

LISA Gravitational Reference Sensors

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Abstract. We review state of the art of the gravitational reference sensor (GRS) for the Laser Interferometer Space Antenna (LISA). LISA consists of three identical spacecraft placed at the corners of an equilateral triangle with a 5 million kilometer baseline. In the LISA baseline design, the spacecraft at each corner will have two optical assemblies subtending an angle of 60 degrees. A proof mass (PM) is housed in a GRS located at the center of each assembly. LISA measures the distance variation between PMs separated by 5 million kilometers to a precision of 40 pm/Hz^{1/2}. The GRS must shield the PM from external disturbances such as solar wind and functions as a drag-free sensor for spacecraft control. The GRS must minimize the back action and cross talk exerted by measurements themselves. Significant progress has been made in the design, fabrication and testing of the GRS. LISA Pathfinder will fly a test GRS system scheduled around 2009. In addition, there have also been new architectures proposed to simplify the LISA payloads by using a single PM and therefore only one GRS per spacecraft. Further a modular GRS (MGRS) structure is proposed to reduce complexity. Optical sensing and large gap size between the PM and the MGRS housing are proposed to lower the disturbance level. Many experimental, engineering design, and trade off studies are underway.

1. Introduction

The Laser Interferometric Space Antenna (LISA) [1-3] is a constellation of three spacecraft designed to measure the gravitational wave radiation at frequencies between 30 μ Hz and 1 Hz. LISA is a highly sensitive space-borne gravitational wave observatory requiring unprecedented precision. At the heart of the LISA spacecraft is the Gravitational Reference Sensors (GRS), in which the positions of proof masses (PMs) are sensed at each end of the 5 million kilometer distance measurement. The PM must follow a free-fall trajectory, as precisely as possible, with a residual acceleration error less than 3×10^{-15} m/Hz^{1/2} at 0.1 mHz. Therefore, the GRS should shield the PM from the external disturbances. The GRS design should also avoid back action and cross talk exerted by the measurements themselves.

The current design of LISA GRS was formed about 10 years ago and has been fine-tuned since then. The spacecraft at each corner will have two optical assemblies subtending an angle of 60 degrees and two GRS units as shown in Figure 1 (a). Extensive effort in developing the GRS has led to significant progress [4-6]. Two GRS units will be flown in LISA Path Finder (LPF) scheduled to launch around 2009. There also have been discussions on a novel modular GRS (MGRS) architecture, (also referred to as “strap down” GRS) featuring a single PM and/or non-direct illumination [8-12], which potentially will lead to lower cost and better performance.

2. LISA Pathfinder (LPF) gravitation reference sensor

LPF [6] is a mission for LISA risk reduction, where GRS sensitivity will be tested at a level a factor of 10 relaxed requirements than the LISA requirements. GRS is the core payload on the spacecraft. The LPF GRS is mainly being developed by the University of Trento [2-6] and its consortium. Figure 1(b) shows a photo of GRS housing structure. The PM design calls for a 70%Au–30%Pt alloy, with composition chosen to achieve lowest magnetic susceptibility, while retaining high density to minimize the displacement caused by disturbances. The motions of the PM have different constraints in different degrees of freedom. In the direction of optical axis along the telescope, the spacecraft is to follow the freely floating PM. However, because each spacecraft contains two independent PMs, this cannot be accomplished to the full extent without some feedback control. With respect to other degrees of freedom, the alignment of the spacecraft is determined by the lines of sight to the distant spacecraft. The PMs must be controlled to follow this alignment by a laterally acting suspension. A capacitive sensing scheme is used to monitor the relative displacements of the PM and spacecraft, and elaborate control techniques afford the control required. The capacitive sensors have split electrode patterns on each side of the housing wall. The gap size between housing and PM is ~ 3 mm. A combination of electrostatic forcing and micro thrusters are used for PM alignment and drag-free control. Cross talk between the two GRS's is currently identified as one of the leading noise sources by mathematical modeling [6].

The GRS noise level has been extensively tested using a soft torsion pendulum oscillating at low frequencies. An acceleration noise level below 10^{-14} $\text{m/s}^2 \cdot \text{Hz}^{1/2}$ was achieved [4, 5]. The electronics noise level is $\sim 2 \times 10^{-7}$ $\text{rad/Hz}^{1/2}$ from ~ 0.1 mHz to 1 Hz, satisfying the LPF requirement, as shown in Figure 1 (c).

Engineering models of various GRS subsystems, vacuum, electronics, PM, and caging mechanism for space flight were developed for the LPF mission. The LPF GRS experiences will be very useful to LISA flight of three spacecraft constellation, and for any other GRS configurations to be potentially used in LISA.

