate gyro noise. Although based on flight data, the estimation has been too high, masking the dynamical features. This can be seen in Figure 3 where especially for gyros 2 and 3 the imposed noise led to an increase in gyroscope position magnitude by a factor of four on average of the actual flight data. Decreasing the noise level by an order of magnitude leads to the more favorable comparison shown in Figure 4.

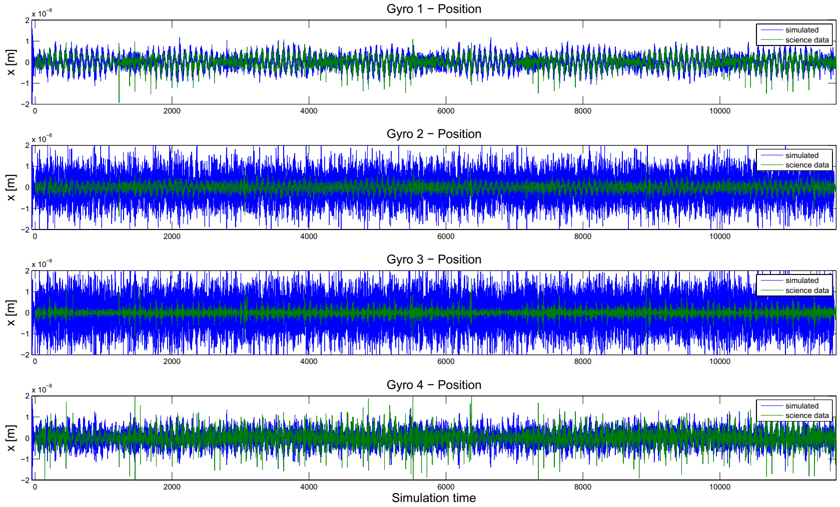


Figure 3 Gyroscope Position

The comparisons in Figures 3 and 4 have been carried out with the idealized input conditions the Hill's simulator has been initialized with, e.g. a perfectly polar orbit starting above the North pole. Two orbit periods of nominal flight data have been extracted from the science data base starting at arbitrary vehicle time. Since the idealized simulation always starts at the top of the orbit the simulated and flight data do not match in phase. To line up with flight data, the simulated states have been shifted such that they can be compared directly to the flight data.

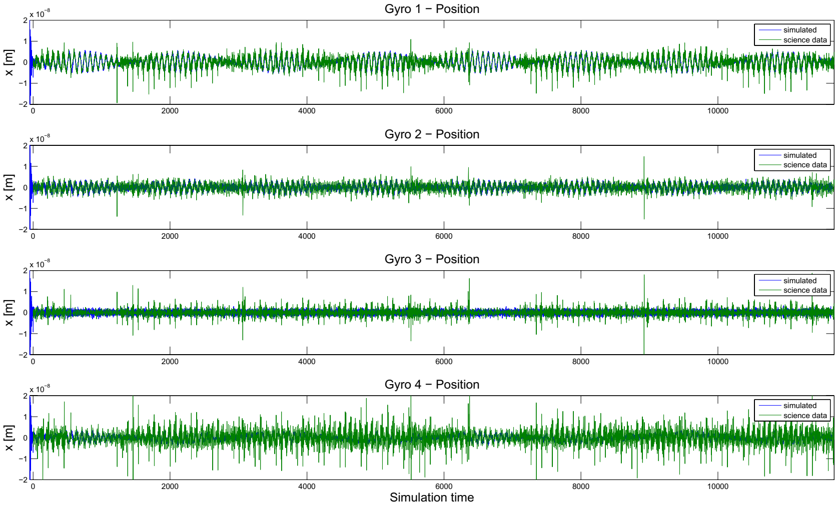
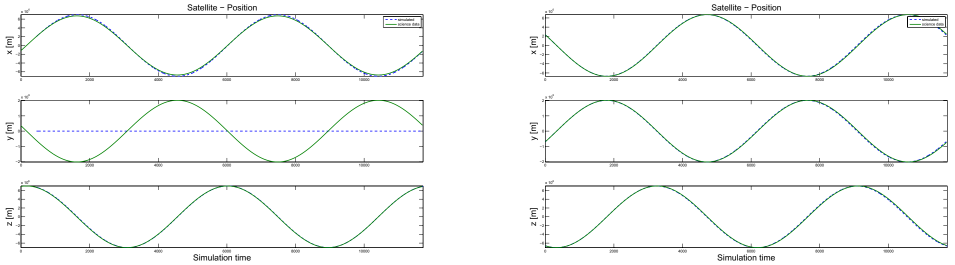


Figure 4 Gyroscope Position

Figure 4 shows, that even for the idealized simulation case good agreement exists between simulated and measured gyroscope data. This does not hold for the spacecraft dynamics since the idealized conditions result in a different orbit for the simulated versus measured spacecraft trajectory (see Figure 5(a)). For future investigations beyond simulator verification, the simulator has been adapted to run with arbitrary input conditions. Initializing the simulation with flight data leads to the results shown in Figures 5(b) and 7. Thereby, the most straight-forward comparison between simulated and flight data is possible. Furthermore, with the simulator adapted to use actual flight data as initial conditions the option to investigate anomal flight conditions reflected in the data is now enabled.

What can be observed in Figure 5(b) is that towards the end of the two-orbit period there is a slight misalignment between the simulation results and the measured data. The same misalignment trend is visible in the blown-up section for the gyroscope position shown in Figure 7. The simulation has been run incorporating a simplified spherical Earth model and without external disturbances. This configuration has been carried over from simulator integration and cross-check between the generic and the GP-B controls simulator.

