Probe-class mission concepts for studying mHz gravitational waves

A white-paper submitted to the *Physics of the Cosmos Program Analysis Group: Probe-Class Astrophysics Mission Concepts.*

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1. SCIENCE DRIVERS

The direct observation of a gravitational wave (GW) signal from the coalescence of two in-spiraling black-holes, announced by LIGO on Thursday, February 11, 2016, represents one of the greatest triumphs in experimental physics today and the beginning of a new era for astronomy. Ground-based detectors such as LIGO are sensitive to the kHz GW band with the seismic noise-wall preventing them from being sensitive below ~ 10 Hz. In order to make astronomical observations in the mHz band, where GW signals are expected to be stronger and larger in number, we propose a radically new concept for a space-based GW interferometer within the probe-class missions. With such a detector we will be able to observe massive ($10^4 – 10^6$ M_0) and supermassive (10^7 – 10^9 M_0) in spiraling binaries black-holes, identify their formation mechanism and their roles in the evolution of galaxies, probe the space-time geometry imprinted into the GW waveforms generated by small objects spiraling into massive black-holes, and identify the spatial and mass-distribution of the hundreds of millions of white-dwarfs binaries in our own galaxy. These were the primary LISA scientific objectives, and we believe a probe-class mission similar to the ones described below will be able to deliver most (if not all of) them at a significantly reduced cost.

2. TECHINCAL CAPABILITIES

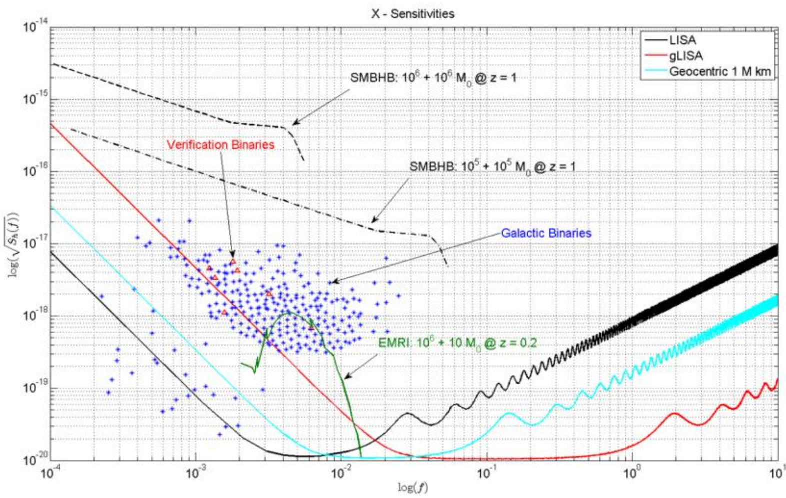
After the end of the NASA-ESA partnership in 2011 and the conclusions reached by the NASA GW RFI study exercise, it became quite clear that, to fly a space-based GW interferometer at a cost lower than $1B, a thinking paradigm shift was needed. It was within this spirit that in 2013 we begun to explore the options offered by the aerospace industry. Recent technological developments to meet the growing demands for low-cost satellites and launching vehicles, together with the existing NASA program for flying scientific instruments onboard geostationary commercial satellites (COMSATS) [1] have opened up a broader set of opportunities of short development cycle and cost reductions for GW missions. With knowledge of this new development, we explored the scientific, technical, programmatic, and cost advantages of flying a geocentric gravitational wave mission with “off-the-shelf” satellites or by hosting the necessary instrumentation onboard three geostationary comsats.

The proposed “dedicated” geocentric mission concept has previously been studied at Stanford, and more details can be found in [2], while the “comsat option” has been discussed at some length in [3, 4, 5]. Both mission concepts have recently gone through a JPL A-TEAM study exercise and their costs have been estimated to be $900M (dedicated geocentric) and $560M (geostationary COMSATS) respectively for a 2 year mission duration. Their expected scientific capabilities are summarized by the sensitivity plot below, which also includes for comparison the nominal LISA sensitivity together with the strengths of various gravitational wave sources expected to radiate in this frequency band.

3. NEW TECHNOLOGIES

Under the assumption of a successful outcome of the LISA Pathfinder mission, the technology needed by our proposed mission concepts will be at a sufficiently high level of maturity for being more quickly developed here in the US. The experimental efforts at Stanford on the Modular Gravitational Reference Sensor (MGRS) design [6] have started to come to fruition, giving us confidence to achieve the required acceleration noise level ($< 3 \times 10^{-15}$ m/s^2 Hz$^{-1/2}$) adopted in the derivation of the sensitivity curves shown in the figure below by the year 2020.

For the geostationary comsat mission option we derived a drag-free design (the so called “two-stage drag-free system”) that reaches the required level of inertia onboard these large and massive satellites. The most interesting feature of this design is that it does not require the use of μN thrusters. Briefly, the two-stage drag-free system can be envisioned by thinking of a small satellite (the “hosted satellite”), residing inside an enclosure located on the nadir-pointing (Earth-pointing) deck of the comsat. It carries onboard the MGRS with its free-floating, spinning, spherical proof-mass (PM). Sensors continuously monitor the position and velocity of the hosted satellite relative to the comsat while now, rather than relying on μN thrusters, electro-magnetic actuators attached to the inside walls of the nadir enclosure act on the hosted satellite to keep it centered on its PM. These actuators, which already exist as they form the key-technology element developed at Stanford for the LIGO active seismic isolation system, can operate within a gap-distance of 1-2 mm. Since the comsat may experience a non-gravitational acceleration of about 10^{-7} m/s^2 due to solar radiation pressure and disturbances caused by its mechanisms, in order to avoid interruption of data acquisition every 140 s or so as the onboard satellite would move by 1 mm over this time scale, additional thrusters (such as cold-gas or ion thrusters) driven by the onboard sensors can act on the comsat to compensate for the non-gravitational acceleration due to solar radiation pressure. This operational configuration allows the hosted satellite to continuously operate in its drag-free configuration and perform heterodyne measurements by exchanging laser beams with the hosted satellites onboard the other two comsats. Although this can be done most effectively by using spherical proof masses, it could also be implemented with a cubic proof-mass.



Sensitivities achievable with the geostationary comsats (labelled **gLISA,** red line) mission, the Geocentric mission (cyan line) and by LISA. The shorter (~73,000 km) armlength of the geostationary configuration results into a sensitivity-degradation by a factor of ~ 70 over that of LISA in the lower-part of the accessible frequency band (10^{-4} – 2×10^{-2}) Hz, and an improvement by the same factor in the remaining part of the band (2×10^{-2} – 10) Hz. Both our proposed missions will meet the PCOS science goals within the cost budget of a probe-class mission.

4. REASONS WHY A PROBE-CLASS MISSION IS NEEDED

Due to the nature of the experiment, three satellites (whether dedicated or comsats) will need to be flown to perform the heterodyne measurements required to generate the interferometric data. The resulting mission costs therefore exceed the cost caps associated with the Explorer and Mid-Ex programs, and are below the cost cap of a probe-class mission.

5. COST ESTIMATE

Earlier this month (February 2016), an A-TEAM mission study was performed at JPL. Its objectives were to study our two mission concepts and identify their costs and scientific capabilities. The resulted costs ($560M and $900M) for a nominal 2 year mission operation give us confidence that both mission concepts could become a reality within the cost cap associated with a probe-class mission.

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