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Modular Gravitational Reference Sensor: Simplified Architecture to future LISA and BBO

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Abstract

We present the Modular GRS (previously named as Stand-Alone GRS), in which the laser light from the remote spacecraft does not illuminate the proof mass. The modular GRS uses only a single spherical proof mass on each spacecraft and optical, as opposed to capacitive, position sensing. The use of a single sphere as the test mass avoids the issue of cross coupling that is inherent for the cubic proof mass, and allows true drag free flight with no forcing. Together, the modular design, optical sensing and a single spherical proof mass reduce the disturbances and the number of degrees of freedom that must be managed for future LISA and BBO.

1. Introduction

Gravitational wave detection is one of the most compelling problems in physical sciences [1, 2]. Laser Interferometric Space Antenna (LISA) [3, 4] and Big Bang Observatory (BBO) [5] are highly sensitive space-borne gravitational wave detectors requiring unprecedented precision. At the heart of the LISA and BBO spacecrafts is the Gravitational Reference Sensor (GRS), which houses proof mass (PM), providing reference at the end point of the distance measurement. [6-9].

Much progress has been achieved in LISA and its pilot studies, LISA Technology Package (LTP) and Space Technologies 7 (ST7) [6-9] in various aspects such as disturbance reduction, interferometry, data analysis, and more. However, there is urgency in studying GRS architecture, which could significantly simplify the LISA, but more importantly future LISA versions, such as BBO and DECIGO [10], and thereby enhancing the sensitivity and reliability and lowering the cost.

Until not long ago, the baseline design for LISA GRS had been direct illumination of the PM as published in 1998 [3, 4]. Beginning in 2003 we have revisited the GRS design with the goals of simplifying the design, reducing cross talk, and moving toward true drag free performance. We proposed the modular GRS architecture (stand-alone GRS) in 2004 [11-13]. 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. Therefore, the GRS is now a module providing positioning reference for external use. 2) Only one PM is used. The GRS measures PM center of mass position. 3) Multiple internal optical sensors are used to measure the gap between the proof mass and the housing. Optical sensing allows a large gap that reduces the disturbances. The single spherical PM has been flown in Triad [14, 15] and Gravity Probe–B (GP-B) missions [16]. Optical shadow sensing was used in Nova. follow-on to the Triad.

Since our presentation, the LISA and BBO baseline designs have changed substantially. The BBO has moved to a single PM [17]. In the new LISA baseline, the laser beam from the remote spacecraft no longer directly illuminates the PM, but instead measures the separation between remote GRS housings [18]. As such, the modular GRS architecture has been adopted partially in

LISA by avoiding direct illumination, and in BBO by using a single PM. In our opinion, the next step should be to use the single-proof-mass modular GRS without direct illumination of the PM.

We have made presentations and submitted several papers [19-25] on various details of Stanford GRS effort for ST-7, LISA, and BBO. This paper presents further development of the modular GRS concept and key technologies. Given the limited space, our account here can only provide high-level physical insights guiding our work. Further details will be presented elsewhere.

2. Review of the modular GRS architecture

Figure 1 shows a schematic overview of the modular GRS architecture [11-13]. The laser light from the remote spacecraft is heterodyned external to the GRS housing and does not illuminate the PM directly. The internal distance measurement is relayed to an external reference via the housing wall. The LISA fleet is intended to fly drag-free, requiring the PMs be shielded inside the housing to reduce disturbances such as solar wind and magnetic fields. The spacecraft follows the movement of the PM in a pure gravitational field. The optical bench and GRS housing are mounted on the spacecraft, which has a relative motion with PM, due to disturbances and the micro thruster noises. Two independent measurements are needed among three targets, namely, the PM, the incoming laser beam, and the position of the housing. In the modular GRS, measurements are naturally made from the PM to the housing wall, and from the housing wall to the incoming laser phase front. This sequence incurs the shortest possible optical path.

