A Geostationary Gravitational Wave Interferometer (GEOGRAWI)

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Abstract

We propose a Geostationary Gravitational Wave Interferometer (GEOGRAWI) mission concept for making observations in the sub-Hertz band. GEOGRAWI is expected to meet some of LISA's science goals in the lower part of its accessible frequency band ($10^{-4} - 2 \times 10^{-2}$ Hz), and to outperform them by a large margin in the higher-part of it ($2 \times 10^{-2} - 10$ Hz). As a consequence of its Earth-bound orbit, GEOGRAWI is significantly less expensive than the interplanetary LISA mission and could be either an entirely US mission or managed and operated by NASA in partnership with the Brazilian Space Agency.

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I. OBJECTIVES AND GOALS

The primary objective of this document, written in response to the NASA Request For Information # NNH11ZDA019L, is to sketch a mission concept for a space-based detector of gravitational radiation capable of meeting most of LISA's [1] science goals at a significantly reduced cost. This mission could be either entirely managed and operated by NASA or flown in partnership with the Brazilian Space Agency. In this case the spacecraft busses and the onboard and ground telecommunication hardware could be provided by the Brazilian Space Agency, further reducing NASA's mission costs.

II. MISSION DESIGN AND ORBIT

Our proposed space-based detector entails three spacecraft in geostationary orbit, forming an equilateral triangle with armlength of about $73,000$ km. The main advantage of such an interferometer over LISA is that it is significantly less expensive to launch and position it in its final orbit. Because of its smaller and constant armlength, further instrument simplifications over that baselined for LISA follow as additional benefits. For instance, no laser ranging modulations nor modulations needed by the Ultra-Stable Oscillator noise cancellation scheme will be required; no articulation of the optical telescopes onboard each spacecraft will need to be implemented; the attitude control subsystem and onboard propulsion units will be down-scaled accordingly to the less stringent needs imposed by the spacecraft trajectories; ground data acquisition can be performed with three small dedicated antennas whose cost is a fraction of the tracking costs LISA would require; in the eventuality of system/subsystem failure a robotic repair mission could be performed. This list of advantages associated with a geostationary configuration is of course not exhaustive. However, if we just consider the cost savings associated with a smaller launch vehicle and propulsion module than those required by LISA as well as those resulting from the more benign orbit, we may already see that the cost of a geostationary interferometer will be smaller than that for LISA. Furthermore, it has been pointed out in recent years that a single, spherical proof-mass could be adopted for achieving the desired inertial reference frame stability required by LISA [2]. In our cost estimate we will assume each spacecraft to be equipped with a single, spherical proof-mass.

III. SENSITIVITIES

Because the armlength of GEOGRAWI is roughly 70 times smaller than the armlength of the LISA mission, its sensitivity to gravitational radiation in the lower part of its accessible frequency band will be proportionally worse than that of LISA (assuming of course onboard accelerometers of similar performance as those baselined for LISA). On the other end, the shorter baseline of GEOGRAWI will result in a much smaller photo-counting error at the photo-detectors and an improved sensitivity over that of LISA by the same factor 70 in the remaining (higher) part of its frequency band.

Using the standard definition of sensitivity for a space-based interferometer [3–6], we have estimated the Time-Delay Interferometric (TDI) sensitivities of a geostationary interferometer under the following three different on-board subsystem configurations:

(I) The onboard instrumentation and its noise performance is equal to that of the LISA mission. We will refer to this configuration as the "Geostationary LISA".

(II) The output power of the onboard lasers and the size of the optical telescopes are assumed to be equal to that of the LISA mission, while the noise performance of the accelerometers is taken to be 10 times worse than that of the accelerometer planned for the LISA mission. This configuration will be referred to as the "Geostationary 1". [1]

(III) The noise performance of each accelerometer is taken to be a factor of ten worse than that of the accelerometers planned for the LISA mission, the output power of the lasers is assumed to be a factor of 10 smaller than that of the lasers onboard LISA, and the diameter of the optical telescopes has been reduced by a factor of $\sqrt{10}$ over that of the LISA telescopes. This configuration will be called "Geostationary 2".

