Drag-free Control and Drag Force Recovery of Small Satellites

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Drag-free satellites provide autonomous precision orbit determination, accurately map the static and time varying components of Earth's mass distribution, aid in our understanding of the fundamental force of gravity, and will ultimately open up a new window to our universe through the detection and observation of gravitational waves. At the heart of this technology is a gravitational reference sensor, which (a) contains and shields a free-floating proof mass from all non-gravitational forces, and (b) precisely measures the position of the test mass inside the sensor. Thus, both test mass and spacecraft follow a pure geodesic in spacetime. By tracking the position of a low Earth orbiting drag-free satellite we can directly determine the detailed shape of geodesics and through analysis, the higher order harmonics of the Earth's geopotential. This paper explores two different drag-free control systems on small satellites. The first drag-free control system is a continuously compensated single thruster 3-unit CubeSat with a suspension-free spherical proof-mass. A feedback control system commands the thruster and Attitude and Determination Control System to fly the "tender" spacecraft with respect to the test mass. The sphere's position is sensed with a LED-based differential optical shadow sensor, its electric charge controlled by photoemission using UV LEDs, and the spacecraft position is maintained with respect to the sphere using an ion electrospray propulsion system. This configuration is the most fuel-efficient drag-free system possible today. The second drag-free control system is an electro-statically suspended cubical proof-mass that is operated with a low duty cycle, limiting suspension force noise over brief, known time intervals on a small GRACE-II -like satellite. The readout is performed using a laser interferometer, which is immune to the dynamic range limitations of voltage references. This system eliminates the need for a thruster, enabling drag-free control systems for passive satellites. In both cases, the test mass position, GPS tracking data, and commanded actuation, either thrust or suspension system, can be analyzed to estimate the 3-axis drag forces acting on the satellite. The data produces the most precise maps of upper atmospheric drag forces and with additional information, detailed models that describe the dynamics of the upper atmosphere and its impact on all satellites that orbit the Earth. This paper highlights the history, applications, design, laboratory technology development and highly detailed simulation results of each control system.