SGO Low: A LISA-Like Concept for the Space-based Gravitational-wave Observatory (SGO) at a Low Price-Point

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Category of Response: Mission Concept

Answers to questions: We are willing to present this concept at the workshop. There is no sensitive or controlled information in this concept that NASA is not already aware of.

1. Executive Summary

Introduction

SGO Low is a variant of the LISA concept presented to the Astro2010 Decadal Survey. The rationale for SGO Low is to reduce the LISA concept to the least expensive variant with four Gm-scale laser links. While this interferometer configuration naturally leads to a 'corner' sciencecraft (SC) and two 'end' SC, SGO Low is instead based on four nearly identical SC with two of them located near one vertex of the triangular constellation and one at each of the other two vertices (see Figure 1). The two corner SC, separated by ~10km, use a free-space optical link to compare their laser frequencies. The SGO Low configuration trades on the expectation that four identical SC are cheaper than three having two different designs. This concept was studied under the acronym LAGOS in the early 1990s.

Concept Description

As shown in Appendix B, SGO Low differs from SGO Mid by:

- Addition of a fourth SC
- A telescope, optical bench, laser, GRS, pointing mechanism and supporting structure and thermal subsystems is eliminated from each payload.
- Two of the four SC have an optical pointing system (small telescope, 2-DOF pointing system) for exchanging laser beams.

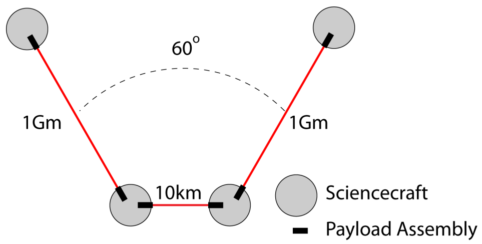


Figure 1: Constellation geometry for SGO Low

Gravitational Wave Science Payoffs

SGO Low will detect and measure parameters for thousands of compact binaries in our Galaxy. It is highly likely that it will detect several massive black hole (MBH) binaries at moderate redshifts and extract physical parameters of these binaries with a precision that is unprecedented for astrophysics. It is also likely that it will detect and precisely measure the capture of compact objects by MBHs, although the large range in event rate estimates allow for some risk that no detections are made. These measurements allow SGO Low to address a number of the science goals identified in Table 1 of the RFI. The most significant loss in science with SGO Low as compared to LISA and the higher-cost SGO variants is in the detection of stochastic and un-modeled sources of gravitational waves (GWs). This directly results from the reduction of links from six to four. Appendix C provides a more detailed comparison of the science yield of the four SGO variants.

Cost Estimate

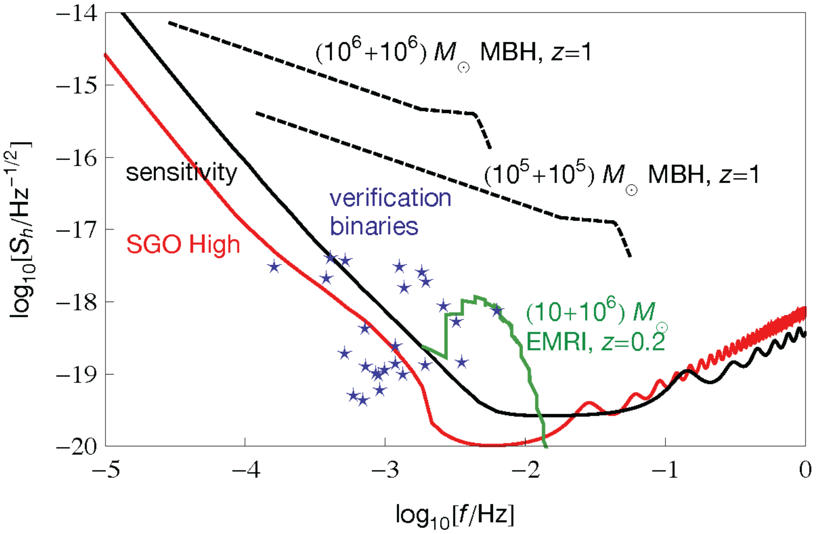
The total estimated cost for SGO Low is \$1.4B in FY2012 dollars. A rough schedule is 108 months for Phase A through D, and 46 months for Phases E and F. Section 7 provides details of the cost model.

