Gravity Probe B Simulators: Design and Test, Ops Training and On-Orbit Uses

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Abstract

The Gravity Probe B mission relied on simulators extensively both in the development and operational phases. They played a critical role in the mission's overall success. The primary simulator was the Integrated Test Facility (ITF) built by Lockheed-Martin. This simulator was assembled to provide spacecraft dynamics simulation as well as flight software validation and verification. There were also subsystem simulators that played important roles. The gyroscope suspension system team developed and built a hardware-in-the-loop gyroscope simulator designed to be able to operate over 10 orders of magnitude in force domain. This simulator evolved during on-orbit operations into a state of the art drag-free simulator. Simulated sensors for the SQUID readout system, telescope readout system and even an artificial star to test the performance of the telescope optics were used extensively for qualification tests prior to launch. One of the more important lessons learned is for missions where the spacecraft to payload coupling becomes the greatest challenge, simulators of the future need to be designed with coupled interfaces and these simulators must be employed early in the design and build phase of the mission.

Telescope and SQUID Simulators used for Develop and Test of Flight Hardware

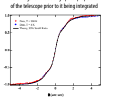
Artificial Star Simulators were used extensively for optical testing of the Gravity Probe B flight telescope.

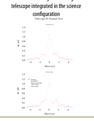
TRE Input Signal Generator used in Acceptance Testing of Telescope Readout Electronics

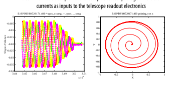
Artificial Star #2: Provided a Simulated star image for evaluating optical properties of the telescope prior to it being integrated

Artificial Star #3: Provided a Simulated star image for testing with telescope integrated in the science configuration

Dual Axis Modulator provides telescope detector package simulated currents as inputs to the telescope readout electronics







Plots showing X & Y slopes vs. time (Left) and X vs. Y Pointing (Right) output by TRE using Dual Axis Modulator

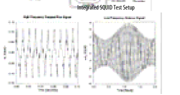
Flight SQUID Sensor and Readout Electronics

"Niobium Bird" Provided Simulated Science Signal using SQUID Sensor for Data Analysis Evaluation Prior to Launch

Integrated SQUID Test Setup

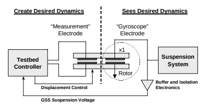
SQUID Simulator Circuit Diagram

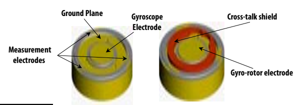
The SQUID Simulator was using extensively for functional testing of the SQUID flight software prior to launch.



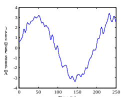
"Niobium Bird" Truth Model Signal: High frequency (Left) and London Moment plus Orbital Aberration (Right)

Hardware Gyroscope Simulator



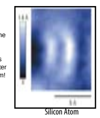


One axis of Gyroscope simulator



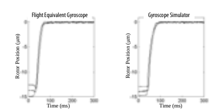
Commanded Sinewave position of Gyroscope Hardware Simulator

Position Resolution of the Hardware Gyroscope Simulator was 1/50 the diameter of a silicon atom!



Silicon Atom Image

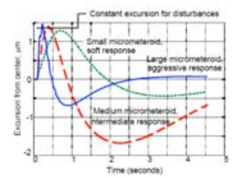
Hardware Gyroscope Simulator



Two plots comparing a flight equivalent gyroscope (left) being lifted by ground suspension system and the Gyroscope simulator being lifted by the same suspension system

Gyroscope Suspension System (GSS) and Hardware in the Loop Simulation

Acceptance of Flight Hardware: using Hardware in the Loop



Plot showing the response of the gyroscope suspension system to three simulated micrometeorite strikes of increasing magnitude to the Gravity Probe B satellite.

Products of Hardware in the loop simulation:

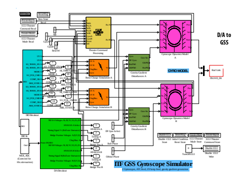
- Acceptance testing of all 4 Gyroscope Suspension System Flight Electronics units.
- Verification of the GSS science requirements
- Development and test of the GSS digital and Analog controllers
- Demonstration of the analog controller's capability to protect the gyroscope from hitting the housing due to micrometeorite strikes

It was clear from the onset that in order to test the Gyroscope Suspension System on the ground a special simulator would be needed. The Hardware Gyroscope Simulator was developed in parallel with the Flight Gyroscope Suspension System and provided exceptional results

Products of the ITF Configuration: Hybrid Software plus Hardware in the loop:

- Develop and test of all operational Gyroscope Suspension System software
- Ground testing of the drag-free control including coupling of the ATC and GSS controllers
- On-Orbit verification of the GSS charge measurement software and on-board algorithms
- Vetting of the GSS gyroscope protection circuitry, the Arbiter board and logic

Software *plus* hardware in the loop simulation



Integrated Test Facility (ITF): Instrumental in Validation and Verification of *Every* Software Command Executed on the GP-B Spacecraft

The Integrated Test Facility provided engineers with a complete simulated spacecraft including hardware in the loop in which to develop and test all operational software algorithms. All communications interfaces with the spacecraft computer (CCCA via 1553 bus) were identical to the spacecraft.

It was noted by several veterans of previous satellite missions that they had not ever seen a mission operations team that worked so well together. It is believed that the 7 Mission Simulations over the course of more than 12 months that were run from the Mission Operations Center with the ITF providing realistic telemetry , (including anomalies of course!) contributed greatly to this accomplishment.

