Precision Attitude and Translation Control Design and Optimization

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Abstract

Future fundamental physics and astrophysics missions will require spacecraft attitude and translation control of unprecedented precision. Design and on-orbit optimization of the Gravity Probe B attitude and translation control system necessitated the development of unique spacecraft simulation facilities that can now be leveraged to model high accuracy attitude control, drag free control, and payload-spacecraft interaction dynamics to enable new mission concepts.

Introduction

Future fundamental physics and astrophysics missions will require spacecraft attitude and translation control of unprecedented precision. Missions requiring Drag Free Control, such as LISA Pathfinder (LPF), LISA, STEP, and BBO, rely on inertial sensors of such high sensitivity that their full performance can only be realized after launch. LISA and the Interferometric Synthetic Aperture Radar missions require multiple spacecraft formation flying, presenting new challenges for attitude and translation control design. The global space astrometry mission, GAIA, requires attitude control that confronts the state of the art.

These challenges levee two prerequisites for mission implementation, 1) development of high fidelity attitude and translation control simulations and 2) development of procedures for in-space optimization of satellite control and on-board instruments. What sets these challenges apart from conventional spacecraft is the complex interaction dynamics of vehicle control with on-board systems - be they motion of inertial reference sensors or fluid propellants.

The Hansen Laboratory Precision Attitude and Translation (PAT) Control Program leverages Stanford University's unique experience in having successfully flown the world's only three-axis drag free satellites, Discos/Triad launched 1972 and Gravity Probe B launched 2004. GP-B employed high precision attitude and roll control - active control of six degrees of freedom.

The PAT Control Program focuses on high accuracy attitude control, drag free control, and payload-spacecraft interaction dynamics. On-going efforts include the implementation of advanced spacecraft environment and dynamics models, development of spacecraft and payload sensor and actuator models, error modeling, parameter identification, state estimation, control algorithm design, and command template formation to establishing realistic expectations and plan post-launch tuning and optimization.

Specific implementation goals:

1 Development of fully integrated sensor-controller-actuator simulations, operating across the payload/spacecraft interface

2 Exploitation of existing modular architecture to enable efficient exchange of software models for hardware units (either in the form of prototype or final flight electronics systems) for hardware-in-the-loop verification

3 Employment of a high fidelity spacecraft bus and flight CPU to enable flight software validation and verification with the science payload.

4 Integrated Mission Operations consoles for command generation and verification and operations training.

Technical Background

The range of implementation goals is based on flight experience with drag free controlled satellites. To date, two three-axis drag free controlled satellites have flown successfully. The first, TRIAD I, managed by the Johns Hopkins University Applied Physics Laboratory for the US Navy Transit navigation system, was launched September 2, 1972. Three-axis translation control (drag free control) was achieved using the DISCOS (Disturbance Compensation System) built by Stanford University. The DISCOS system enabled the spacecraft to "follow" an internal, shielded, inertial sensor to compensate for the disturbances from aerodynamic drag, magnetic torques, gravity gradient torques, and radiation pressure. The second three-axis translation controlled satellite, Gravity Probe B, was launched April 20, 2004 and has successfully completed its science data phase. In addition to three-axis translation control, GP-B was simultaneously under precision attitude control so all six spacecraft degrees of freedom were actively controlled. For both missions a macroscopic sphere is used as the inertial sensor (PtAu alloy for DISCOS, quartz for GP-B). A detailed analysis of GP-B flight data has shown that the dynamics of the inertial sensor couple to the spacecraft dynamics in a complex way [1,2,3]. This has the effect of increasing the number of degrees of freedom under control: that is, one must simultaneously control the spacecraft degrees of freedom plus the relevant sensor degrees of freedom. For Gravity Probe B this means the ATC (attitude and translation control system) must control nine degrees of freedom, the full six spacecraft and the three translational DOF for the sensor. Lessons learned from these missions, presented below, indicate that high fidelity simulations are an essential tool for successful controller operation and tuning.

Lessons Learned from Drag Free Controlled Missions

The Gravity Probe B satellite actively monitors and controls 9 interacting degrees of freedom during normal operation:

A. 3 in orientation of the space vehicle to keep the tracking telescope pointed at the guide star and maintain a constant roll rate and fixed roll phase with respect to the orbital plane

B. 3 in translation of the space vehicle to keep the vehicle in a drag-free orbit about the geometric center of the one of the science gyro's housing cavities

C. 3 in translation of the gyroscope rotor with respect to the housing cavity

The other 9 degrees of translation freedom of the remaining 3 gyroscopes are slaved to the first 9 described above and do not significantly interact with the dynamics of the vehicle as a whole. Note that the rotational degrees of freedom of the gyroscopes are not controlled by design.