Risk

The SGO Low concept benefits from the significant amount of effort that has already been expended in retiring risk for the LISA mission. However, there are certain elements that increase risk relative to LISA and the SGO High/Mid concepts. The most significant of these is the reduction from six to four links, the minimum required for GW detection in practice. Unlike a six-link mission, all four SGO Low links must remain operational to retain any science performance. SGO Low is also more exposed than SGO Mid or SGO High to science risk, the risk that current estimates of event rates are too optimistic.

2. Science Performance

GW astronomy is poised to make revolutionary contributions to astronomy and physics during the next two decades. In particular, space-based GW detectors will open up the low-frequency GW spectrum, $3\text{x}10^{-5}$ Hz to 0.1 Hz, which is guaranteed to be rich in GW sources. The Astro2010 whitepapers about low-frequency GW astronomy [3–6, 8–11] provide a very good picture of its excitement and promise. Over its two-year science mission, SGO Low will detect thousands of individual GW signals from a variety of source classes. Many of these sources will be detected with sufficiently high signal-to-noise ratio (SNR) that their astrophysical parameters (masses, spins, distance, sky location, etc.) will be measured with high precision. These detections and measurements will enable SGO Low to address a number of the key GW science questions[1,3] identified Table 1 of the RFI.



Box 1. The solid black curve shows SGO Low's rms strain noise, in units of $\text{Hz}^{-1/2}$. Roughly speaking, all sources above this curve are detectable by SGO Low. The blue stars represent the frequencies and strengths of known Galactic binaries ("verification binaries"); their height above the noise curve gives their matched-filtering SNR in a one-year integration. The two dashed black curves and the dashed green curve represent sources (two SMBH binaries, and an EMRI, respectively) whose frequency evolves upward significantly during SGO Low's observation time. The height of the source curve above the noise strain approximates the SNR contributed by each logarithmic frequency interval. See [1, 2] for more details. For comparison, the noise curve for SGO High is shown in red. For SGO High, instrumental noise and confusion noise from unresolved Galactic binaries are both significant; the latter causes the "hump" around 1 mHz. For SGO Low, the Galactic confusion noise is almost insignificant.

Sources and Sensitivity

The expected detections for SGO Low come from at least three distinct source classes. Box 1 displays the strength of a few representative GW sources from each class along with the sensitivity of the SGO Low instrument. A summary of detection rates and measurement precision for each class is given in Table 1.

Table 1: Detection rates, source parameters, parameter measurement accuracy, and science targets for source classes expected to be detected by SGO Low. The numbers in parentheses in the "Science Objectives" fields correspond to the LISA science objectives [2,3] addressed by observations of these sources.

