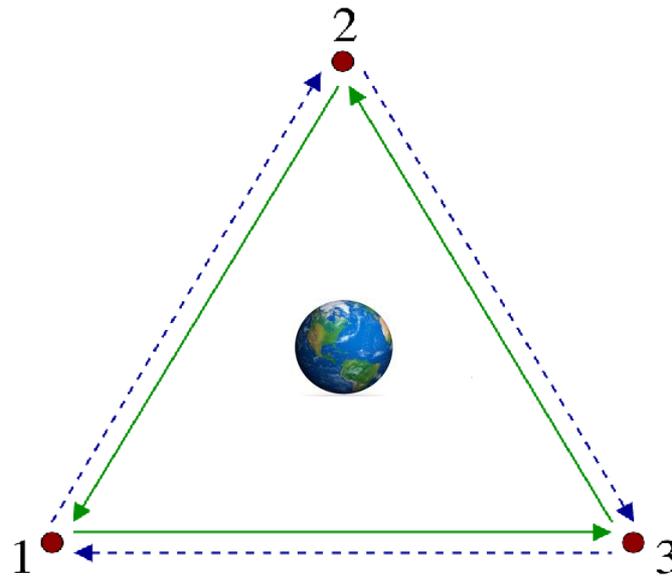




# A geostationary Laser Interferometer Space Antenna

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# Introduction

- We are witnessing an historical and pivotal moment in the field of gravitational waves.
  - aLIGO announced its first detection (02/2016), and the observation of an additional signal (06/2016);
  - LISA Pathfinder was a success (06/2016)!
- Many important scientific discoveries resulted into substantial increase in budget allocations.
- As an example, in August 1996 NASA announced the presence of a microfossil in one of the 124 meteorites deemed to be originated from Mars.

# Introduction...(cont.)

- It is very likely we will be able to simultaneously fly 2 (or more) missions!
- Should the two missions have comparable size?
- Alberto Sesana has implicitly answered this question (*Phys. Rev. Letters*, June 2016).
- It is critically important to fly missions that can naturally complement and enhance each other's scientific capabilities!



# Historical Background

- In 2011, shortly after the end of the ESA-NASA LISA partnership, NASA engaged the US scientific community with an RFI for a GW mission concept that could deliver good science at a reduced cost.
- It was within this spirit that, in collaboration with colleagues at INPE (Brazil) and at Stanford University, I started to analyze the scientific capabilities and possible technological implementations for a geostationary gravitational wave mission.
- At the same time, independently, Dr. Sean McWilliams also focused his attention on a similar mission concept (GADFLI)
- Geosynchronous/geostationary trajectories are easy to reach, providing a triangular array with  $\sim 73,000$  km arm-length.

