Abstract: The NASA New Millennium Program Space Technology 7 (ST7) project was selected for the purpose of flight validation of technology for minimizing disturbances on spacecraft and freely-floating test masses. Measurements of the motion of test masses are used for determining the gravitational field in its location, providing information on the nearby mass distribution or looking gravitational waves generated by distant star systems. Any unmeasured forces acting on the test mass cause a deviation from a purely gravitational trajectory and so limit the accuracy of the gravity field estimation. The ST7 project will validate the capability to eliminate unwanted forces to a level 3000 times lower than the current state of the art. The ST7 design is based on the concept of a freely-floating test mass surrounded by a spacecraft which shields the test mass from unwanted disturbances. Since some disturbance of the test mass can be caused by motion of the spacecraft itself with respect to the test mass, the disturbance reduction system includes the capability of precisely measuring the position of the spacecraft with respect to the test mass and control of the spacecraft position to within 1/100 of a wavelength of light. The overall system performance of the ST7 project will be infused into space observatories for gravitational waves such as the Laser Interferometer Space Antenna project, and into future missions for mapping the time-variable Earth gravity field. The ST7 precision control capability also has applications for separated-spacecraft interferometric imaging projects. ST7 will consist of an instrument package and a set of microthrusters, which will be attached to the European Space Agency’s LISA Pathfinder spacecraft with launch scheduled for 2008.

Keywords: New Millennium Program, ST7, gravitational waves, formation flying, colloidal microthrusters, disturbance reduction.

Introduction
The ST7 project is based on the concept of a freely floating test mass contained within a spacecraft that shields the test mass from external forces. The test mass will ideally follow a trajectory determined only by the local gravitational field. The spacecraft position must be continuously adjusted to stay centered about the test mass, essentially flying in formation with the test mass, to minimize changes in forces acting on the test mass due to the spacecraft itself. The ST7 system performance is characterized by the extent to which unwanted accelerations appear on the test mass and the accuracy with which the spacecraft is centered on the test mass. The project goals are to demonstrate acceleration levels below $9 \times 10^{-28}$ m/s$^2$/Hz and position control to 100 nm/Hz over a frequency range of 1 mHz to 30 mHz.

In order to measure the level of accelerations appearing on the test mass, its trajectory must be compared with a reference trajectory. For ST7, the reference is provided by a second identical test mass located within the same instrument assembly. Being located in the same spacecraft, the second test mass must be controlled at frequencies below the measurement bandwidth to keep its position relative to the primary test mass, while being free of control forces within the measurement bandwidth to provide a reference for acceleration measurements. The position of the second test mass will be measured with respect to the spacecraft. To keep the second test mass as free from external disturbances as possible within the measurement bandwidth, the spacecraft attitude will be controlled to follow the motion of the second test mass in axes perpendicular to the line between the two test masses.

The functionality of the ST7 system is indicated in Figure 1. The two cubical test masses are enclosed within cubical housings rigidly attached to the body of the spacecraft. Electrodes on the inner faces of the housings are used to measure the position and orientation of the test masses with respect to the housings. This capacitive sensing mechanism has been used in many previous missions, including the Triad drag-free demonstration [1] and on Gravity Probe-B [2]. A laser interferometer will measure changes in distance between the two test masses to infer the residual acceleration noise. Colloidal microthrusters will be fired to oppose external forces, which are primarily due to solar radiation pressure acting on the spacecraft solar panel for the ST7 validation project. The thrust will be continually adjusted to keep the spacecraft centered about the test masses.

The spacecraft position control requirements are derived both from the desire to demonstrate the ability to control spacecraft position to a fraction of a wavelength of light and to minimize variation on the forces exerted on the test masses from the gravitational attraction of the spacecraft components and from spacecraft magnetic and electric fields. In order to control the position of the spacecraft with an accuracy of 100 nm/Hz, the position of the test mass with respect to its housing will be measured with an accuracy of 9 nm/Hz, and the thrusters will have output controlled with a step size of 0.1 $10^{-6}$ N and a stability of...
Gravity disturbances are monitored by non-contacting capacitor plates divided by the distance between test masses, which is nominally 30 cm.