Massive Black Hole (MBH) Mergers	
Detection Rate	~ 12/yr total, < 1/yr at $z < 2$
Characteristics	• Redshifts: $0 \lesssim z \lesssim 12$, $\tilde{z} \sim 5$ • Mass: $10^3 M_\odot \lesssim M \lesssim 10^6 M_\odot$ • Signal Duration: $\sim$ hours to months • SNR: $10 \lesssim \rho \lesssim 1000$, $\rho \sim 100$ @ $z = \tilde{z}$
Observables	• Masses: $\frac{\sigma_M}{M} \sim 1\%$ @ $z = \tilde{z}$; $\frac{\sigma_M}{M} \lesssim 0.3\%$ @ z=1; • Spins: $\sigma_\chi \sim 3\%$ @ $z = \tilde{z}$; $\sigma_\chi \lesssim 1\%$ @ z=1 • Luminosity Distance:$\frac{\sigma_{D_L}}{D_L} \sim 20\%$ @ $z = \tilde{z}$; $\frac{\sigma_{D_L}}{D_L} \sim 3\%$ (weak lensing) @ z=1 • Sky Localization: $\sigma_\Omega \sim 80$ deg^2 @ $z = \tilde{z}$; $\sigma_\Omega \lesssim 10$ deg^2 @ z=1
Science Objectives	• Formation of MBHs (1) • Growth and merger history of MBHs (2) • Confront General Relativity with observations (5)
Captures of Stellar Mass Compact Objects by MBH	
Detection Rate	Best estimate: ~ 20/yr; Pessimistic: < 1/yr
Characteristics	• Compact Object: mostly BH with $M \sim 10 M_\odot$ possibly some NSs and WDs • MBH Mass: $10^4 - 5 \times 10^6 M_\odot$ • Redshift Range: $z \lesssim 0.15$ • Orbital Period: $10^1 - 10^3$ s • Signal Duration: $\sim$ years
Observables	• Masses: $\frac{\sigma_M}{M} \sim 0.01\%$ @ $z = 0.1$ • Spins: $\sigma_\chi \sim 0.01\%$ @ $z = 0.1$ • Luminosity Distance: $\frac{\sigma_{D_L}}{D_L} \sim 20\%$ @ $z = 0.1$
Science Objectives	• Growth and merger history of MBHs (2) • Stellar populations in galactic nuclei (3) • Precision tests of General Relativity and Kerr nature of MBHs (5)
Ultra-Compact Binaries	
Detections	$\sim 2 \times 10^3$ individual sources, including ≈ 7 known "verification binaries"
Characteristics	Primarily compact WD-WD binaries; mass transferring or detached Orbital periods: $\sim 10^2 - 10^4$ s
Observables	Orbital frequency; Sky location to few degrees; Chirp mass and Distance from $\dot{f}$ for some high-f binaries
Science Objectives	• $\sim 10-$fold increase in census of short-period Galactic compact binaries (4) • Evolutionary pathways, e.g. outcome of common envelope evolution (4) • Physics of tidal interactions and mass transfer (4) • WD-WD as possible SN Ia progenitors (4)

The most numerous sources are compact binaries in our own Galaxy, which generally have a fixed frequency and amplitude over the SGO mission lifetime. A subset of this population are the "verification binaries", astrophysical systems that are known through electromagnetic (EM) observations and whose GW strength and frequency has already been computed. SGO Low is capable of detecting seven of these "guaranteed" sources.

The highest-SNR sources observed by SGO Low are merging massive black holes (MBH) resulting from galaxy mergers. As the merging MBHs approach coalescence, they will sweep into the SGO Low frequency band and typically merge within band. In some cases, these signals will be observed for months and have integrated SNRs of up to several hundred, enabling highly precise estimates of the system parameters.

A final source class that is expected to be detected by SGO Low is Extreme Mass Ratio Inspirals (EMRIs), the capture of stellar-mass compact objects by nuclear MBH in nearby galaxies ($z < 0.15$). Rate estimates are uncertain, but it is likely that SGO Low will detect some EMRI events and measure parameters with high precision.

It is also possible that SGO Low will detect GW sources for which current astrophysical understanding is not capable of computing event rates. One interesting example is the case of Intermediate Mass Black Holes (IMBHs). If a MBH-IMBH merger were to occur within $z < 3$, SGO Low would be capable of detecting it. Non-detection could also be used to place an observational constraint on the IMBH population.