One gyro serves as the drag-free sensor (accelerometer) for the satellite. The three control efforts required to keep the gyroscope rotor centered in its housing are fed to the space vehicle. The space vehicle, in turn, applies compensating forces via its thruster set to null the forces felt by the gyroscope rotor. See Figure 1. These six degrees of freedom significantly interact. The gyroscope position control loop bandwidth (Gyroscope Suspension System or GSS) is made small to minimize disturbance torques on the rotor, and is on the order of 2 Hz. The space vehicle ATC system bandwidth is of the same order and is limited by thruster authority and ATC processing. These two control loops interact significantly during operation.

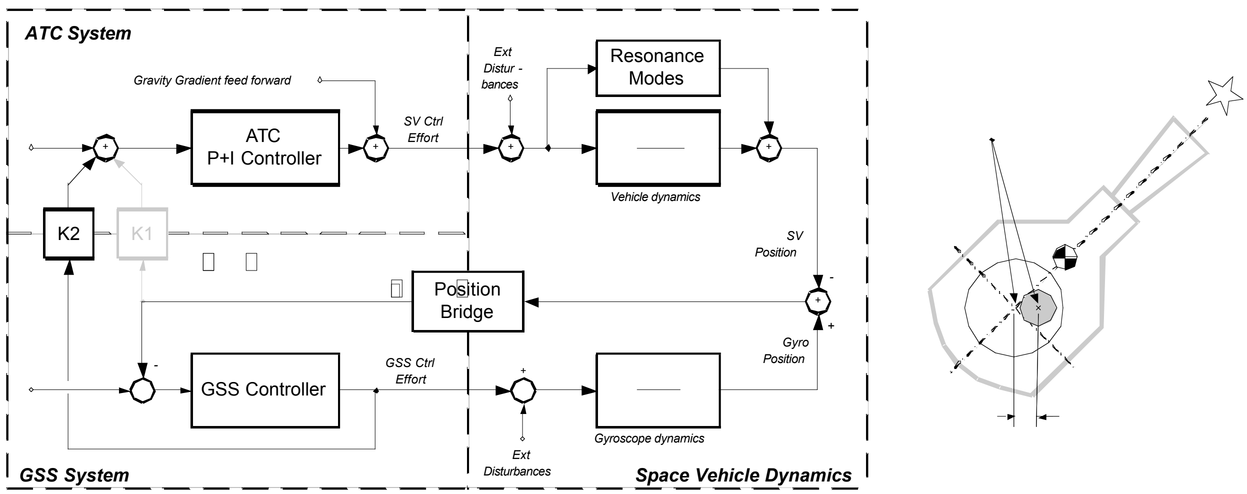

Figure 1: Interacting degrees of freedom

Additional coupling between the translational DOF comes from orientation changes. The center of mass of the vehicle is not at the center of the drag free sensor's housing, thus any change in orientation tends to be about the center of mass of the vehicle. The drag-free action nulls these orientation-induced forces and thus moves the effective center of mass of the vehicle to the center of the drag free sensor's housing. Again, the orientation control loop bandwidth is the same as the translation control bandwidth and thus this control loop, as well, interacts significantly with the gyro suspension control loop.

This brief overview shows, in outline form, that the 9 degrees of freedom are strongly coupled in normal operation and thus cannot be easily separated into simpler and isolated control subsystems.

Gravity Probe B on-orbit drag-free performance

The Gravity Probe B satellite provides the science satellite community with the state of the art demonstration of drag-free technology to date[2,3]. The GP-B drag-free system reduced the gravity gradient and environmental forces acting on the spacecraft by a factor of 10,000 by simultaneously controlling 9 degrees of freedom (6 of the spacecraft and 3 of the gyroscope suspension system).