For ST7, the key new technologies are the microthrusters and the test masses combined with the means for measurement and control of the test mass with respect to the spacecraft into a Gravitational Reference Sensor (GRS). The GRS units are being developed at Stanford University. The microthrusters are being developed by Busek Co., Inc. The control algorithms and software for adjustment of the spacecraft position and orientation are being developed by the NASA Goddard Space Flight Center. The laser interferometer and interface electronics are being developed by JPL. The ST7 equipment will be hosted on the European Space Agency LISA Pathfinder spacecraft, which will carry ST7 and related European experiment equipment to the Earth-Sun L1 Lagrange point for the purpose of demonstration of the system capabilities. The ST7 project elements are described below.

Gravitational Reference Sensors
Each Gravitational Reference Sensor (GRS) consists of a test mass that floats freely in its housing. The separation between the test mass and its housing in all six degrees of freedom is monitored by non-contacting capacitor plates fixed to the housing. The largest disturbances to the inertial trajectory of a spacecraft (radiation pressure, residual gas drag, and particulate impacts) are cancelled by the basic concept of a drag-reduction system. The final performance of the system will be limited by a number of smaller disturbances. These disturbances fall into three categories: 1) variations in the gravitational potential at the test-mass location, 2) momentum transfer to the test mass by residual gas and cosmic radiation particles, and 3) variations of the electromagnetic fields at the test-mass location. The main gravitational fluctuations are due to the thermal distortion of the spacecraft and to the relative displacement of the test-mass with respect to the spacecraft. Improving the thermal shielding, using materials with low temperature coefficient, and maximizing the symmetry of the mass distribution of the spacecraft will reduce the thermal-distortion effects. Reducing the gravity gradient and displacement of the test mass minimizes the gravity noise caused by spacecraft displacement. For reasonable space-experimental pressures, $10^{-7} – 10^{-9}$ Pa at 250 – 300 K, the forces caused by residual gas impacts are dominant compared to forces produced by cosmic radiation, though well below the requirement level. A number of electromagnetic effects cause test-mass disturbances, and each can be minimized to a considerable extent. Radiation-pressure differences across the gravitational sensor housing are reduced by thermal isolation and making heat leaks as symmetrical as possible. Discharging the test-mass, reducing its displacement, and maximizing the test-mass-to-housing gap minimizes electric forces on the charged test mass. Fluctuating magnetic fields cause magnetic forces and, for a charged test mass, Lorentz forces. These forces are reduced by choosing a test-mass material with magnetic susceptibility of less than $10^6$ and by discharging of the test mass.

The GRS test mass will be a cube of low magnetic susceptibility Au-Pt that is 4 cm on a side and has a mass of approximately 1.2 kg. A sample test mass is shown in Figure 2. The surrounding housing will form a cubical cavity with a 2 mm gap between the test mass and the housing. Electrodes will be deposited on the sides of the housing as shown in Figure 3. One main electrode will be used to measure position in the direction of the second test mass, with a hole in the electrode for the laser beam used by the interferometer. To measure position and orientation, two electrodes are located on the ‘top’ and ‘bottom’ faces of the housing and four electrodes on the ‘left’ and ‘right’ side faces. To minimize thermal gradients across the housing it is constructed of BeO ceramic which has high thermal conductivity while providing an insulator substrate upon which the electrodes can be formed by deposition coatings.