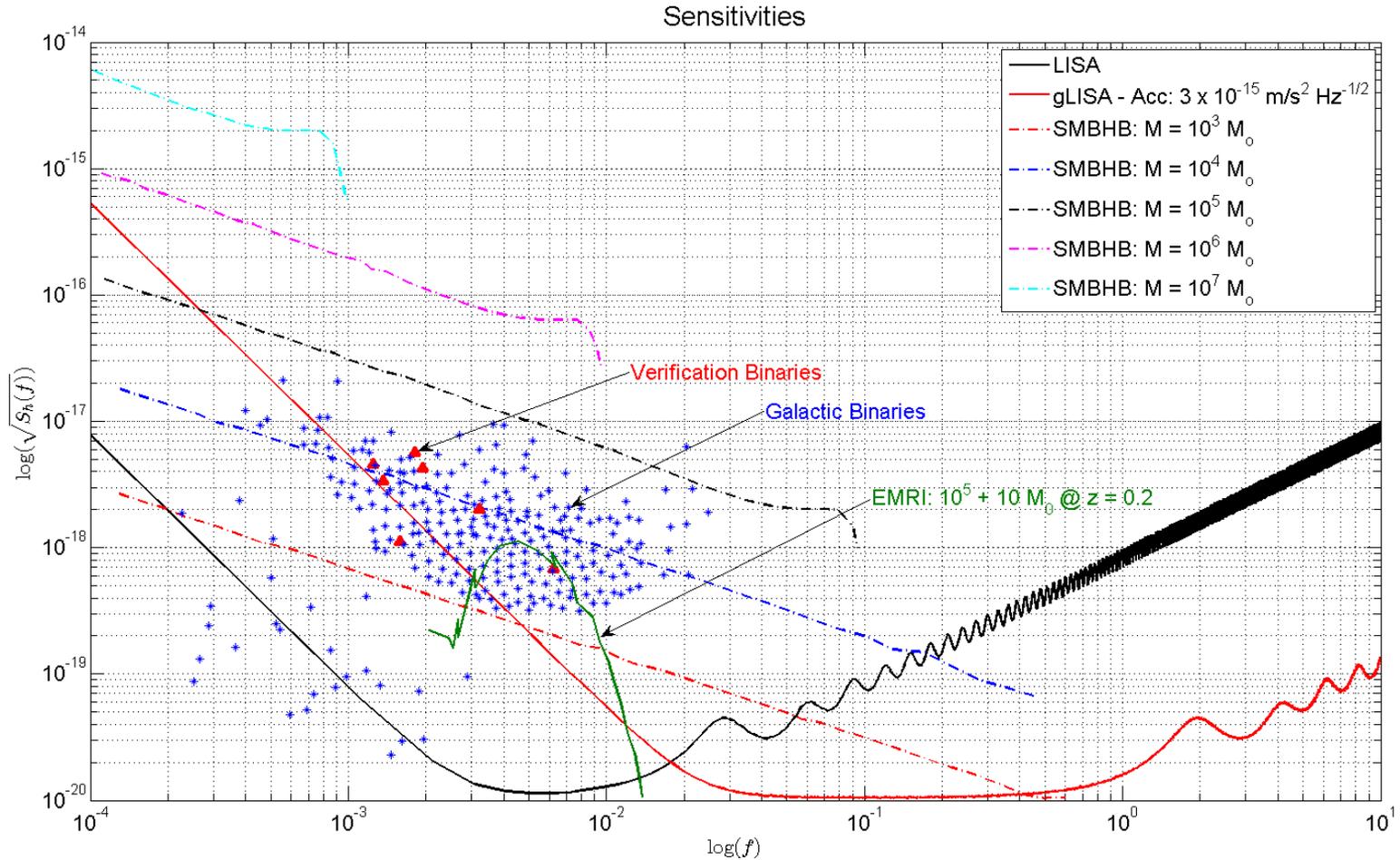


# References

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- M. Tinto, D. DeBra, S. Buchman, S. Tilley, “gLISA: geosynchronous Laser Interferometer Space Antenna concepts with off-the-shelf satellites”, *Review of Scientific Instruments*, **86**, 014501 (2015).
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- Sean T. McWilliams, *Optimizing LISA for cost and science*, 9<sup>th</sup> LISA Symposium, Paris, France (May 24, 2012)
- Sean T. McWilliams, *GADFLI*, presentation given at the NASA RFI workshop, December 2011

