

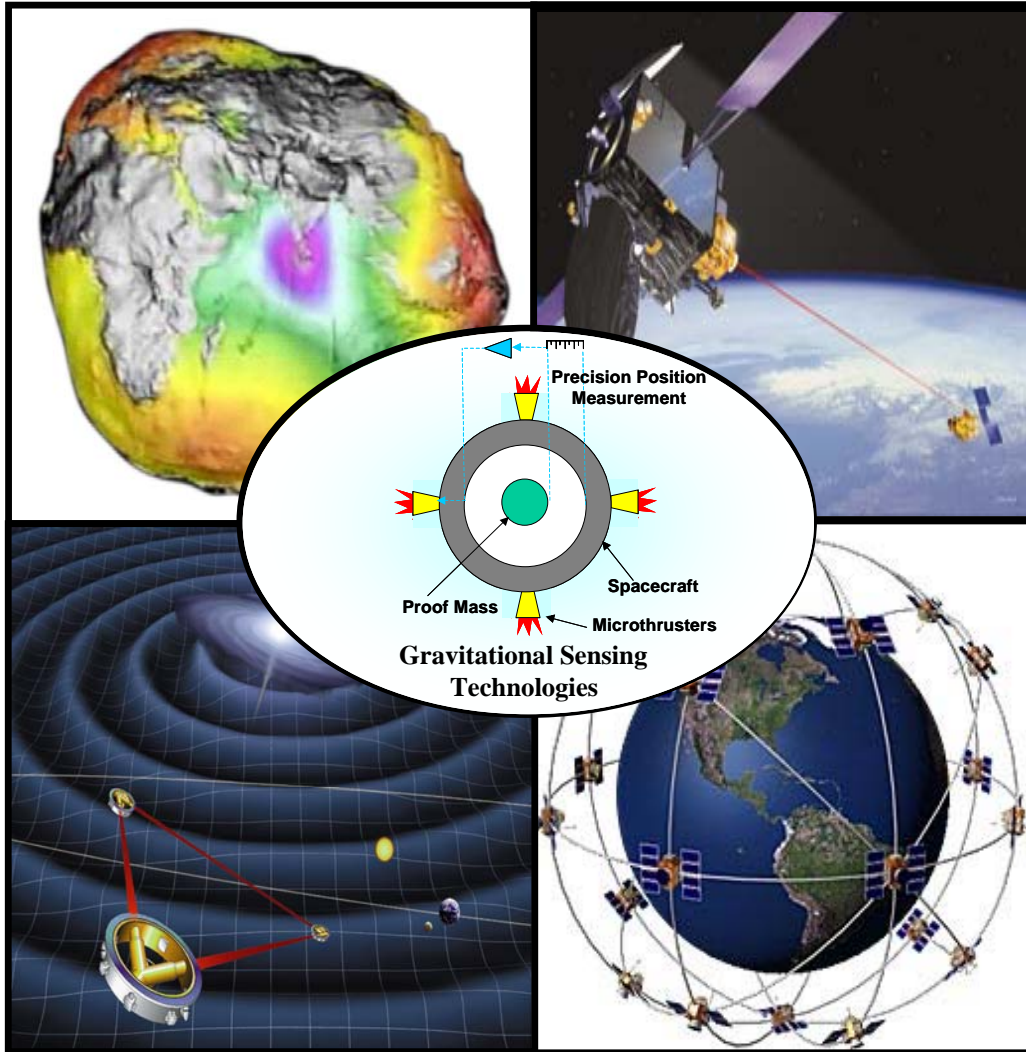
Gravitational Reference Technologies: Critical for U.S. Space Leadership

*Sasha Buchman, Robert L. Byer, John Hanson, Daniel B. DeBra, David L. Klinger, Scott D. Williams
Stanford University, Stanford CA 94305*

*Larry D. Dewell, David B. Schaechter, Nelson Pedreiro, Domenick J. Tenerelli
Lockheed Martin Space Systems Company, Palo Alto CA 94304*

Geodesy, Natural Resources,
and National Security

Earth and Space
Imaging



Gravitational Wave
Detection

Satellite Orbit
Management

June 07, 2004

Gravitational Reference Technologies: Critical for U.S. Space Leadership

“Aerospace is a technology-driven industry. Long-term research and innovation are the fuel for technology. U.S. aerospace leadership is a direct result of preeminence in research and innovation.”