In Figure (1) we plot the sensitivities of the TDI combination X [6] for the various on-board hardware configurations discussed above and, for sake of comparison, we include the LISA sensitivity. At high-frequencies the sensitivity of any of the geostationary interferometers considered is significantly better than that of the LISA mission while, at lower

[1] This accelerometer noise level is equal to that of the accelerometer to be flown on-board the LISA Pathfinder mission [7]

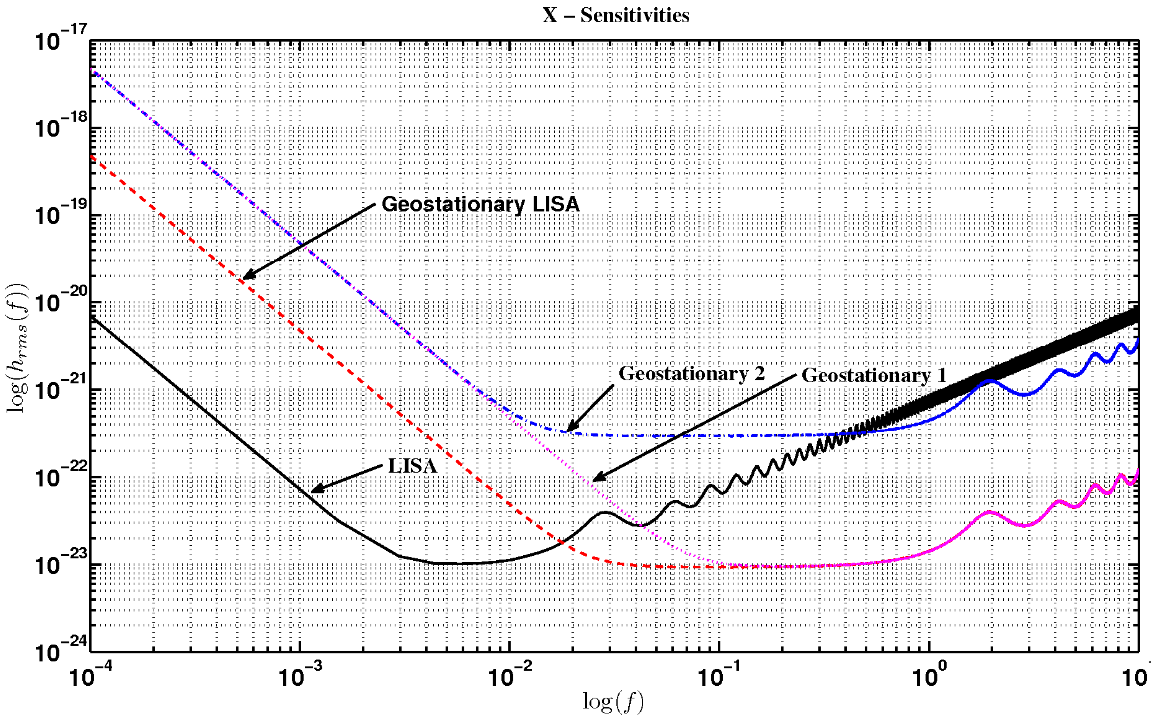

FIG. 1: Sensitivity of the X combination of a geostationary interferometer. Its noise performance is characterized by the noise spectra given in [5] for the LISA mission and properly scaled here for the three different onboard subsystem configurations. The estimated LISA sensitivity is included for sake of comparison.

frequencies, the longer armlength of LISA results in a better sensitivity in this part of the band.

IV. SCIENTIFIC OBJECTIVES

The enhanced sensitivity of GEOGRAWI at frequencies larger than about 20 mHz implies that it will be able to observe massive and super-massive Black Holes (SMBHs), stellar-mass binary systems, several binary systems present in our own galaxy (the so called "calibrators") [1], cosmic strings, and a stochastic background of astrophysical or cosmological origin. Although GEOGRAWI will be unable to detect the zero-order cyclic spectrum of the white dwarf-white dwarf galactic binary confusion noise, it will however detect and measure the higher-order "cyclic spectra" present in the data because of the rotatory motion of the interferometer around the Sun. The cyclic spectra can be observable as they are not affected by the instrumental noise if this is stationary [8]. Under this assumption, GEOGRAWI will still detect the so-called "Confusion Noise", and infer properties of the distribution of the white-dwarf binary systems present in our galaxy [8].