A NASA program similar to LPF, called the ST7 GRS [7], was also developed to an advanced stage.

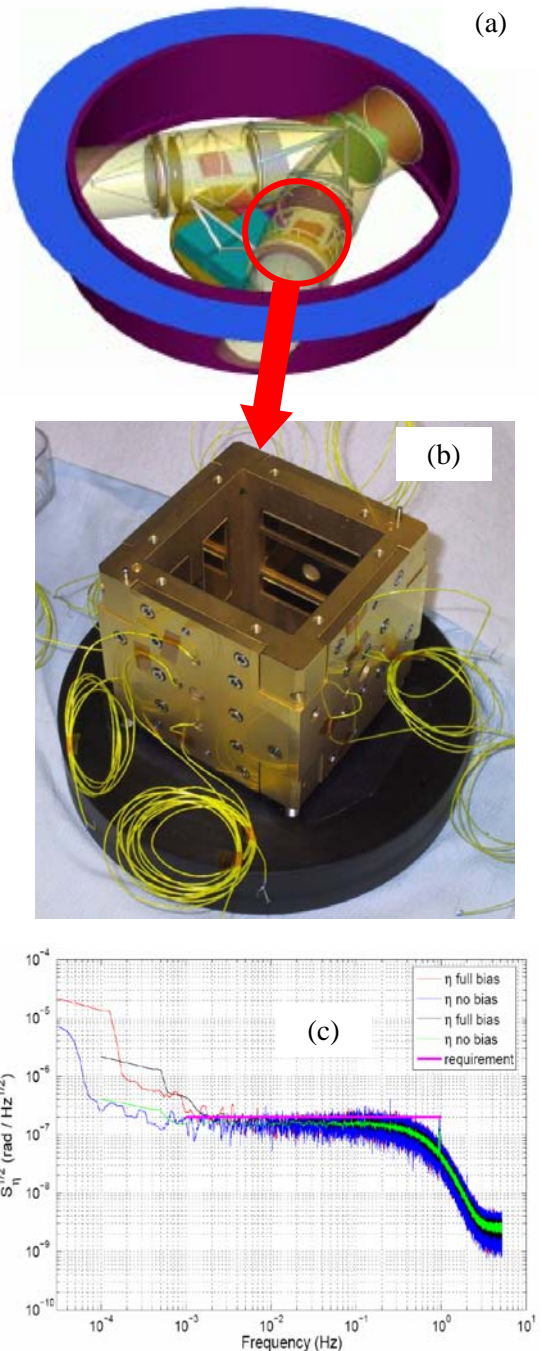


Figure 1: (a) LISA spacecraft structure. GRS position is circled. (b) GRS housing. Electrode pattern for capacitive sensing are shown. (c) Readout electronics noises. (Courtesy of Stefano Vitale)

3. Modular Gravitational Reference Sensor (MGRS)

To enhance LISA performance and lower cost, the Stanford team has been developing a novel MGRS. Figure 1 shows the conceptual design of the MGRS [8-10]. This is a multi-layer proposal containing several key suggestions: 1) The laser beam from the remote spacecraft does not directly illuminate the PM, but illuminates the GRS housing surface. The GRS is a module that provides an external position reference. 2) Only one PM per spacecraft is used to permit true drag-free operation. The MGRS measures the position of the PM mass center. 3) Multiple internal optical sensors are used to measure the gap between the PM and the housing. Optical sensing allows a large gap which reduces disturbances. In the all-reflective version of the MGRS, measurements are made from the PM to the inside of the housing wall and from the housing wall to the incoming laser beam phase front. This sequence ensures the shortest possible optical path, reducing thermally-induced fluctuations at low frequencies. The PM may be spun up. Grating patterns can be imprinted on the PM for angular sensing and surface map tracking. The telescope will use a multiple element configuration, enabling the steering of the telescope by adjusting the smaller binary and tertiary mirrors rather than moving the whole telescope.

The MGRS only uses a single PM instead of two. Measurement of a gravitational wave needs only one PM per spacecraft. The disturbances to the single PM are lower than the two-mass system by at least a factor of $\sqrt{2}$. But more importantly, the single PM eliminates the constraint forces required in a multiple PM system. Cross coupling of these constraint forces along the sensitive axes is a significant source of acceleration noise. Elimination of these constraint forces would reduce the disturbances by more than $\sqrt{2}$. A single spherical PM is preferred due to reduced control complexity and cross coupling. Much progress has been made in MGRS experiment and design, as discussed in [9], and extensive references therein.