- Commission on the Future of the U.S. Aerospace Industry
Final Report, Nov 18, 2002

Executive Summary

US development of Gravitational Reference Sensor Technology is essential to continuing our traditional leadership role in science, technology and national defense. Creating this technological infrastructure will enable new and exciting missions in disciplines ranging from the fundamental sciences to national security – missions that require an ultra-precise anchor to inertial space.

The Gravitational Reference Sensor (GRS), by physically shielding a proof mass from stochastic non-gravitational disturbances, provides the basis for this inertial anchor. By itself, or when integrated with a complete drag-free control system, the GRS opens new frontiers in Earth imaging and space science, from the imaging of black holes, to the formation of precision distributed Earth-observing sensors, to the detection of subsurface mineral deposits and structures.

Over the past thirty years, the United States has taken GRS technology from concept, to hardware, to flight. The first GRS, called DISCOS, was developed by Stanford University and performed on-orbit on the U.S. Navy’s TRIAD drag-free spacecraft in 1974 [1]. Recently, GRS technology found application in space science, lying at the heart of the recently launched NASA Gravity Probe B mission to test Einstein’s Theory of Relativity. The GRS will again be crucial to the Laser Interferometer Space Antenna (LISA), part of the NASA SSE Strategic Plan; the LISA GRS will require performance improvement of *at least four orders of magnitude* over current GRS performance. Stanford University’s current GRS development for the ST-7 mission, part of the NASA New Millennium Plan, demonstrates continued technical excellence in GRS technology.

Despite this deep heritage, the United States faces the real possibility of ceding leadership in this critical technology area. The European Space Agency has demonstrated a strong commitment to GRS technology development, through its LISA Test Package, a competitor to the U.S. GRS design for LISA, as well

as its proposed Gravity Field and Steady-State Ocean Circulation Explorer (GOCE). Committed US investment is imperative to maintain leadership in this important enabling technology.

Introduction

From its inception in the ‘70s for providing precision geolocation to the US Navy, drag-free technology now forms the basis for space-based general relativity experiments and gravitational wave observatories, and opens new horizons for future space missions. Drag-free technology and its constituent components (depicted in *Figure 1*) revolutionize space mission design at three levels (see *Table 1*):

1. the Disturbance Reduction System (DRS) enables autonomous, precision orbit determination and maintenance, underground structure detection, and precision spacecraft formation flying
2. the Gravitational Reference Sensor (GRS), which forms the basis for the ultra-precise inertial sensing in the DRS, enables advances in autonomous spacecraft navigation and space-based target tracking
3. drag-free component technologies yield significant spin-offs in materials, integration and test processes, and electronics.

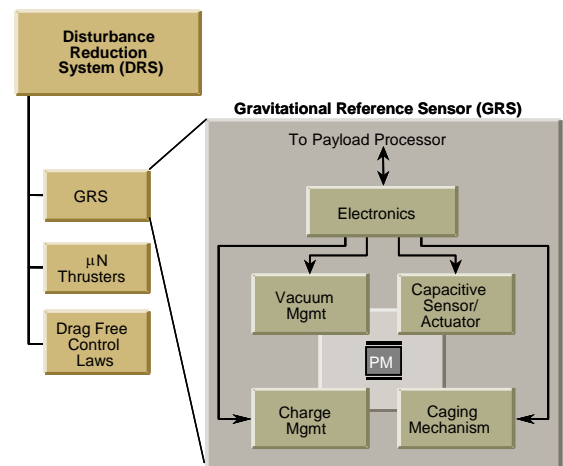


Figure 1 Drag-Free Capabilities Arise from Integration of Systems, Subsystems and Technologies