The capacitive measurement technology for position readout and attitude control of the test masses is based on the similar system used for GP-B. For GP-B, the test mass position is measured with capacitance bridges, using a 40 mV-PP 34 kHz sinusoidal sense signal superimposed onto the drive electrodes. The high-precision, low-noise

![Conceptual diagram of the ST7 Disturbance Reduction System](image-url)
design of the bridge results in an operational noise floor of 0.01 nm²/Hz, a resolution that allows the control system to meet the centering requirements for the GP-B mission at the cost of increased electrical force noise acting on the masses. (The GP-B test masses are spheres with primary purpose of providing an inertial spin direction; thus the electrostatic control forces keeping the spheres centered do not, to first order, affect the GP-B primary science measurement.) For ST7, in order to reduce force noise from the measurement system acting on the test mass, the position readout requirements will be relaxed to 9 nm²/Hz.

Figure 2. Test mass for ST7

Figure 3. Electrode layout for ST7

The two GRS units will be contained within a single titanium chassis with separate vacuum enclosures for the two test masses as shown in Figure 4. The optical bench for the laser interferometer for measuring the relative positions will be mounted at the center of the chassis.

**Colloidal Microthrusters**

ST7 requires microthrusters capable of smoothly varying thrust from 1 to 20x10⁻⁶ N with 0.1 10⁻⁶ N resolution and temporal stability of 0.01 10⁻¹² N²/Hz for control of the position and attitude of the spacecraft. For ST7, the maximum thrust is determined by the need to counter the solar radiation pressure on the spacecraft, which is 30x10⁶ N. The thrust will be controlled with 0.1 10⁻⁶ N resolution in order to control the spacecraft position with respect to the reference (test mass) within 100 nm²/Hz. The microthrusters must smoothly and continuously counter all external disturbances with control authority over all six degrees of freedom of the spacecraft motion.

The ST7 microthrusters use a propellant which is a colloidal fluid. The fluid is fed through a needle by a pressurizing system. At the tip of the needle, a high electrical field is applied, which causes droplets to form and to be ejected from the tip of the needle. The droplets are spontaneously charged and accelerated by the electric field. Precise changes in thrust can be achieved by changes to the accelerating voltage. In order to prevent the spacecraft from becoming negatively charged by the continual ejection of positively-charged droplets, the microthrusters include a carbon-nanotube cathode to emit electrons to keep the spacecraft neutral.

Figure 5 shows a functional diagram of a typical microthruster needle. In general, the smaller the tube diameter the better, but practical considerations limit the tube inner diameter to some tens of microns. The propellant is relatively nonvolatile to minimize its evaporation when exposed to the vacuum of space and has a high electrical conductivity. When sufficient voltage is applied between the extractor and the microtube (emitter), the liquid surface deforms into a cone, as sketched in Figure 5. Taylor [3] found that this cone has a fixed angle of 49.3°, regardless of the type of fluid, its exact properties, or emitter geometry. Equilibrium on the surface of the cone is maintained by the balance of the liquid surface tension and electrostatic pressure. Near the tip, the electric field intensifies to a value that cannot be counteracted by the surface tension, and the cone tip transitions into a small-diameter jet of charged droplets, which are accelerated to produce thrust.
A typical single emitter needle thruster produces a maximum thrust of $3 \times 10^{-6}$ N. To achieve larger thrust, multiple needles are needed. For ST7 each thruster will use an array of 9 needles as shown in Figure 6 [4]. Two clusters of thrusters will be used, with four thrusters per cluster. Each cluster consists of the thrusters, one carbon nanotube emitter, the propellant feed system and the power-processing unit (PPU). The PPU contains all the DC-DC converters to power the system and the autonomous controls for the carbon nanotube field emission neutralizer. The full thruster cluster configuration is shown in Figure 7. Measurements of thruster performance have been carried out and shown to meet performance requirements [5].

**Dynamic Control System**

The spacecraft position and attitude are controlled with respect to the two GRS test masses. One test mass must be controlled (suspended) with respect to the second (free) test mass at low frequencies to keep it within its reference housing. The suspension force on the controlled test mass is exerted by applying control voltages to electrodes on the reference housing. This control force is a function of the position of the test mass within its housing, which couples motion of the spacecraft into a change in force on the test mass. In the absence of the control force, there would still, in general, be forces on the test masses that vary with the position of the spacecraft. One such coupling will arise from the gravitational force from the spacecraft components acting on the test masses (self gravity) that will be position dependent unless the mass is distributed with complete spherical symmetry.