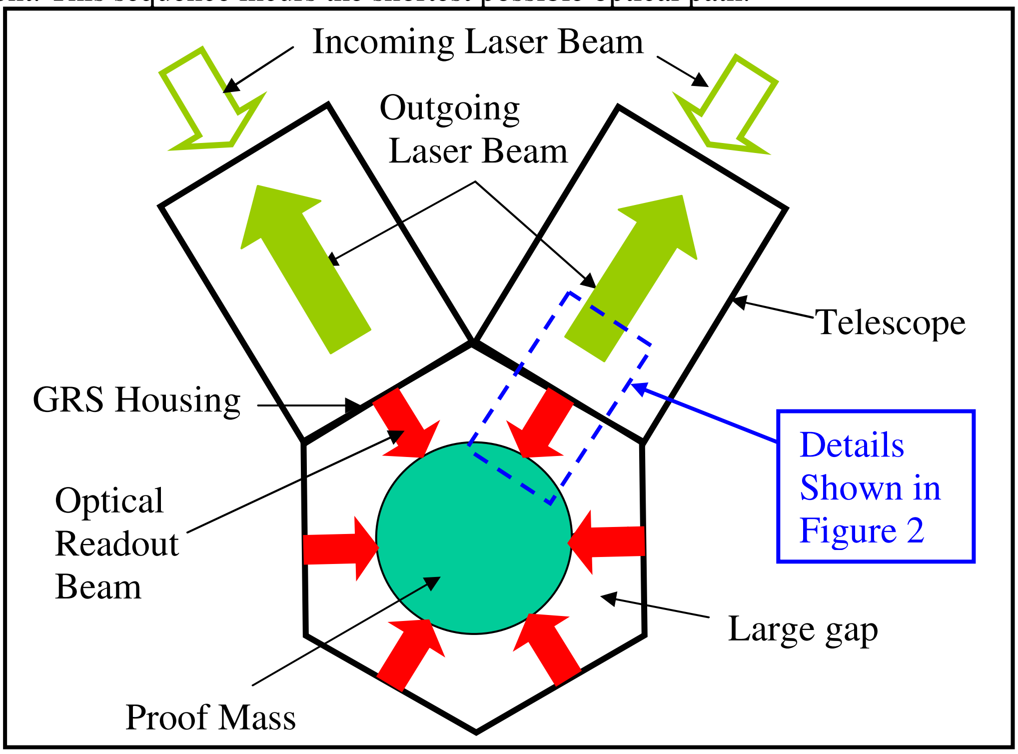

Figure 1: The concept of the modular GRS with two telescopes [11-13]. The external laser beam does not illuminate the proof mass. The GRS is a modular unit, where the internal distance measurement is made from proof mass to housing inside the GRS. The precision measurement is relayed directly to external surface through the housing wall. with a calibrated thermal expansion.

Figure 2 (a) shows an all-reflective optics implementation of the interface portion of the modular GRS, in which the optical paths are free of the transmittance through bulk optics and therefore do not incur optical path length variation due to dn/dT effects. A spherical PM is used. The gap size is measured utilizing the resonator formed by the grating Littrow mounted on the housing and the PM surface. The cavity is chosen because no other reference surface is needed. The grating is double-sided, with the outside grating designed for external interferometery [11-13], avoiding optical windows on the housing. The precision measurement is relayed through the double-sided grating made of well-characterized material. There may be other thermal effects such as the groove density change of the grating with temperature rise. However, since the laser beam only interacts with surface layer of the grating, the thermal effects are small compared with that of transmissive optics. The only sensitive path in the modular GRS is the gap between the PM and housing wall. The shortened, and thus more thermally stable optical path length is important to lower the noise level in low frequency band.

3. Single proof and multiple optical sensors

One of the core features of our modular GRS proposal is the use of single PM instead of two. In principle, science measurement of gravitational wave needs only one PM in a spacecraft. The single PM serves as the common inertial reference for measurements in two arms. The Stanford team has conducted a study on the spherical proof mass for high precision GRS applications [26].

The disturbance to the single-proof-mass system is lower than the two-mass system by a factor of $2^{1/2}$. Therefore, the adoption of a single proof mass GRS lowers the acceleration noise to 2.1×10^{-15} m/s^2 from 3×10^{-15} m/s^2 in a two proof mass configuration, which is a significant improvement, especially in the low frequency region where acceleration noise dominates.

But this could be significantly less important then the added disturbances from cross coupling of unnecessary constraint forces introduced by having two proof masses or having one or more faceted proof masses. Drag free control requires a reference degree of freedom (DOF). For a single spherical spun proof mass the orientation is passive and no forces or torques are required to be applied to the proof mass. Two faceted proof masses have 9 DOF that have to be controlled: 3 in translation and 6 in orientation. Cross coupling of these controls into the sensitive drag free DOF is an additional source of disturbance in a design that is already stretching to achieve a many order of magnitude increase in the state of the art. In our opinion this cross coupling would be greater than the added noise due to a $2^{1/2}$ increase.

