Design, construction and optical test of a laser-ranged test mass for deep space missions

To probe gravity in the outer solar system and avoid the experimental complications such as, for example, the so-called “Pioneer Anomaly” (which is the apparent deceleration of the Pioneer 10 and 11 spacecrafts with respect to the $1/r^2$ force-law of about 10^{-9} m/sec^2), a new concept of interplanetary mission has been conceived by JPL and other European research groups (including LNF, through COFIS). Deep Space Gravity Probe mission proposed to NASA and as a candidate ESA mission for Cosmic Vision, will study gravity at large distance from the Sun (up to 80 AU) and will verify the PA. Presently the formation consists of a main active satellite that will release few spherical laser-ranged test masses. The motion of a mass with respect to Earth will be measured through radio waves from Earth to active satellite and through laser ranging from active satellite to test mass: when the laser beam hits the test mass, the returning beam is focused through a telescope on a detector which don’t interfere with the out coming beam. The deep space test masses are spheres equipped with CCRs. The mother-ship active spacecraft will be forward-backward symmetric. Starting from Saturn, more than one test mass will be released by the mother-ship during the interplanetary journey, in order to test the $1/r^2$ force-law in different regions of the solar system.

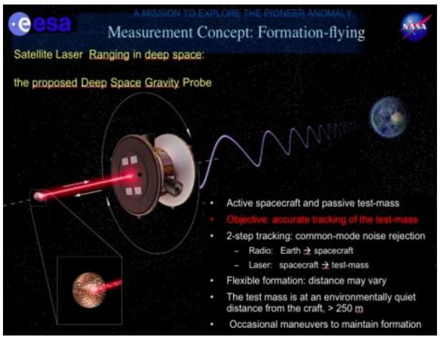


Figure 1: concept of the DSGP satellite formation.

Laser-ranged test masses for Deep Space missions

In deep space the magnitude of Thermal Thrusts (TTs) is enormously reduced compared to those suffered by payloads near the Earth, since beyond Saturn (>10AU) the solar constant is reduced by more than two orders of magnitude compared to the Earth solar constant AM0 (1370 W/m^2). TTs are proportional to the Surface/Mass (S/M) ratio and to the solar constant AM0. This means that several test masses small and light enough to be conveniently carried by an interplanetary spacecraft will have a good SLR performance keeping the TT background well under control with respect to the value of the PA. Thinking of this, the mechanical drawing and machining of the test mass prototype has been realized by the SPCM service of the Technical Division at INFN-LNF. The test mass mechanic structure has been funded by LNF, as well as the future SCF-Test campaign.
This is a spherical aluminum shell of 16 cm diameter and 2Kg weight, equipped with 102 BK-7 CCRs, each of active area of approximately 18 mm^2. All the retroreflectors for this prototype have been purchased, FFDP-tested individually and found to meet the optical specifications. They had been all mounted on the two half-shells and for this partially equipped shell we performed optical FFDP characterization in air and isothermal conditions.

Figure 2: the INFN-LNF DSGP test mass

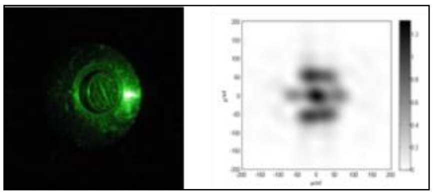
Test mass optical characterization

On April 2010 we started taking data with the complete test mass mounted inside the SCF cryostat. The laser beam (90 mW Nd-YAG 532nm) has a diameter of about 40mm with a Gaussian intensity distribution over the cross-section. Two different CCDs were used to take the horizontal and vertical polarized components of the FFDP separately. After the acquisition the two components were combined by the analysis software. As a first measurement phase we decided to take some FFDPs with the beam hitting several retroreflectors at the same time, in different significant configurations (like those, for example, shown below). Every plot is coupled with an image taken with a standard IR camera, showing the actual beam-retroreflectors attitude in which the FFDPs has been acquired. We have no longer observed only one but several CCRs mounted on a spherical surface with a small curvature radius and, thus, with:

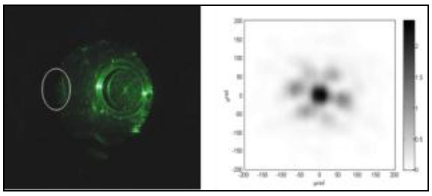
- large (compared to the single CCR diameter) non-reflecting “dead zones” ;
- angles between the front face and the laser beam direction that, for some configurations, could rise to the retroreflection limit.

This situation can lead to have, in some cases, that more CCRs, illuminated at the same time, show a light return similar or even lower compared to that of a single CCR. This can be explained by two main reasons:

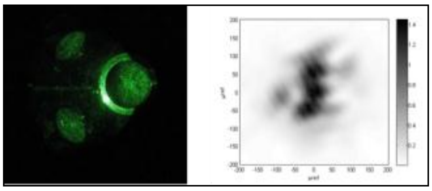
- the laser beam has a Gaussian decreasing trend along the radius and the single CCR is right at the center of the beam, while the three CCRs are at the edge;
- the single CCR has his face perpendicular to the beam while the three CCRs are tilted.



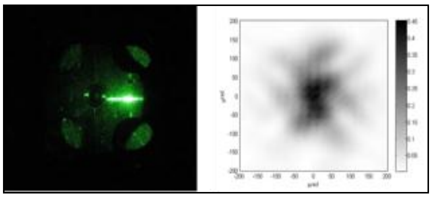
Configuration 1: a single CCR is completely hit by the central part of the laser beam.



Configuration 2: one CCR completely hit plus another half of the contiguous (highlighted with a white ellipse).



Configuration 3: three CCRs hit at the same time. One almost completely and the others just for a half.



Configuration 4: four CCRs hit at the same time. Each for less than a half.

It was interesting to investigate the differences in the amount of light return between all configurations we considered. In particular we have normalized the FFDP no longer with the Airy peak but with a new reference that is represented by the configuration in which only a single CCR is orthogonal and completely hit by the central part of the laser beam.

Conclusions and future prospects

We designed, built and performed the in-air and isothermal optical characterization of a test mass for the proposed Deep Space Gravity Probe mission. The research activity of WP5200 of the COFIS study reached all goals foreseen in the three-year program. By complementing the COFIS activity with additional support by INFN-LNF, we have carried out an original hardware construction and preliminary test. This prototype instrument is the initial step to study also other future mission in the interplanetary space of the Solar System. At the moment we are investigating new opportunities to propose this prototype (as well as additional prototypes) for an SCF-test in the context of the new ESA roadmap for Solar System science. JUICE (JUpiter ICy moons Explorer) is an L-class missions for the ESA Cosmic Vision program that could represent an opportunity to use laser ranged test masses during the long-lasting transfer orbits to the gaseous giants. JUICE is a planned European Space Agency (ESA) spacecraft to visit the Jovian system, focused in particular on studying three of Jupiter's moons; Ganymede, Callisto, and Europa. It will characterize these worlds, all thought to have significant bodies of liquid water beneath their surfaces, as potentially habitable environments.
Recently (July 17, 2012) the JPL on the official website (http://www.jpl.nasa.gov/news/news.cfm?release=2012-209) released important news and findings on the Pioneer anomaly. This will change part of the prospects and the purposes on the deep space missions for ESA and NASA but also remarks the importance of a completely passive, spherical test mass to test the $1/r^2$ force-law.