In relation to binary black-holes systems, we have recently analyzed how well and how many of them GEOGRAWI will be able to detect, as these sources were of primary interest to LISA [9]. Since a significant amount of GW energy can be released during the three evolutionary phases (inspiral, merger and ring-down) of these systems, we have calculated the maximum redshift, for a given signal-to-noise ratio (SNR), at which these systems could be detectable during these three phases. From these results we then inferred the event rate by relying on the work recently done by Filloux *et al.* [10] on the formation and evolution of massive and supermassive black-holes. We found that the Geostationary LISA configuration could see as many as 19 black-hole binaries per year with a $SNR = 10$ out to a maximum redshift of 10. This number of events rate is slightly larger than that for LISA as a consequence of the fact that this geostationary interferometer has a better sensitivity at higher frequencies where smaller black-holes binaries radiate. Since smaller black-holes are easier to form and are therefore larger in number, a geostationary LISA will be able to see more of them than LISA.

V. ESTIMATED COST

In order to estimate the cost of a geostationary gravitational wave interferometer, we have relied on the latest cost estimate for LISA included in the document titled: "Laser Interferometer Space Antenna (LISA) Astro2010 RFI #2 Space Response", dated 3 August 2009, which was submitted by the LISA project to the NRC Decadal Review panel as a Request For Information [11]. At page 57 of the above document a break-down table of the US costs for LISA is provided. We have used that table to generate a similar breakdown for a Geostationary LISA, i.e. a geostationary interferometer whose spacecraft are equipped with the same LISA instrumentation. As mentioned in the previous section, this is a somewhat conservative assumption as some instrument simplifications will result from a more benign mission orbit.

The table below compares the LISA break-down and total costs against those of a geostationary interferometer detector under the assumptions of (i) either an entirely US-funded mission, or (ii) a partnership with the Brazilian Space Agency will lift the NASA costs associated with the spacecraft, propulsion modules, and ground data system. Explanations of the main cost differences between a "Geostationary LISA" and LISA are included in the Table. We find the final NASA cost of a Geostationary LISA to be equal to about $ 1.1 B for an entirely US-managed mission. A joint partnership with the Brazilian Space Agency would further reduce down the NASA costs to about $ 940 M.

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

VI. ACKNOWLEDGMENTS

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FIG. 2: Cost estimates for a Geostationary interferometer, under the assumptions of it being (i) a US-only mission, or (ii) flown in partnership with the Brazilian Space Agency. Reserves have been assumed to be at the 20 % level. The cost of the LISA mission is included for comparison.

ITEM	**LISA Costs ($M)**	**GEOGRAWI NASA Costs ($M)**	**GEOGRAWI NASA Costs (Brazilian Partnership) ($M)**	**Comments on Δ-costs between LISA and GEOGRAWI**
Phase A Concept Study	11	11	11	
Science (Pre-Launch)	33	33	33	
GRS+Laser+Telescopes	409	249	249	GRS costs are reduced by a factor of 2 by adopting a single spherical proof-mass/Spacecraft
LIMAS	70	70	70	
Thrusters	85	85	85	
Propulsion Module	81	27	0	Smaller propulsion modules to position the spacecraft in their final orbit are needed. The Brazilian Space Agency could contribute this system.
Spacecraft	263	120	0	The GRACE mission spacecraft costs were assumed. The Brazilian Space Agency could contribute this system.
Ground Data System Development	55	2	0	A geostationary orbit requires smaller ground antennas for data collection and communication. The Brazilian Space Agency could contribute this system.

MSI&T	24	24	24	
Launch Services	243	60	60	A SpaceX Falcon 9 launch vehicle was assumed
Education/Outreach (from Science) thru Phase D	4	4	4	
MO&DA Science (Post Launch) Engineering Support Mission Operations Education/Outreach (from Science) Phase E	 81 2 52 1	 81 2 2 1	 81 2 2 1	A significant cost reduction in mission operation activities is expected to directly follow from the proximity and trajectory of the spacecraft.
SUB Total Hardware & Operations	**1,414**	**771**	**622**	
PM/SE/MA (less Instr. PM/SE) PM/SE/MA (MO&DA Phase E) Instrument PM/SE	122 24 18	122 24 18	122 24 18	
SUB Total Hdwe,Ops&Mgmt	**1,578**	**935**	**786**	
RESERVES (20%)	315.6	187	157	
TOTAL COST	**1,894**	**1,122**	**943**	

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