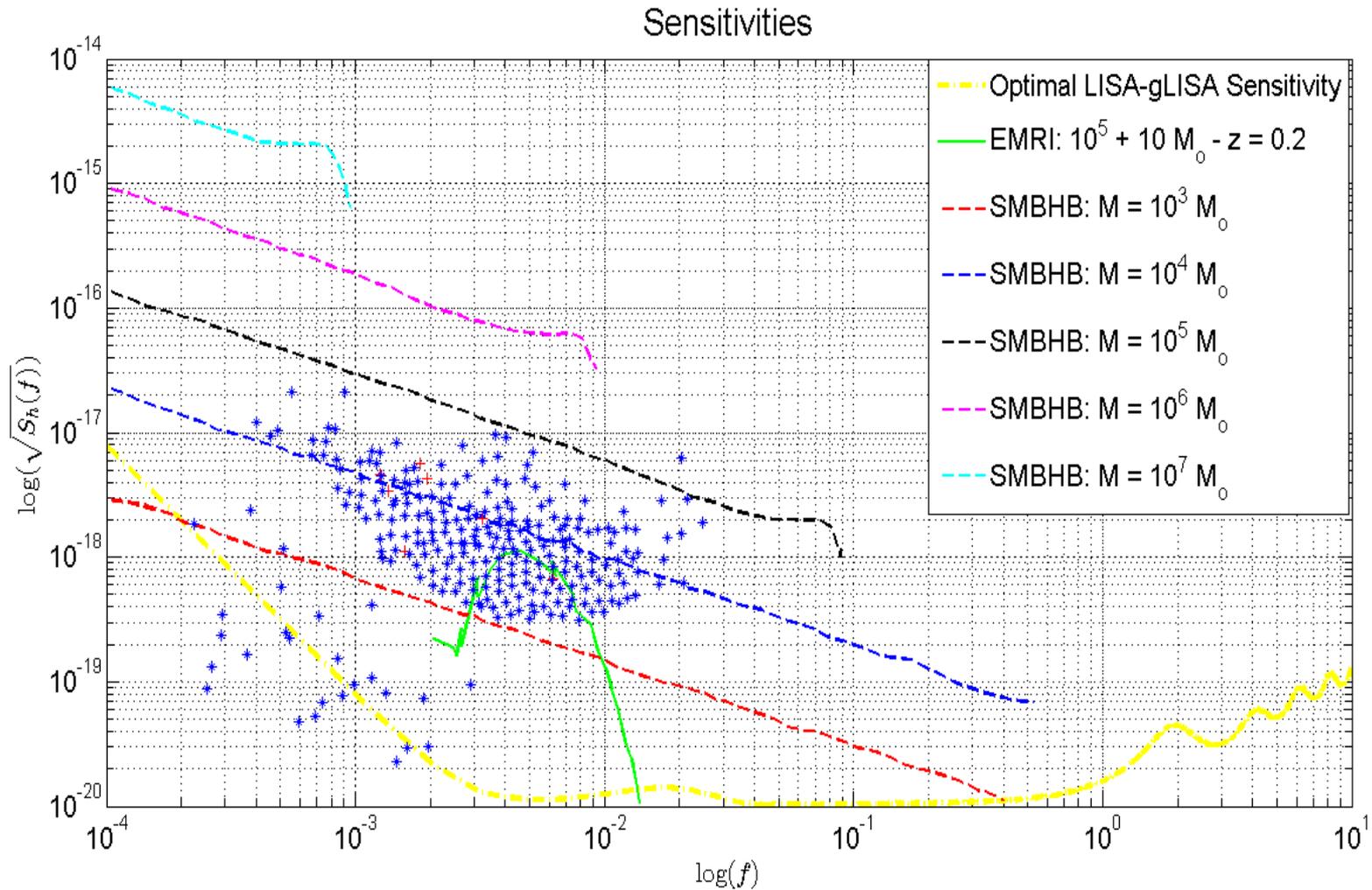


# Sensitivity





# Optimal Sensitivity



# Summary

- We are witnessing an historic moment in our field, which will lead to a new era for astronomy.
- We all need to “sensitize” the funding agencies.
- The opportunity exists for flying 2 (or more) missions that can scientifically complement each other by covering a frequency band wider than those characterizing each individual mission.