Science Objectives

The high-level scientific objectives of SGO Low are essentially the same as the first five objectives for LISA [2,3]:

1. Understand the formation of massive black holes
2. Trace the growth and merger history of massive black holes and their host galaxies
3. Explore stellar populations and dynamics in galactic nuclei
4. Survey compact stellar-mass binaries and study the structure of the Galaxy
5. Confront General Relativity with gravitational wave observations

LISA's other two major objectives [10,11] are likely not addressable by SGO Low:

6. Probe new physics and cosmology with gravitational waves
7. Search for unforeseen sources of gravitational waves

1. Understand the formation of massive black holes

Understanding MBH formation requires identification of lower-mass BH "seeds" from which the MBHs evolved via accretion and successive mergers. From Table 1, SGO Low will detect 25~35 MBH mergers in its two-year lifetime, with a median redshift of 5. Mergers of the seeds themselves will occur at higher redshifts, with the precise range depending on the formation model used. While SGO Low is capable of detecting MBH mergers out to $z \sim 12$ and even making moderately-precise parameter estimates (masses to 10% at $z \sim 10$), the event rates at high redshift are too low to expect that a merger involving a BH seed will be observed. Instead, SGO Low will constrain the seed population by observing subsequent generations of MBH mergers at lower redshift (see Objective 2).

2. Trace the growth and merger history of massive black holes and their host galaxies

Just as facilities such as JWST and ALMA will study the evolution and growth of galaxies out to high redshift, SGO Low will undertake the complementary study of MBH evolution and growth. For the MBH mergers occurring at the median redshift range ($z \sim 5$), SGO Low will measure masses to ~1%, spins to ~3%, and distances to ~20%. By comparing the observed distribution of masses and spins with merger tree models, some constraints on MBH seeds and MBH accretion rates can be made. The precision with which this can be done will be limited by small number of events and the poor distance information, which results from the reduction in six links to four.

For the same reason, the volume of the SGO Low error cylinder is typically ~100 times greater than that of SGO Mid. This would likely eliminate the chance of identifying the host galaxy or locating an EM counterpart for a particular MBH merger [4].

Should SGO Low detect EMRIs, as the best rate estimates indicate it will, they can also be used to study MBHs in the local universe ($z<0.15$). The masses and spins of the MBH are precisely measured in any EMRI observation due to the long duration of the signal and its high complexity.

3. Explore stellar populations and dynamics in galactic nuclei

SGO Low will observe EMRI events with a best-estimate rate of ~20/yr. The event rates and mass distribution should help characterize the immediate environments of the MBHs in galactic nuclei. However we emphasize that the EMRI event rate is still highly uncertain, and could be two orders of magnitude lower than our best estimate. With SGO Low there is some risk that zero EMRIs would be observed.

4. Survey compact stellar-mass binaries and study the structure of the Galaxy

SGO Low will detect ~2,000 individual compact binaries in the Galaxy and measure their orbital periods and sky distribution. Data analysis algorithims capable of simultaneously fitting parameters for all of these sources have been validated in the Mock LISA Data Challenge exercises. These distributions will shed light on the (now) poorly constrained formation mechanisms and evolution of these binaries. The shortest period binaries will provide insight in the physics of tidal interactions and mass transfer, while also revealing the chirp masses and distances for some of them. See [1,6,7,9] for additional information.

5. Confront General Relativity with Observations

SGO Low will test General Relativity in several ways [1, 8]. First, SGO Low will use the verification binaries to measure GWs directly and confirm that their properties are consistent with the amplitude, orbital period, phase, and other characteristics determined from EM observations. Second, SGO Low will use EMRI observations to effectively map out the spacetimes of central galactic objects, testing precisely whether they are the Kerr black holes predicted by general relativity, or more exotic objects such as naked singularities and boson stars. Third, SGO Low will observe the inspiral, merger, and ringdown of MBH merger. The strongest MBH signals will have SNRs of order hundreds, allowing close comparisons between the SGO Low measurements and the predictions of numerical relativity.