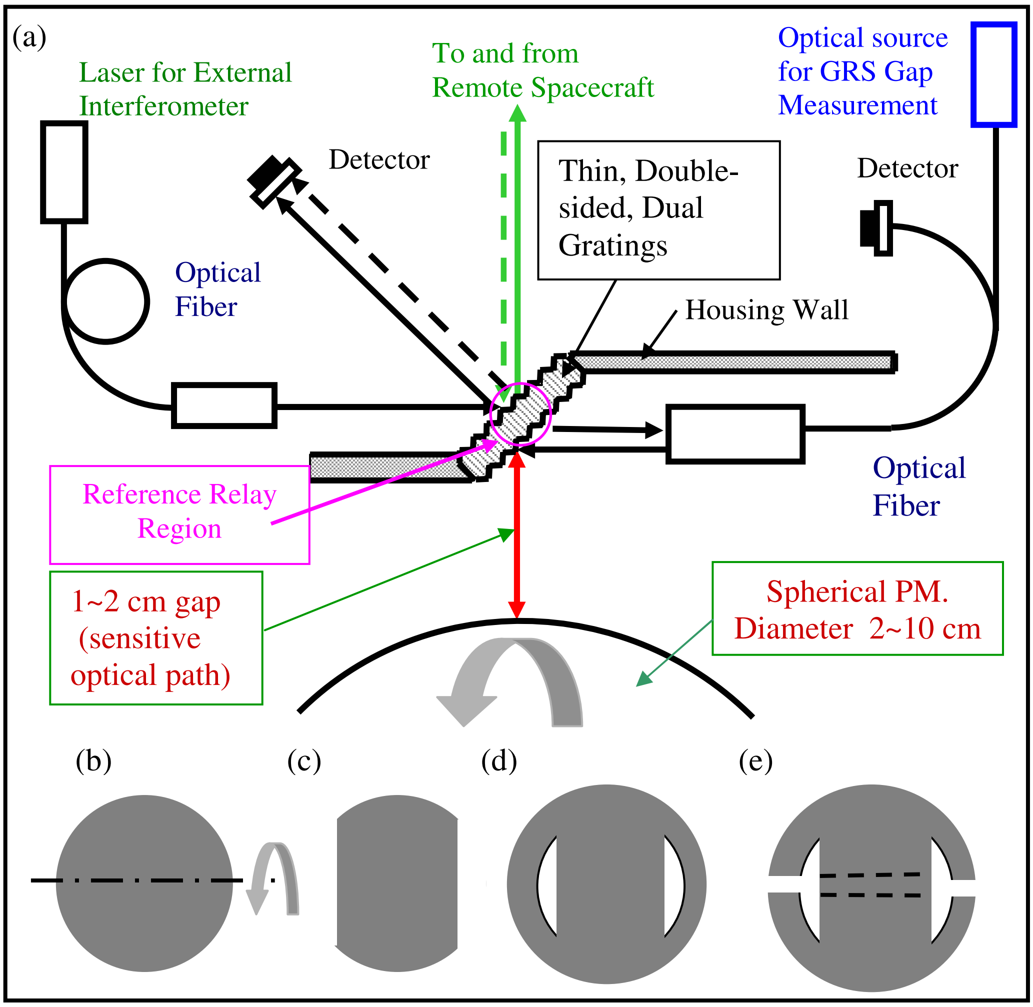

Figure 2. The details of modular GRS and some options for proof mass shape. (a) Modular GRS structure for LISA. The only sensitive path is the red section between the thin grating and the proof mass. An interferometric measurement in the back yields the center of mass information. Direct precision transfer of distance measurement through a double-sided grating made of well-characterized, low thermal expansion material. (b)-(e) Possible shapes for PM. For captions see text in section 3.

Figure 2(b) – (e) illustrates possible PM shapes. A simple sphere shown in Fig. 2(b) is a possible candidate. The sphere will be spun up to average out the surface irregularities. A potential problem is that the polhode movement may appear as a noise source below the spinning frequency. Higher percentage difference between principal moments of inertia can be used to raise the polhode frequency above the signal band [26]. This can be accomplished by truncation of the sphere, as shown in Fig. 2(c). To provide a larger smooth surface area for optical sensing, the external truncation of the sphere can be replaced by internally-hollowed cavities in north and south poles, as shown in Fig. 2(d). Finally, to facilitate a simple caging mechanism, an axial hole along the initial spin axis can be used to allow caging by pinning the axial hole as shown in Fig. 2(e).