<i>DRS capabilities...</i>	<i>...open new horizons</i>
Autonomous forward prediction of spacecraft orbit	Dramatically improves GPS constellation performance without ground tracking
Automatic, continuous maintenance of low-earth orbit	Eliminates the need for coordinated stationkeeping operations; reduces ground staff; increases payload availability
Detection of propagating gravitational waves	New observations of the universe from gravity waves
Detection of temporal variation of Earth's gravitational field	Improves knowledge of Earth's ecosystem; detection of underground oil and mineral deposits; detection of underground man-made structures
<i>GRS capabilities...</i>	<i>... bring new possibilities</i>
Integrated precision inertial sensing of translation and rotation	Improves the performance and autonomy of the present GPS constellation; enables autonomous spacecraft rendezvous, guidance and space-based target tracking
<i>GRS component technologies...</i>	<i>... enhance U.S. technical leadership</i>
Proof mass manufacture	Materials processing; contamination control
Non-contact sensors and actuators	Precision control systems; electro-optical systems
Low-noise electronics	Ultra-sensitive space and biomedical instruments

Table 1: Drag-Free System Technologies Revolutionize Space Mission Possibilities

The Disturbance Reduction System

Simple in concept, yet exquisite in detail, the DRS consists of three elements:

1. the GRS (sensing),
2. microthrusters (actuation), and
3. control algorithms

These three elements combine to produce a control system with the capability of significantly counteracting the non-gravitational disturbances acting on a spacecraft.

Currently, non-gravitational forces, such as atmospheric drag, solar radiation pressure, solar wind, and micro particle impacts represent an impenetrable noise floor for autonomous Precision Orbit Determination (POD) of spacecraft. Due to the uncertain and stochastic nature of both the disturbance environment and the spacecraft-environment interaction, modeling alone falls well short of filling the POD need. A DRS-enabled spacecraft nearly eliminates this principal noise by providing a spacecraft the intrinsic,

autonomous ability of near-perfect cancellation of these non-gravitational forces.

Spatial variations in the Earth's gravitational field also result in orbital deviations, but the spatial variation is largely static, so once characterized at drag-free technology levels, their effects can be included in orbital mechanics models to provide improved POD and satellite autonomy.

Since the dawn of space flight, orbit determination and spacecraft orbital control (station keeping) maneuvers drive mission life cycle costs. Maneuvers, queued and managed by spacecraft ground operations crews and based on ground tracking, require a dedicated (and expensive) ground support team. One recent example is the managing of the Iridium spacecraft constellation [2].

A DRS-enabled satellite constellation offers the potential of greatly enhanced autonomy. *Figure 2* depicts such a constellation, the Global Positioning System (GPS), which has already simplified orbit determination and control. GPS enables real-time navigation feedback to spacecraft equipped with GPS receivers, and autonomous scheduling and execution of orbital correction maneuvers. GPS satellites *themselves* do not derive any POD benefit from the GPS constellation, but must also be updated regularly through ground tracking, thus limiting autonomy. The augmentation of future GPS constellations with DRS technology would add enormous autonomy to this critical U.S. space asset.



Figure 2 Drag-Free Control Enables Reduced Costs with Autonomous, Precision Orbit Determination

Continuous compensation of atmospheric drag as provided by DRS is more fuel-efficient than periodic orbit corrections based on GPS measurements [2]. Moreover, the control architecture for drag-free control is much simpler than a GPS-based navigation filter, which requires complex and uncertain models

for atmospheric drag, and is sensitive to software upsets. Finally, it should be noted that the real-time navigational accuracy of a spacecraft equipped with a GPS receiver could be improved significantly by the addition of DRS capability [2, 3], since the uncertainties in the process noise contributing to GPS navigation errors are essentially removed.