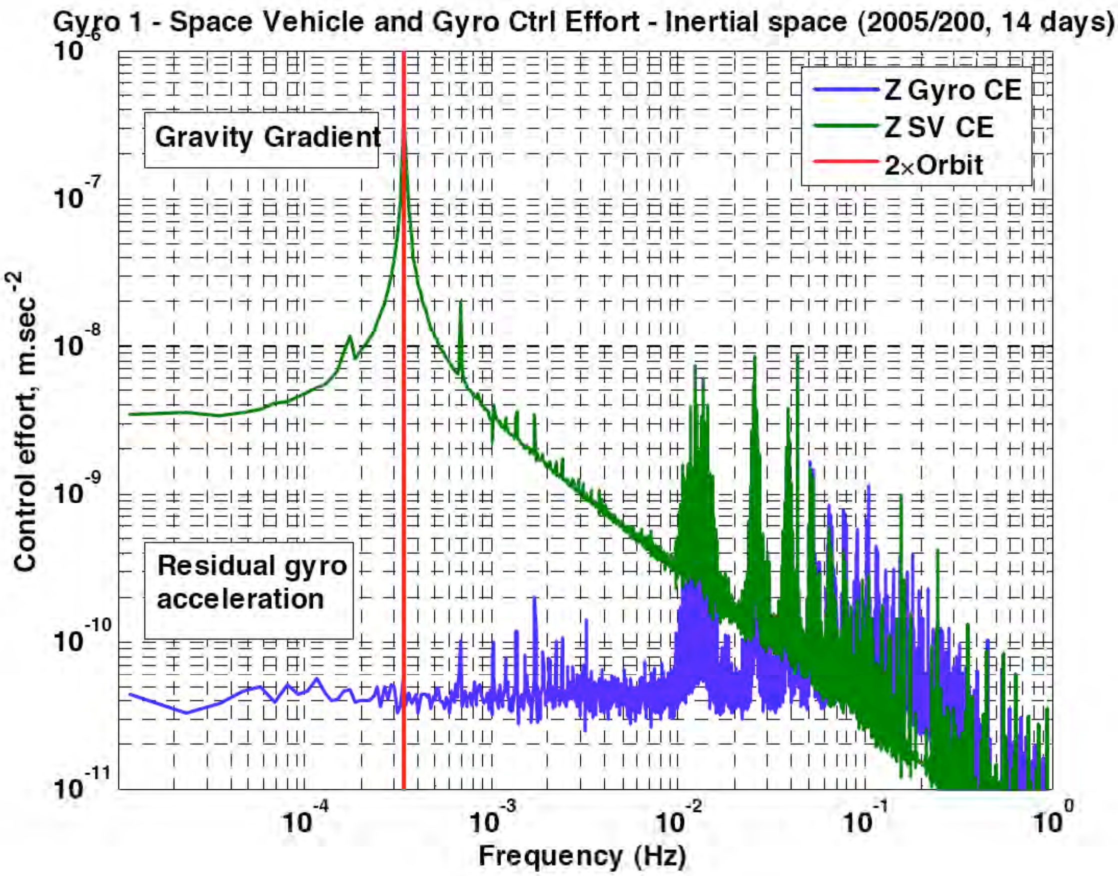

Figure 2 – Drag-free performance showing vehicle and gyroscope accelerations.

The ATC system was programmed to implement two different forms of drag-free control, the Prime and suspended or accelerometer mode. In the Prime mode the gyroscope suspension system (GSS) releases control of the rotor position allowing it to float freely in the housing. The rotor position is sent to the ATC where it was included in the closed loop control of the spacecraft. The spacecraft now flies an orbit such that the rotor position does not exceed 4 micrometers off-center otherwise the gyroscope suspension system reacquires control and opens the drag-free loop. As the proof mass rotor is ideally shielded from all external forces, by following it the spacecraft maintains a perfectly gravitational orbit. This was the intended mode of operation and was in fact demonstrated on orbit.

The suspended drag-free mode has the GSS maintain control of the rotor position and sends the control efforts needed to keep the gyroscope centered to the ATC. The ATC then adjusts its control of the spacecraft such that the GSS control efforts are minimized.

The two modes of drag-free control demonstrated on orbit are shown in Figure 3 –In the end it was the suspended mode of drag-free operation that was chosen for both performance and risk mitigation reasons.