The modular GRS uses multiple optical sensors. Currently we propose to use 18 optical sensors surrounding the PM. Optical power of each sensing direction is of the order of 10 μW, so that the total power delivered to the proof mass is below 180 μW. In principle we only need 6 out-of-plane sensors to implement the measurement of the center of mass. The high redundancy enhances the reliability. The modular GRS may use two independent laser systems, for the external interferometry and the GRS sensing laser.

Using multiple optical sensors achieves higher sensitivity than a single sensor, or just two sensors in front or the back. For example we explicitly estimate the sensitivity of a GRS with 18 internal sensors around a spherical PM. The optical sensors are distributed inside the GRS housing so that in the sensitive direction, the combined signal is given by

$$\sum_i \delta x_i \approx \left[2 + 8\cos(60^\circ) + 8\cos^2(60^\circ)\right]\delta x_d = 8\delta x_d \tag{1}$$

where δx_i (i=1,2,…,18) are the displacement signals measured by each sensor, and δx_d is the displacement measured at the sensor along the displacement direction. In equation (1), we have considered the projection angles between measurement and displacement directions.

4. Grating interferometers and noise coupling issues

Gratings have been extensively studied both experimentally and theoretically. The recent progress in grating development has made low loss, high quality gratings available [27, 28]. Grating interferometers have been studied for gravitational wave detection [29], and have shown promising performance recently. We have demonstrated 30 pm/Hz$^{1/2}$ displacement sensitivity using a grating cavity [12], and 10 nrad/Hz$^{1/2}$ sensitivity using a grating angular sensor [23]. These performances have exceeded the LISA requirements.

There have been concerns expressed about the displacement noise coupling problems for grating used in gravitational wave detection [30]. However, recent analysis and experiments [31] have shown that the alignment requirement and displacement noise coupling for a grating beam splitter is actually at the same order of magnitude as that of a mirror. Experiments also show that there is a null direction along which the grating motion does not induce a phase shift to the diffracted beam. Viewing a grating as a fixed acoustical modulator is a simple but insightful way of understanding the physical scenario.

5. Point behind angle and telescope articulation angle

The LISA spacecrafts are ~5 million kilometers apart. The time for light to complete a single transit is ~17 seconds, and ~34 seconds for a round trip. To compensate for the spacecraft movements during light transit time, the receiver pointing direction needs to be biased for a point behind angle [4]. The modular GRS provides a new solution to these problems. Since the PM is not directly illuminated by the incoming laser beam, there is no need to tilt the PM for aligning the point behind angle. The position and angular orientation relative to housing wall can thus be kept constant. The control logic is thus simplified, and the data integrity is improved. The use of the diffractive grating as a beam splitter provides a simple solution to the point behind angle.

Figure 3 shows the configuration of using a diffractive grating as a beamsplitter [11-13]. The zeroth diffractive orders follow a simple geometric reflection law. The –1 orders of both the incoming beam and the out going beam are collected at the detector for heterodyning. An additional design freedom brought about by the diffractive optics is the adjustment of the grating density, or inversely the grating period between two adjacent grooves, *d*. By proper adjusting the grating period, the outgoing beam can have a compensation angle with the incoming beam while keeping the –1 orders aligned at the detector. From the grating equations, we show that the proper grating period d to realize the compensation is given by

$$d = \frac{2\lambda}{[\sin\theta_{out} + \sin\theta_{in}]} = \frac{\lambda}{[\sin(\theta_{out} + \frac{1}{2}\theta_{comp})\cos(\frac{1}{2}\theta_{comp})]} \quad , \tag{2}$$

where θ_{out} is the angle of the outgoing beam, θ_{in} is the incoming beam angle, θ_{comp} is the compensation angle or the point behind angle, and we have used the relation of $\theta_{in} = \theta_{out} + \theta_{comp}$. The use of diffractive optics to correct the point behind angle does not require any moving parts, and therefore is more stable and reliable during the space mission. It also simplifies the control of the telescope pointing angle.