# Backup Slides



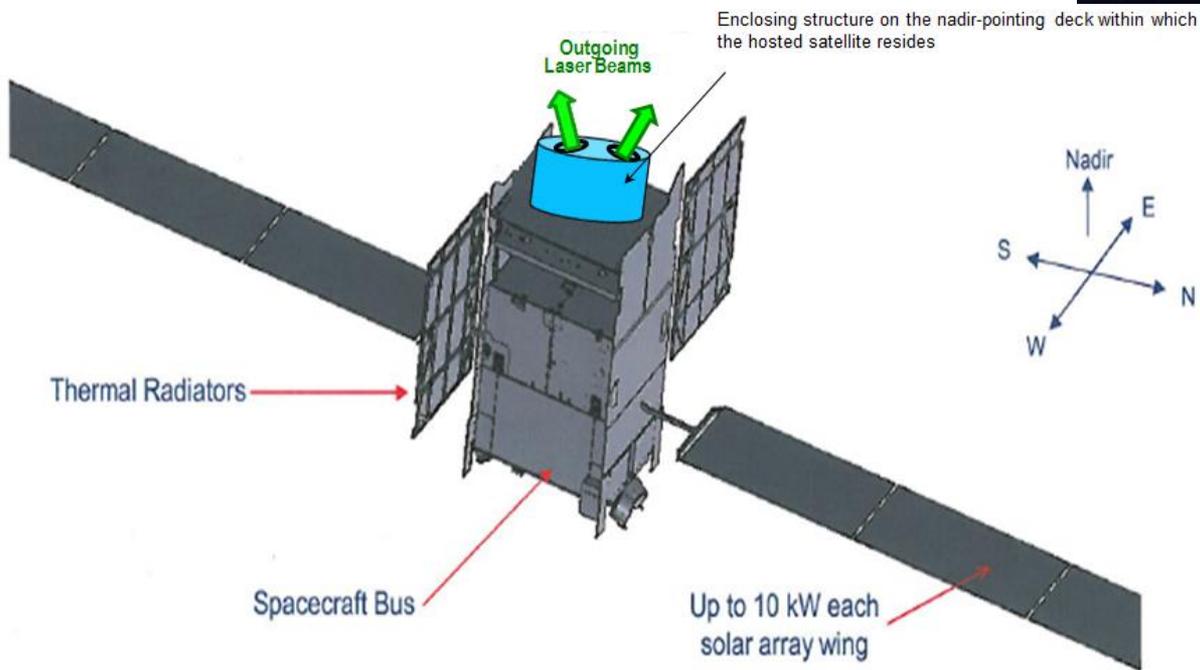
# Comsats

- Several aerospace companies (Loral, Boeing, Lockheed, ...) offer to fly for a fee (which varies between \$30 - \$70 M) scientific instruments on their planned geostationary satellites. This is possible under the NASA science instrument hosting program.
- They can be launched three at the time (for achieving telecom world coverage) and at a rate of ~ 20 per year.
- They can weigh as much as 6 tons, have large resources of power and cargo space, easily carry ~ 300 kg of additional mass, and transmit the science data to their ground stations at a very high data rate!
- By paying a fee we can save the costs associated with the satellites, the launching vehicle, the onboard and ground telecom systems, and minimize part of the engineering costs inherent with the construction and integration of the entire mission.



# Comsats (cont...)

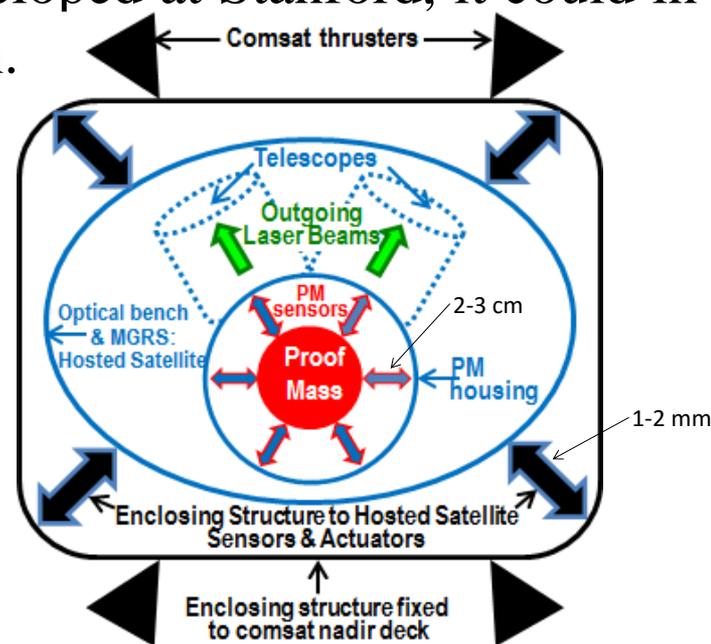
- They **cannot** be operated as “traditional” drag-free satellites!