The benefits of drag-free control do not necessarily come only with a high development cost. The DRS has been developed heretofore to address the extreme accuracy requirements levied by space science missions, such as LISA. The specific *level* of drag-free performance is determined by DRS component technologies, such as proof mass residual magnetic moment, residual self-gravitation, and microthruster resolution. This implies that DRS designs are scalable in cost and performance to a level appropriate for a particular spacecraft mission.

The impact of the DRS moves from significant to revolutionary when one considers missions in which the DRS *is* the spacecraft sensor, or for which drag-free motion is integral to the spacecraft mission. Specifically, we identify three areas in which precision drag-free control enables a marked leap in capability:

1. gravitational wave observation,
2. precision Earth geodesy, and
3. precision formation flying for distributed aperture sensing.

The Laser Interferometer Space Antenna (LISA) depicted in *Figure 3*, a joint project with NASA and the European Space Agency, affords astronomers a new method for observing the universe through gravitational waves. Einstein's theory of General Relativity predicts the presence of these gravitational waves, minutely distorting the fabric of space-time. LISA currently provides advanced research and development funding for competing DRS architectures and technologies in both the US and Europe.

For gravitational wave detection, LISA requires drag-free motion of proof masses at acceleration levels at least four orders of magnitude beyond the current state of the art. Such capabilities necessitate advances in DRS component technologies, including non-contact sensing schemes, microthrusters and proof mass manufacturing techniques, all of which have applications beyond LISA and science. The Big Bang Observer (BBO), a proposed NASA gravitational wave mission targets observations of the inflation era of the universe and black holes. BBO requires drag-free performance improvement beyond that of LISA to achieve its science objective [4].

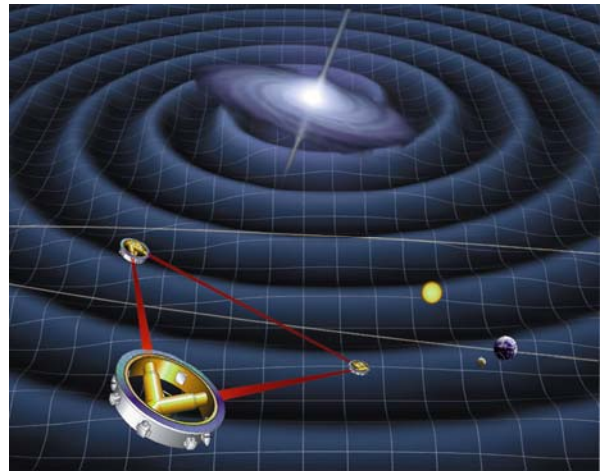


Figure 3 The LISA Observatory Requires Over Four Orders of Magnitude Improvement in Drag-Free Capability

Gravitational wave observatories such as LISA and BBO rely on the precision measurement of the changes in distance between two proof masses fixed in inertial space and separated by distances commensurate with the scale of the Solar System. Such proof masses moving through the spatially-varying gravitational field of Earth would measure to unprecedented precision the Earth's gravitational field and structure. The Gravity Recovery and Climate Experiment (GRACE), jointly funded by NASA and the German Aerospace Research Center (DLR), first used accelerometers to compensate for external disturbances in order to characterize the Earth's gravitational field and produced the geoid model in *Figure 4*. The follow-on to GRACE, EX-5, will characterize local geodetic variation over tens of kilometers of the Earth's surface [5], allowing scientists to address: interactions between ice masses, oceans and solid earth; the implications to sea level change; magma movement and evolution; and conditions prior to volcano eruption.