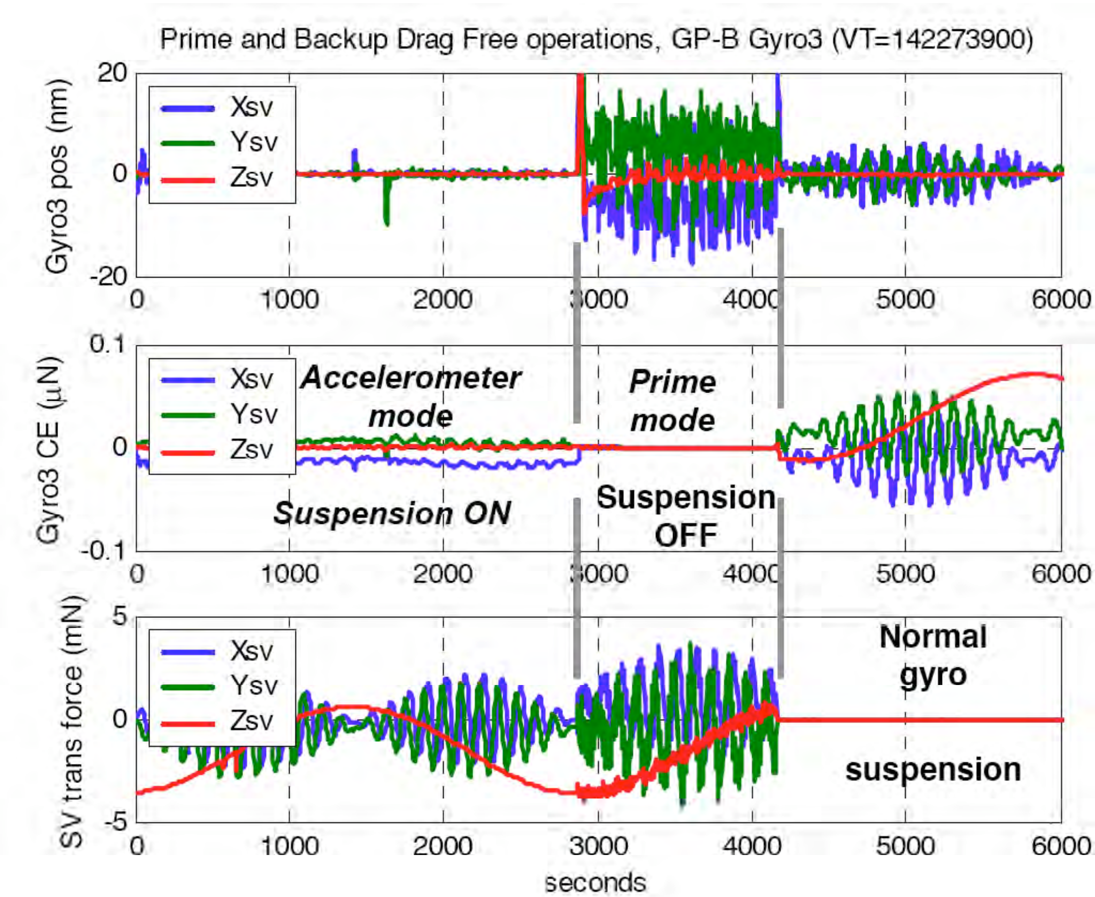

Figure 3 – Comparison of suspended and unsuspended drag-free and drag-free off

Although ATC setup and tuning was more complex than anticipated by the completion of the Initial Operations Checkout phase the mission's stringent drag free and attitude control requirements were met. The fundamental conclusion of the Gravity Probe B lessons-learned study is that high fidelity simulation capability played an essential roll in the successful operation and tuning of the GP-B attitude and translation control system.

Future missions
Future missions pose even greater ATC challenges for the following reasons.