# The two-stage Drag-Free Concept

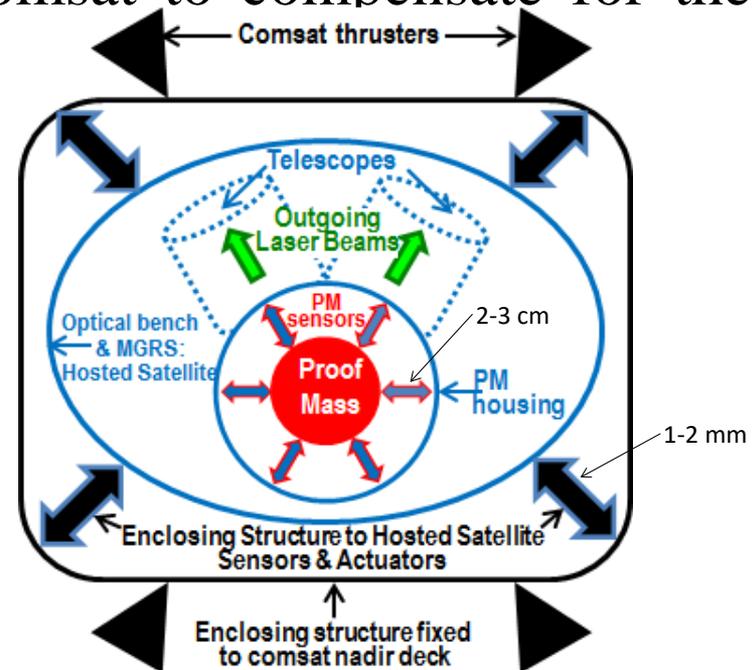
- This new drag-free design is the result of collaboration with Daniel DeBra and Sasha Buchman at Stanford University.
- Although it was conceived by making it compatible with the Modular Gravitational Reference Sensor (MGRS) developed at Stanford, it could in principle work with the European cube design.
- Conceptually it can be understood by considering a small spacecraft (containing the proof-mass) freely-floating inside the enclosing structure mounted on the Earth-pointing deck.
- Sensors continuously monitor the position and velocity of the comsat relative to the hosted satellite while now, rather than relying on  $\mu\text{N}$  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.