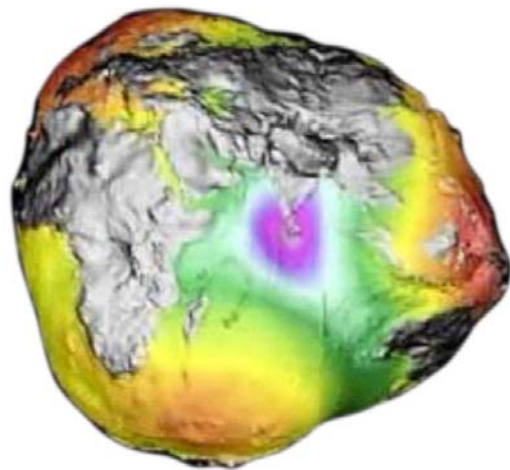


Figure 4 Drag-Free Enabled Precision Geodesy Yields a Means for Subsurface Detection

Precision Earth geodesy offers tantalizing possibilities in new areas, including:

1. detection of hidden deposits of natural resources, such as subterranean oil deposits [5]
2. detection and geolocation of underground man-made structures, such as large bunkers, storage facilities and laboratories
3. a stealth sensor, which produces no detectable signature and cannot be spoofed or jammed

Spacecraft formation flying is central to many future space missions. Both LISA and the GRACE follow-on, EX-5, require formation flying at heretofore-inaccessible precision levels. Drag-free technologies enable these challenging formation flying requirements. When formation flying spacecraft are configured to form a sparse aperture for a Synthetic Aperture Radar (SAR) or optical imaging system, such a stable baseline provides dramatic improvements in two key performance areas: sensor integration time (which directly translates into sensor sensitivity) and sensor repeatability over multiple orbits. Moreover, the task of constellation control of a formation of drag-free spacecraft is vastly simpler, since all differential forces affecting each spacecraft are continuously cancelled, resulting in less frequent impulsive thruster maneuvers to maintain the spacecraft formation.



Figure 5 Drag-Free Control Enhances Precision Spacecraft Formation Control

The GRS Subsystem

The GRS, which lies at the heart of drag-free control, promises substantial benefits outside the realm of the drag-free system architecture discussed earlier, in such areas as inertial sensing. The GRS consists of:

1. a proof mass that is free to translate and rotate within
2. a precision vacuum housing,
3. a complement of non-contact sensors that measure the position of the housing relative to the proof mass, and
4. a non-contact charge management system to prevent the buildup of electrostatic potential difference between the proof mass and housing.

These four elements are critical for drag-free *sensing*. The addition of non-contact proof mass actuators unleashes yet further possibilities in precision inertial sensing. A proof mass with non-contact sensors *and* non-contact actuators forms the basis for a *precision accelerometer*, which operates by forcing the proof mass to maintain its alignment relative to its housing using the non-contact actuators and feedback from the position sensors. In such an operating mode, the non-contact actuator commands necessary to maintain proof mass null position produces a measure of spacecraft acceleration.

In addition, further enhancements to the basic GRS component set allow this GRS-accelerometer to operate as a *precision gyroscope*, thus producing a complete inertial reference sensor for the spacecraft. Such a precision gyroscope provides the intrinsic science sensing on the Gravity Probe B spacecraft whose mission is to verify experimentally the frame-dragging effect predicted by General Relativity [6].

A natural synergy and complementary relationship exists between the technology investment path for DRS and drag-free control; and advances in precision GRS-based inertial spacecraft sensors. A GRS-based accelerometer will outperform the most precise standard accelerometers by several orders of magnitude. This performance leap arises because many of the stringent performance drivers required by GRS components to support drag-free operation (such as low-noise position sensors, precision proof mass charge management, etc) also yield improved accelerometer sensitivity.

Inertial reference sensors have always been critical spacecraft technologies, and their importance escalates with increasing demands for spacecraft autonomy. The GPS constellation, mentioned early in the context of drag-free control, would benefit greatly from precision accelerometers. Accelerometer information allows each spacecraft to propagate autonomously its ephemeris further into the future, thereby preserving the integrity of the GPS navigation signal in the event of ground station outages during periods

of critical geo-political conflict. Also, autonomous spacecraft rendezvous (see *Figure 6*), terminal guidance, and intercept, critical capabilities in future offensive and defensive counterspace, rely on precision accelerometers to meet their objectives. Finally, precision inertial attitude sensing, made possible by ultra-precise gyroscopes, provides strategic defensive systems (such as the Space-Based Laser) the ability to determine their target inertial state estimate, whose accuracy is fundamentally limited by errors in inertial angular rate measurement.