4. Novel payload architectures for LISA

Similar to the MGRS concepts, Astrium Germany – as prime contractor of two subsequent industrial studies in 1999 and 2005, respectively, - had also defined and assessed novel payload architectures [11, 12]. The promising concept is similarly characterized by a single optical bench and a single active inertial sensor, serving both adjacent interferometer arms via two rigidly connected off-axis telescopes. In-plane triangular constellation “breathing angle” compensation is accomplished in the fixed telescope configuration by common in-field of view pointing actuation of the transmit/received beams line of sight. Therefore a dedicated actuation mechanism located on the optical bench is employed in addition on bench actuators for differential pointing of the transmitted and received direction perpendicular to the constellation plane, a function mandatory for all payload concepts.

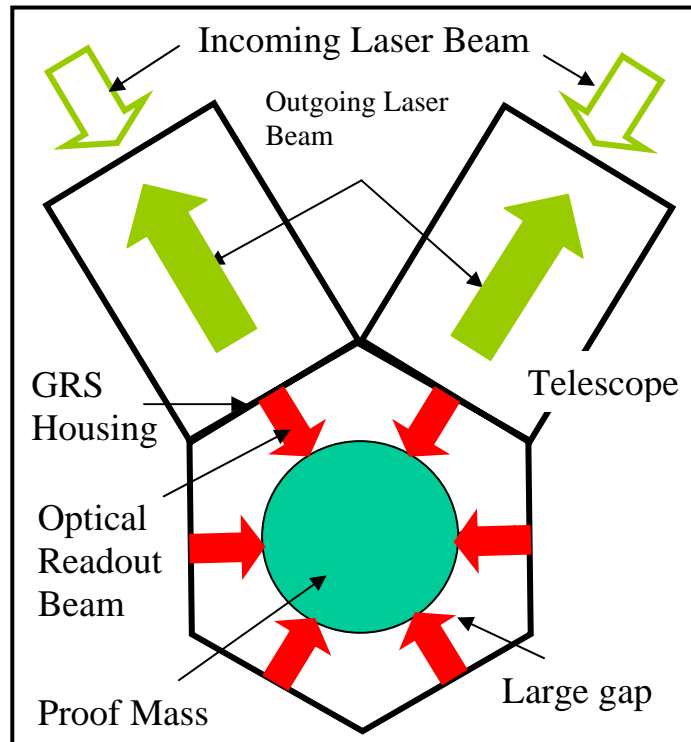


Figure 2: The concept of the modular GRS. The external laser beam does not illuminate the proof mass. The GRS is a modular unit, where the internal distance measurement is made from proof mass to housing inside the GRS. The precision measurement is relayed directly to the external surface through the housing wall.

A technical challenge is the actuation mechanism pointing jitter, and the monitoring and calibration of the laser phase walk which occurs while changing the optical path inside the optical assembly during re-pointing. Two-step interferometry (strap down) and a dedicated full laser interferometer read out of critical degrees of freedom of the PM are employed. The single PM is maintained as cubic, but in free-fall in the lateral degrees of freedom within the constellation plane. Also the option of a completely free spherical PM with full laser interferometer readout has been conceptually investigated. The spherical PM would rotate slowly, and would be allowed to tumble. Imperfections in roundness and density would be calibrated on-ground and in space and further, by providing attitude information via a grid of tick marks etched onto the surface and monitored by the laser readout.

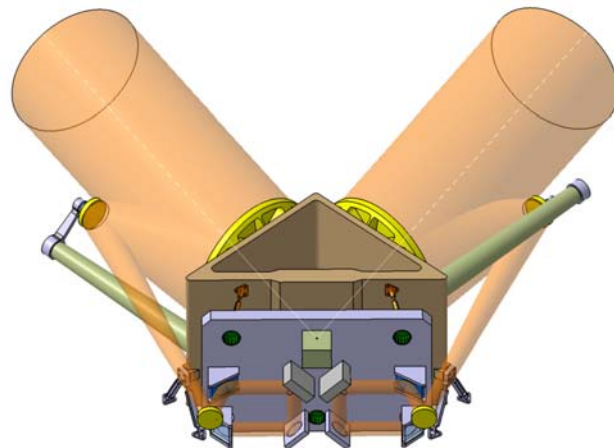


Figure 3: Single proof mass and single GRS payload structure.

5. Summary

LISA GRS research has made considerable progress in enabling LPF mission to perform the testing required by LISA. A novel MGRS architecture holds the promise of a simpler structure with true drag-free performance.

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