# The two-stage... (cont.)

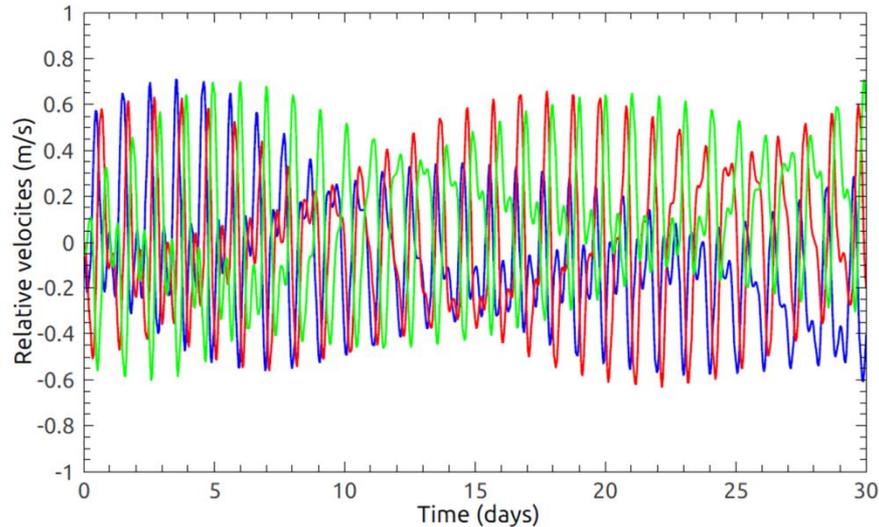
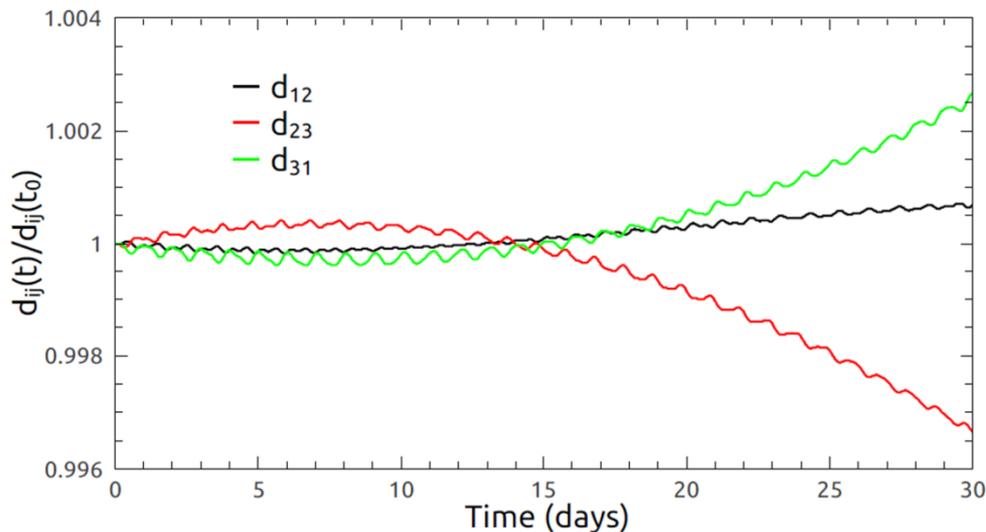
- These actuators can operate within a gap-distance of 1-2 mm.
- Since the comsat may experience a non-gravitational acceleration of about  $10^{-7}$  m/s<sup>2</sup> due to solar radiation pressure and disturbances caused by its mechanisms, in order to avoid interruption of data acquisition additional thrusters (cold-gas or ion thrusters) driven by the onboard sensors can act on the comsat to compensate for the non-gravitational acceleration.
- 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.