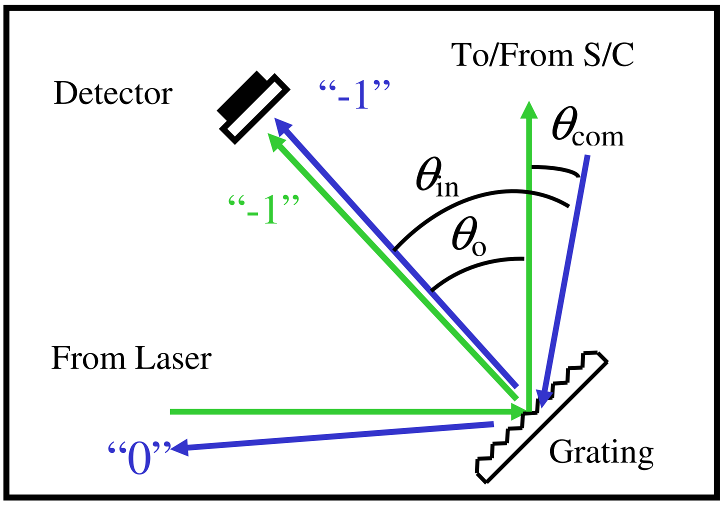

Figure 3: Using grating beam splitter for point behind angle compensation. The –1 orders point to the detector. By adjusting the grating period, the incoming laser beam can be separated from the outgoing laser beam by the compensation angle.

For the telescope articulation, we suggest using a four-element telescope structure as shown in Fig. 4. The key advantage is that the fine articulation of the telescope can be accomplished by steering the smaller mirrors. There is no need for large mass movement and only minimal down time for telescope steering. The adding of two reflective mirrors improves the collimation of the input and the output beams by correcting residual optical aberrations. In addition, this configuration is all-reflective, and eliminates the use of the entrance negative lens in sensitive optical path [3, 4].

A mature design can be built on the experience of the James Webb Space Telescope (JWST) [33]. Figure 4 shows the three-mirror anastigmat (TMA) configuration akin to that in JWST. The aberrations are largely corrected by the TMA system. M1, M2, and M3 are the curved primary, secondary, and tertiary mirror respectively. The fine steering is realized by rotating the flat mirror M4, or in combination with M3. The scattered stray light can be shielded by adding aperture stops around the intermediate image plane. Using M4 as the fine steering mirror can effectively reduce the number of the large movements of the telescope body. A CCD imager behind M3 facilitates the imaging for coarse acquisition of the beam coming from a remote spacecraft. The small steering mirror M4 can be actuated at higher speed. This enables faster scan of the field of view in both incoming and outgoing directions, accelerating the acquisition process. We are conducting a design study on multi-element telescope for LISA [33].