1 The drag free control requirements are more stringent. Drag free residual accelerations in measurement bandwidth:

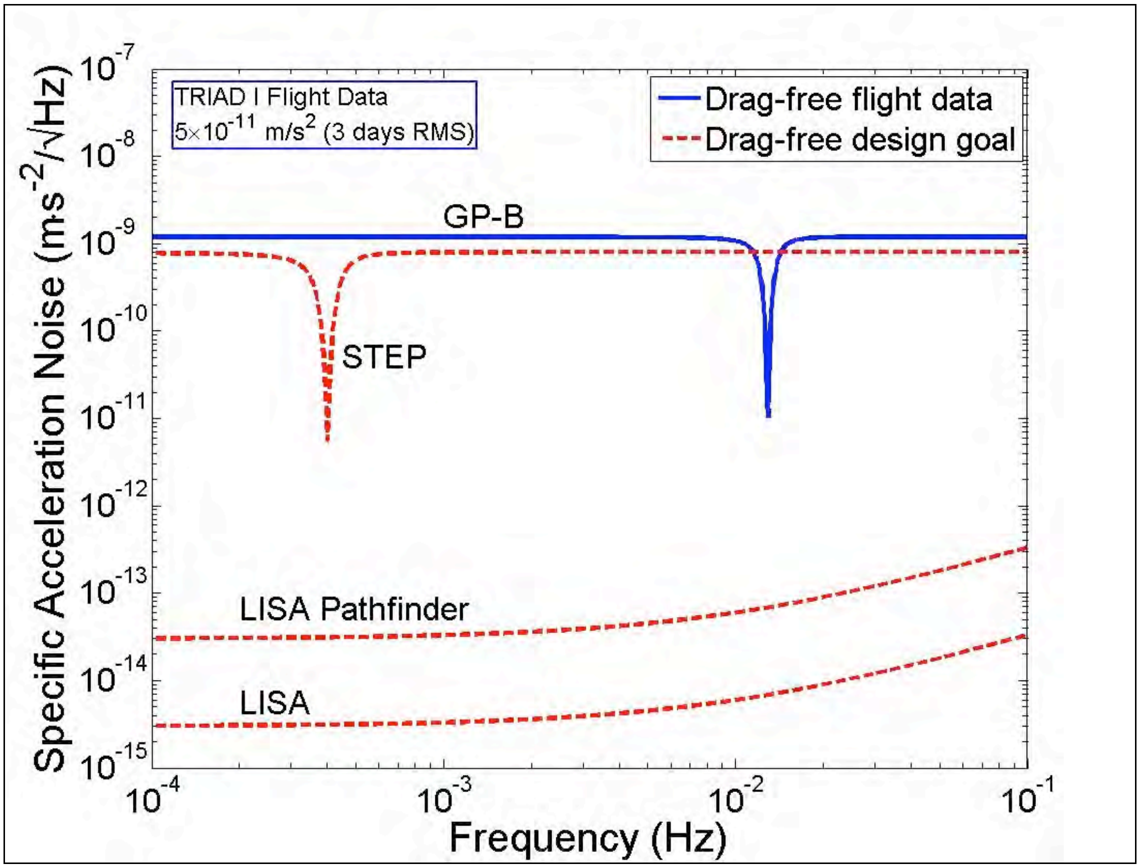

Figure 4 – Comparison of drag-free control requirements

2 Complexity of inertial sensor. DISCOS and GP-B used a sphere requiring a suspension that controlled just the three translational DOF. STEP, ST7 and LISA have inertial sensors of belted cylindrical or cubical shape that require six DOF sensor control. In addition STEP, ST7 and LISA also use 2 masses per inertial sensor package thus requiring 12 DOF of sensor control in addition to the spacecraft DOF.

3 Formation flying requirements. The LISA mission consists of 3 independent drag-free and attitude controlled spacecraft flying in formation. Even without specific control requirements on maintaining formation, multiple spacecraft add complexity.

4 Operations Limits. As stated previously the on orbit setup and tuning of the GP-B ATC system occurred during an IOC phase lasting 4 months. Such a long set-up phase may not be advised for missions of shorter duration than GP-B, e.g. the entire STEP mission is proposed to last 6 months. Further the low earth orbit of GP-B enables frequent communication through the TDRSS network and ground stations. Ten thousand commands were sent during the setup phase. ST7 will be launched into the L1 Lagrange point while LISA will be in orbit around the sun trailing the earth by 20 deg. As compared with GP-B, this will lead to significantly reduced communications opportunities; high fidelity hardware-in-the-loop simulation will be an essential element for success.

The Stanford simulation facility has been enhanced since the completion of GP-B and during a three-year collaboration with ZARM, University of Bremen, Germany [4]. The enhancement enabled the construction of a hardware-in-the-loop simulation facility that allows users to build executable architectural models capable of investigating complex system interactions. This system is mature and ready to be applied to future missions.

Future missions requiring precision attitude and translation control demand a robust simulation capability due to their increased complexity, heightened performance requirements, and more limited communications opportunities.

References

1. Bencze, W.J., DeBra, D.B., Herman, L., et al. "On-Orbit Performance of the Gravity Probe B Drag-Free Translation Control System" Proc. 29th Guidance and Control Conference. American Astronautical Society, Breckenridge, Colorado, (2006).

2. J. Li, W.J. Bencze, D.B. DeBra, G. Hanuschak, T. Holmes, G.M. Keiser, J. Mester, P. Shestople and H. Small ; "On-Orbit Performance of Gravity Probe B Drag-Free Translation Control and Orbit Determination" *Advances in Space Research*, *Volume* ***40****, Issue 1 pp 1-10* (2007)

3. Gravity Probe B Final report; pp.441-460 (2008). http://einstein.stanford.edu/content/final_report/GPB_FinalPFAR-091907-scrn.pdf,

4. I. Pelivan, S. Smoot, D. Hipkins and Stephan Theil "Generic Drag Free Control Simulaiton: Lessons Leaned from Gravity Probe B," AAS 08-011, 31st Annual AAS Guidance and Control Conference, Breckenridge, Colorado, Febuary (2008)