Because of these coupling terms the spacecraft motion with respect to the test mass needs to be minimized. The spacecraft position in each of three translation degrees of freedom can be controlled relative to the free test mass. The position of the suspended test mass is controlled (below the measurement band) in the direction of the free test mass using electrostatic suspension. The spacecraft attitude will be adjusted in two angular degrees of freedom to minimize motion of the spacecraft relative to the suspended test mass in the directions transverse to the direction between the test masses. The spacecraft will be controlled about the direction between test masses to keep the spacecraft solar panel pointed at the sun. Each test mass will then be
controlled in orientation to match the attitude of the spacecraft using electrostatically applied torques.

The Dynamic Control System determines the thruster commands to control the spacecraft position and attitude, based on the measurements of the position of each test mass relative to its housing. The electrostatic forces and torques for the test masses are a function of the GRS units. The spacecraft control requirement is to keep the spacecraft centered about the two test masses to less than 100 nm²/Hz within the measurement frequency band of 1 mHz to 30 mHz.

The spacecraft position control requirements can be met with classical controller techniques, given the accurate position measurements of the test masses and the low level of thrust noise provided by the colloidal microthrusters. Figure 8 shows the power spectral behavior of a simulated system response for the position of the spacecraft with respect to the free test mass. The position control accuracy requirement is met throughout the measurement band. The position noise exhibits a slight increase near the controller unity gain frequency near 0.1 Hz. The selection of the crossover point represents a trade off between controller update rate and thruster dynamic range requirements. A higher controller update rate requires higher data and command transmission rates and lower data latencies, requiring high bandwidth and increased computation capability. A lower controller update rate results in larger variation in commanded thrust. An update rate of 10 Hz has been selected to be compatible with serial data transmissions while keeping thruster variations to 20% or less of nominal over time scales shorter than 1000 seconds.

**Figure 8.** Power spectrum of simulated spacecraft control response for the position relative to the free test mass

**Laser Interferometer**

The ST7 includes a laser interferometer for validation of the gravitational reference sensors. While the laser interferometer is not a technology requiring spaceflight validation, its performance is key to achieving the flight demonstration goals. The interferometer design chosen is a simple homodyne system with an unmodulated laser beam. This design has been chosen to give adequate performance within the ST7 project cost constraints.

The homodyne interferometer is based on a simple Michelson interferometer, and compares the distance between the two GRS test masses with the length of a stable reference arm. The reference arm is formed by two mirrors on the optical bench. The stability of the reference arm comes through using a material of low thermal expansion for the optical bench combined with an environment of high thermal stability. The thermal stability requirements are driven by the need to keep thermal radiation force variations on the test masses sufficiently small; the interferometer thermal stability requirements are less stringent.

Figure 9 shows a schematic diagram of the interferometer. Light from the laser is brought to the optical bench via a fiber. The laser beam is split so that half goes to each of two simple Michelson interferometers which measure the change in distance between each test mass and the optical bench. For each test mass, light from the laser is divided at a beam splitter with half reflected off the test mass and half reflected off a reference mirror. The beams recombine at the beam splitter and are imaged on a quadrant photodiode. A change in position of the test mass causes the intensity of the beam on the photodetector to change. The change in intensity is recorded by an analog-to-digital converter in the GRS computer electronics. This double-Michelson design allows separate readouts for the two test masses. Quadrant detectors are used to measure the angle between the normal to the test mass surface and the laser beam direction. The pointing information is used to adjust the orientation of the test mass by applying voltages to the orientation control electrodes.

**Figure 9.** Functional block diagram of ST7 homodyne interferometer

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