The discrepancies between the two data sets are mainly attributed to the neglection of higher-order terms in the gravitational field of the Earth. Figures 6(a) and 6(b) display a detail blown-up part of the spacecraft position comparison between simulation and flight results towards the end of a two-orbit period. In Figure 6(a) the detail simulation from Figure 5(b) is shown and in Figure 6(b) the simulation is repeated including higher order spherical terms in the Earth gravitational field. For the latter case a more favorable match

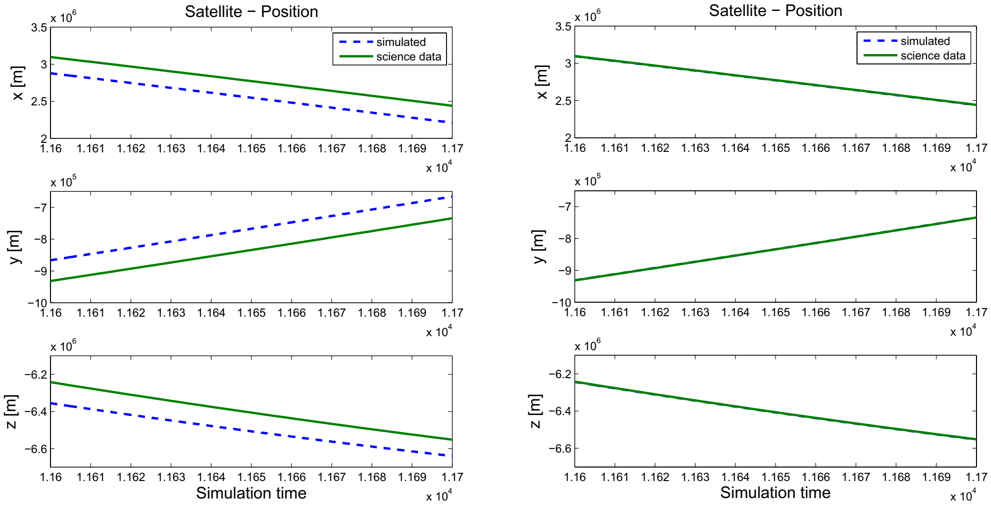


(a) Idealized Simulation

(b) Flight Inputs

Figure 5 Spacecraft Position.

between simulated and flight data also towards the end of two orbits is achieved. For the resolution shown, already the first higher order harmonic modelling the oblate Earth accounts for the previous difference.



(a) Simulation with Spherical Earth Assumption

(b) Simulation with Oblate Earth Assumption

Figure 6 Comparison of Simulated Spacecraft Position and Flight Data.

For the gyroscope position, Figure 7 furthermore shows that different noise levels are apparent in the gyroscope data. The flight data is generally noisier than the simulated data, also there is a higher noise level in gyro 4 measurements compared to the other gyros. Both of these findings suggest further investigation on appropriate dynamic or noise modelling.

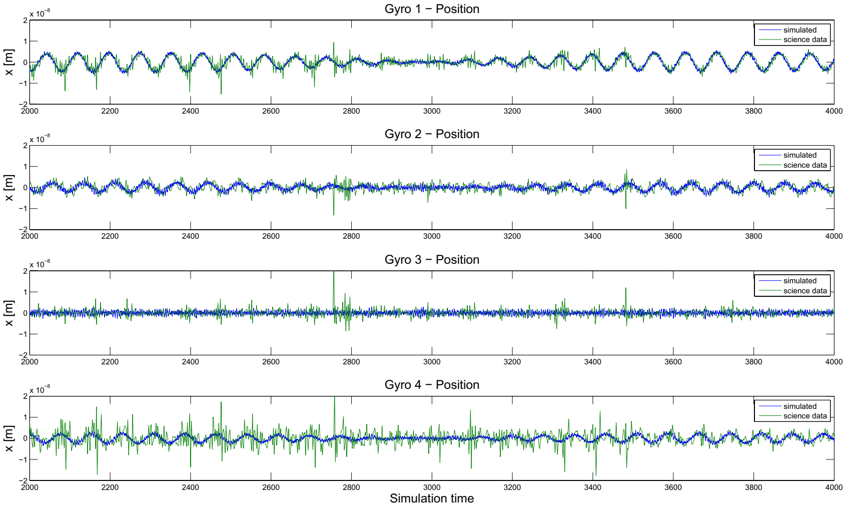


Figure 7 Gyroscope Position, Flight Inputs

SUMMARY AND OUTLOOK

A high-fidelity dynamics and control simulator has been adapted to the Gravity Probe B mission for simulator verification and model improvement. While validation for simplified dynamics, e.g. comparison to Hill's or Mathieu solutions have been carried out in the past, this is the first time that the full dynamics have been verified in their main features. The GP-B simulator also serves as reference for missions where high requirements on measurment accuracies and disturbance reduction exist.

In order to achieve mission goals commonly new key technologies have to be developed which have to be tested and verified in advance. The generic simulator combined with mission specific control tools can be applied for that purpose as well as prediction of mission scenarios. It furthermore aims to aid in on-orbit anomaly resolution and post-mission data analysis. Out of these four targets the first two have been accomplished for GP-B to a certain level, i.e. test and verification of key control technologies plus post-simulation of the nominal science phase which shows the simulator's predictive ability for undisturbed orbits. One outlook for the near future is anomaly reconstruction and investigation with the full simulator including environment and dynamics adapted to observed anomal conditions, e.g. presence of higher environmental disturbances than usual or spacecraft module failure. Application to future science missions is anticipated in an on-going collaborative effort with the prime candidate STEP.

ACKNOWLEDGMENTS

This work is supported by the Marie-Curie program of the European Union under contract number MKTD-CT-2004-014188.

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