Integrated Test Facility replicated GP-B software execution

Step 1

Gravity Probe B Required every software command that was to be executed on the spacecraft or payload be successfully run through the ITF before uploading

Step 2

Photograph of mission operations team during the last simulation before launch.

List of Electronic simulators employed in the ITF:

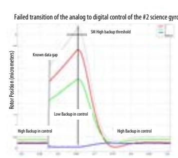
- SQUID Simulator with square wave excitation
- SQUID Bracket temperature Control simulator
- Star Tracker (Dual Axis Differential Modulator) Simulator
- Electronics Control Unit Load/Source Simulator
- Gyroscope Simulator (4)
- Charge Control Simulator
- Gas Management Assembly Simulator

Plus the following flight equivalent Hardware in the loop

- Electronic Control Unit
- SQUID Readout Electronics (SRE) (x2)
- Gyroscope Suspension Systems (GSS) (x4)
- Telescope Readout Electronics (TRE)
- Command & Control Computer Assembly
- GPS Unit
- Proton Monitor

GSS On-Orbit Tuning and Anomaly Resolution

Failed transition of the analog to digital control of the #2 science gyro

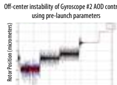


Two days into the on-orbit calibration phase all four gyroscopes fail to center using the digital controller!

- Root cause was determined in 24 hours using the HIL gyroscope simulator. Rotor charge 5 times the anticipated level was determined by the simulator.
- New code was written, tested and uploaded within 72 hours and all four successfully centered.
- Rotor was discharged and verified the estimate of the rotor charge within 10 % found using the simulator.

Non-optimal controller performance was identified on orbit using procedures developed on the ground prior to launch

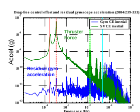
Off-center instability of Gyroscope #2 AOD controller using pre-launch parameters



- More than 10 performance tests were designed and coded prior to launch using the GSS/Gyro simulator in the ITF.
- The tests executed exactly as designed and one uncovered a problem with the position control of science gyro #2.
- Rotor position control was found to be unstable for off-center positions using GSS #2 AOD controller. (See plot to the left)

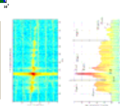
- After reproducing the instability on the ground and comparing the plots, it was found that the voltage modulation frequency was causing the instability.
- A new parameter for the modulation frequency was uploaded and the test was re-run with the results shown on the plot to the right.
- Further investigation of the other 3 GSS/Gyro systems revealed the same problem to a much lesser degree. They too were updated and optimized.

Results after uploading new controller parameters



- Optimal performance of the drag-free control was achieved after an on-orbit tuning was completed with the help of the GSS and ITF simulators.
- Cross-track accelerations were reduced below specification following the adjustment of the drag-free control gains once on orbit.
- Plot to the left shows the spacecraft control efforts helping to reduce the local cross track accelerations on the "proof mass" gyroscope

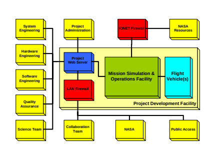
- Anomaly 117: Spacecraft dynamics due to a standing wave in the liquid He resonates with the drag-free control algorithm.
- Plot to the right shows the drag-free control passing through resonance with the liquid He standing wave on day 272.
- The resonance was confirmed using data obtained from the development work performed using the GSS/gyro simulator



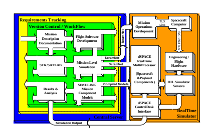
On-orbit tuning involving simulator provided insight into spacecraft and payload dynamic interactions

Conclusions and Observations

Proposed Architecture for Implementation of Lessons Learned



Proposed comprehensive architecture for future missions designed to integrate the use of simulation from the earliest possible stages of mission development



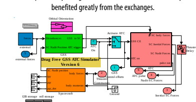
Hypothetical implementation of the Gravity Probe B simulators with requirement tracking and reporting, hardware in the loop simulation development and test, and mission operations development included

Important Lessons taken from the Gravity Probe B Experiment

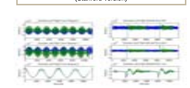
1. The use of hardware in the loop simulators for future missions will aid future challenging science mission satellite experiments beyond what is commonly believed
2. Hardware in the loop simulation helped provide the Gravity Probe B mission with nearly flawless software performance, both in an operational and flight software sense. "Test it as you fly it" was shown to be an extremely valuable philosophy. This same philosophy should be extended to the development, testing and on-orbit performance of flight hardware.
3. Manage the simulation facility like the vehicle; devote significant program resources and use aerospace best practices to maintain the design and configuration of the system.

Stanford and ZARM are collaborating on two complimentary full mission simulators

In December of 2005, the Gravity Probe B project entered into a collaboration with the Center for Applied Space Technology and Microgravity (ZARM, at the University of Bremen, Germany) under a grant from the European Union named "First Look". The collaboration involves the co-development of ZARM's spacecraft simulator and the Gravity Probe B simulator and to use of GP-B's flight data to compare with the simulators' performance as a way of ensuring the highest fidelity of the simulator models. The two centers bring complimentary backgrounds to the effort and have already benefited greatly from the exchanges.



Simulink diagram of the Drag-free GSS ATC Simulator (Stanford version)



Early results below show simulated vs. flight orbit data where the dynamics of the drag-free control efforts are on the left and vehicle orientation with respect to an inertial reference are in the right.

This research supported by NASA on contract NAS8-39225