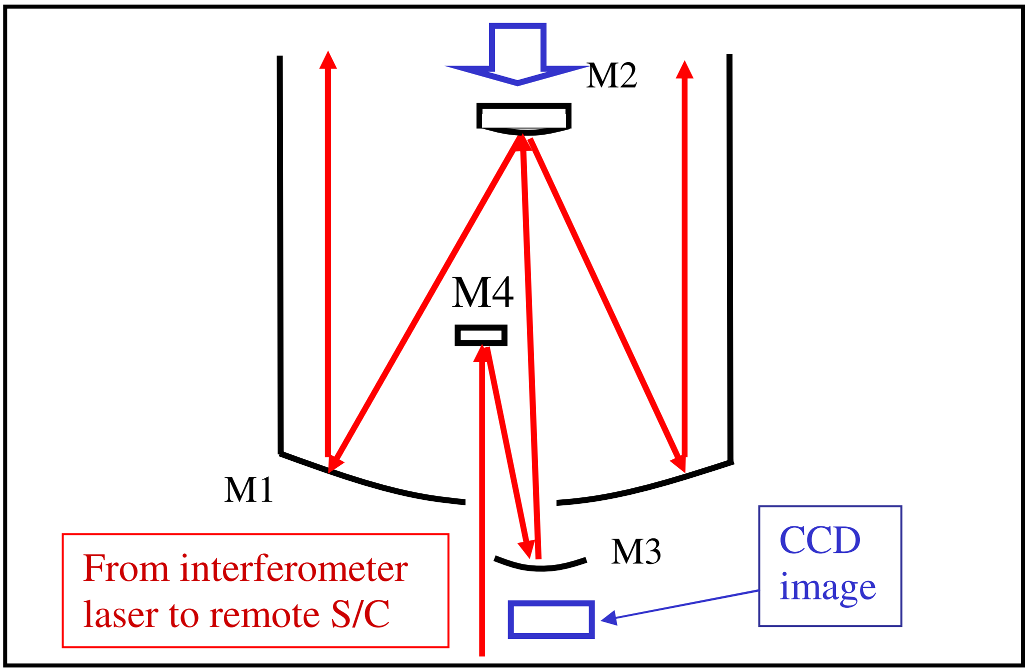

Figure 4: Multi-element telescope. M1: Primary. M2: Secondary, M3: Tertiary. M1, M2, M3 are curved mirrors. The articulation angle tracking is implemented by rotating smaller mirrors but not telescope body. A CCD camera behind M3 is for the acquisition of laser beam from the remote spacecraft.

6. Simplification of Control

The control process in LISA is challenging [34, 35]. A high level metric to estimate the complexity of a dynamic control system is the number of DOF [36] that determines the dimension of transfer matrix. The coupling between DOF is a further metric that accounts for the off-diagonal elements of the transfer matrix. LISA has many sensing signals. However, not every sensing signal is a DOF. As counted in Ref. [34], each LISA spacecraft has 19 DOF, and the three-spacecraft fleet has 57 DOF. Since there are two PMs within the same spacecraft, consolidation between two PMs incurs complex maneuvers. Communication bandwidth is relatively low for LISA, since the fleet is in solar orbit trailing behind the earth at a distance of approximately $50x10^6$ km. LISA orbits the sun in one year. Therefore, it is never "fixed" in direction like GP-B but must accommodate a ~1 angle change each day.

The GP-B experience provides a basis for appreciating the complexity of in flight operation control. The GP-B carries four gyros, among them only one is flown drag free, and others are forced to follow the drag free gyro. Therefore only the 3 DOF of the drag-free gyro are counted. The drag free gyro has only 3 translational DOF since the rotational DOF is suppressed by using spinning spheres in an inertial reference. Adding the translational and rotational DOF for the satellites, the GP-B has a total of 9 DOF. The telescope in GP-B is constantly aimed at a star. GP-B is near earth with a high communication bandwidth. GP-B spent a longer time (~4 months) than anticipated to configure the single satellite into the science mode. From GP-B experience, one needs to prepare the time needed for LISA to align and operate in the science mode.

The modular GRS simplifies the control system by reducing the number of DOF, and by decoupling the GRS internal DOF from the external DOF. The modular GRS requires only a single PM. Depending on the shape of the PM, only 3~6 DOF are needed. A spherical PM requires only 3 translational DOF, and therefore only needs translational control in 3 directions. Taking into account 6 DOF of the spacecraft and one DOF for telescope articulation, each spacecraft with a single spherical PM has only 10 DOF, and the three spacecraft fleet has 30 DOF, much fewer number of DOF compared with two proof-mass GRS.

Further, in a modular GRS, the external measurement is only concerned with the distance between the beam splitters on two remote spacecraft. Locally at the each spacecraft, the external measurement is accomplished by the heterodyne detection of the laser beam phase without having to have knowledge of internal DOF of the PM. The laser pointing acquisition can be accomplished first. Drag free control is highly simplified in single proof-mass modular GRS. Instead of following complicated procedures to maneuver between the two PMs and the spacecraft, the modular GRS allows to simple tracking of the PM position.

Table 1 summarizes control DOF counts of several missions for a comparison to the GRS. In Table 1, we have indicated the DOF counts in modular GRS as 3+7, to reflect the decoupling of the internal and external DOF in modular GRS.

Table 1: DOF count comparison for LISA missions and modular GRS

DOF Counts		GP-B	LISA	Modular GRS
Single Space Craft	Displacement DOF	6	9	3+3
	Angular DOF	3	9	3
	Other DOF		1	1
	Total DOF		19	3+7
Total Fleet DOF		9	3x19	(3+7)x3
Matrix Dimensions		9x9	57x57	30x30

8. Conclusion

We have extended the concept and incorporated improvements to modular GRS, which has impacted GRS design for LISA and BBO. Our modular GRS architecture is easily interfaced with various external measurements, and therefore may enhance the preparedness for future gravitational wave detection missions beyond LISA.

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