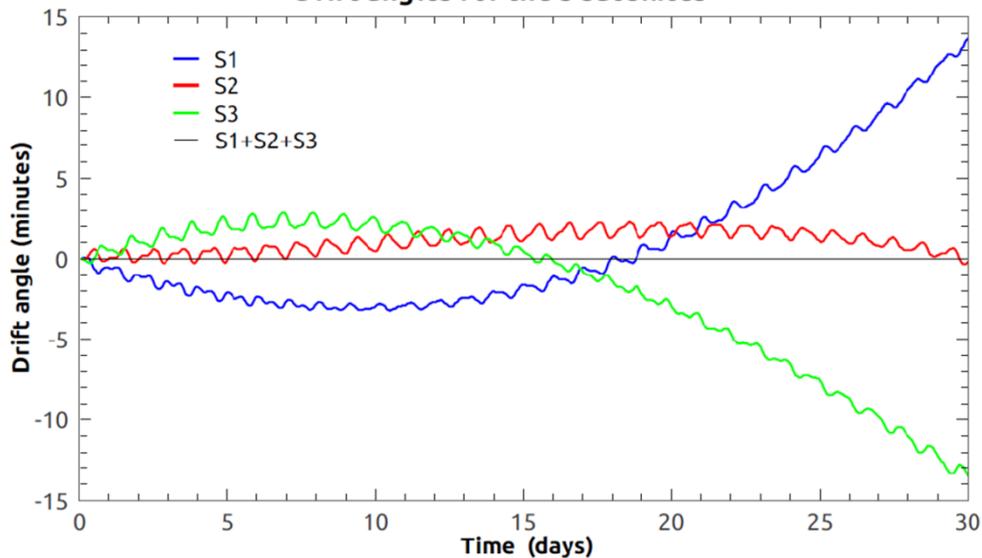


# Geosynchronous Trajectories

Distances



Drift angles for the 3 satellites





# Gravity-Gradient (GG) Noise

- Among all the noise sources considered, the comsat-induced gravitational acceleration noise turns out to be the most serious one.
- Based on a model of the mass distribution of a Loral satellite (SSL 1300 platform), we have numerically estimated the magnitudes of the gravitational acceleration ( $1.4 \times 10^{-8} \text{ m/s}^2$ ) and gravity-gradient ( $8.7 \times 10^{-9} \text{ s}^{-2}$ ) experienced by the PM at its nominal location.
- These values are incompatible with the gLISA acceleration noise requirements (i.e. the square-root of the acceleration noise spectrum to be equal to  $3.0 \times 10^{-15} \text{ m/s}^2 (\text{Hz})^{-1/2}$  in the observational frequency band).
- To suppress this noise we need to identify the number, location, and values of additional masses to be added onboard to simultaneously null the comsat-induced gravitational acceleration and gravity-gradient at the nominal location of the PM!



# GG Noise Compensation Scheme

- At the nominal PM location,  $\mathbf{o}$ , let's consider the expressions of the acceleration and the gravity gradient (GG)

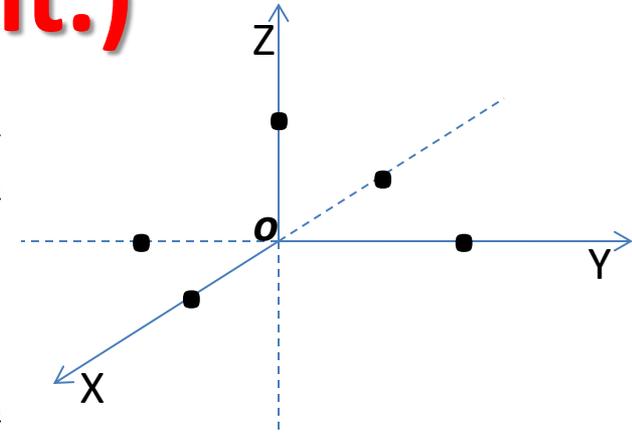
$$a_i = \frac{\partial V(\vec{r})}{\partial x_i} \quad ; \quad \frac{\partial a_i}{\partial x_j} = \frac{\partial^2 V(\vec{r})}{\partial x_i \partial x_j} \quad V(\vec{r}) = \text{comsat gravitational potential}$$

- The GG is a symmetric tensor whose trace is equal to zero because of the Poisson's equation in vacuum.
- Let us consider the GG tensor in the coordinate system defined by its eigenvectors (i.e. in which it is diagonal). Since the trace is an invariant, we conclude that the GG due to the comsat is determined by two independent components.
- Since in this coordinate system the acceleration still has three independent components, we may argue that to simultaneously cancel the acceleration and its gradient we need 5 masses.



# GG Noise...(cont.)

- To identify the location and values of the compensating masses, we have assumed them to be of spherical shape and constant mass density.
- In the coordinate system given by the eigenvectors of the gravity gradient, it is then easy to see that the directions along which the 5 masses will have to lie on coincide with the three coordinate axes (X, Y, Z).
- By adding two pairs of spheres on the X- and Y- axes respectively and located in such a way to “bracket” point  $\mathbf{o}$ , we can compensate both the acceleration and gravity gradient components along these two directions, while the remaining mass will instead need to be located on the positive Z- axis in order to counter-balance a negative Z- component of the gravitational acceleration.
- By fixing the distance to point  $\mathbf{o}$  of each compensating mass, we can then derive the values of the masses by solving a non-homogeneous linear system of 5 equations in 5 unknowns.
- The gravitational compensation scheme we have derived addresses what was considered to be a major road-block to the gLISA mission concept.



A vertical timeline consisting of a horizontal line with five tick marks extending upwards. The labels for the tick marks, from top to bottom, are: 10 yr, 1 yr, 1 week, 1 day, and 1 hr.