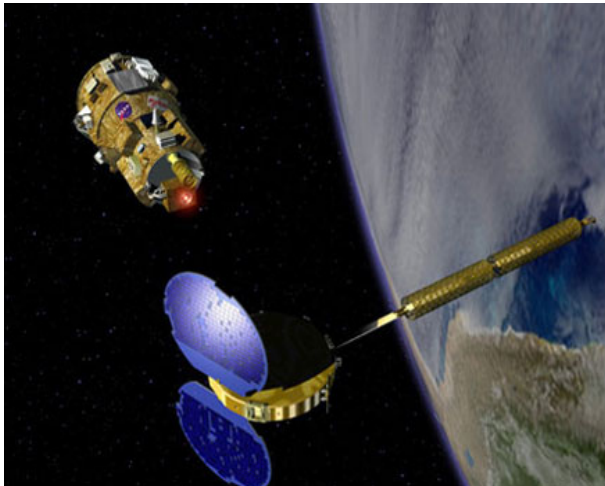


Figure 6 The Gravitational Reference Sensor Enables Autonomous Rendezvous and Tracking

Drag-Free Technology Spin-Offs

Investment in drag-free space systems today yields future payoffs. Drag-free spacecraft operation requires the integration of components and subsystems that themselves have potential stand-alone applicability to other space systems. The DRS relies on microthrusters which have variable throttle setting, and which have ultra low residual thrust noise; these thrusters are also applicable to precision spacecraft formation flying applications.

The GRS contains several component technologies with high spin-off potential. Manufacture of the proof mass requires the development of precision machining, cleanliness and contamination control to meet extreme surface finish and material uniformity; these same processes may be critical to related space materials, such as ultra-high-efficiency solar arrays, and high-performance ceramic materials. The GRS relies on ultra-sensitive and low-noise non-contact sensors to perform drag-free control; these same sensors may find applicability for precision control of space interferometry optical delay stages. In order to verify the analytical acceleration noise performance of drag-free control we develop sophisticated mathematical

models of acceleration error sources and sensor noise; the modeling of these noise sources may spur new methods for controlling and reducing these errors, leading to innovations in low-noise electronics and electromagnetic shielding.

Summary

Gravitational reference technologies open the door to unique possibilities in space science, earth science, national security, and engineering excellence; and as such, must be protected as a unique US asset. The United States must define and shape the drag-free future.

References

- [1] Staff of the Space Department of the Johns-Hopkins Applied Physics Laboratory and the Staff of the Guidance and Control Laboratory at Stanford University, "A satellite freed of all but gravitational forces", *AIAA J. Spacecraft*, v. 11, no. 9, Sept. 1974, pp. 637-44.
- [2] Leitner, J. et al, "Investigation of drag-free control technology for Earth science constellation missions", Final Study Report, NASA Earth Science Technology Office, 15 May 2003.
- [3] Axelrod, P., LaBreque, J. and Hartley, J., "Precision Navigation", NASA Earth Science Enterprise Technology Planning Workshop, 23-24 Jan., 2001, presentation materials.
- [4] Montemerlo, M., "Enabling technologies for future missions the Origins and SEU (Structure and Evolution of the Universe) themes", NASA HQ technical memorandum, Feb. 22, 2004.
- [5] Moring, F., "Orbiting gravity mappers might spot oil fields", *Aviation Week and Space Technology*, 2002.
- [6] S. Buchman et al , 'The technology heritage of the relativity mission, Gravity Probe-B' Proceedings of the Eighth Marcel Grossman Meeting on General Relativity. Ed: Tsvi Piran, World Scientific, Singapore Part A, pp1139-1159, 1999.