6-7. Probe new Physics and cosmology, and search for unforeseen sources of gravitational waves

As mentioned above, as one descopes from SGO Mid to SGO Low, the most important loss in performance comes in these two objectives. The principal reason is the decrease from 6 laser links to 4. With only 4 links, only a single Time-Delay Interferometry (TDI) observable can be constructed. With one observable, a stochastic GW background would be very difficult to distinguish from some unexpected source of instrumental noise. By comparison, a 6-link SGO permits the construction of 3 independent TDI observables, from which one can independently estimate the magnitudes of both the instrumental noise and the GW "noise" from the early universe.

Similarly, consider the case of searches for GW bursts from cosmic (super-) strings, which have a characteristic sine-Gaussian shape. Detected in only one channel, it would be very difficult to be confident that the burst was not some instrumental artifact. With either 5 or 6 links, one can measure both components of polarization and provide a powerful veto for non-GW bursts. More generally, for almost any unforeseen GW burst observed in a single channel, it would seem difficult to conclude with confidence that it was not instrumental noise. Nor does it seem likely that one would be able to use coincidences between candidate GW events and events observed electromagnetically to build confidence in their astrophysical nature. The reason is that, for burst sources, SGO Low would provide practically zero localization of the source on the sky. With ten billion galaxies on the sky, it seems likely that there would be a vast number of EM "events" that could conceivably be associated with any putative GW event.

3. Mission Description

The science instrument for SGO Low is a constellation of four *sciencecraft (SC)* arranged in a 60 degree-opening angle "V" configuration with two SC separated by 10 km at the vertex and two equal arms of 1 Gm each (see Figure 1). The sensitivity to gravitational waves is provided by the two 1 Gm arms; SGO Low is classified as a 2 arm/4 link configuration as compared to the 3 arm/6 link configurations of LISA and SGO High/Mid. A small (8 cm) telescope allows the two corner SC to exchange light over a 10 km free-space link for the purposes of measuring the relative phase of the laser sources aboard each corner SC. Each SC consists of a tightly integrated scientific payload and spacecraft bus (denoted S/C), illustrated in Figure 2. This section describes the elements of the SC, including the scientific payload, the S/C bus, and the propulsion module (P/M).

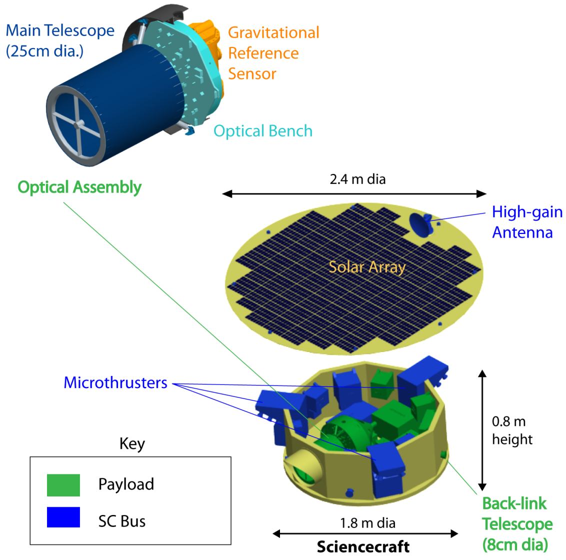


Figure 2: SGO-Low sciencecraft configuration showing the major scientific payload and S/C bus components. The propulsion module is not shown (see Appendix E).

Scientific Payload

The payload for SGO Low is derived from the payload for the classic LISA baseline mission **[**12**]**. The major difference is that there is only one optical assembly per spacecraft. Additional savings are realized through removal of components (OATM, arm locking for frequency stabilization instead of an on-board reference), relaxed requirements on components (telescope, laser, control laws), and reduced size (telescope diameter, SC bus), and simplification (UV-LEDs for charge control, GRS front-end electronics).

The measurement system (Table 2) is divided into a Disturbance Reduction System (DRS) and an Interferometric Measurement System (IMS). The function of the DRS is to place the test mass (TM) into inertial free-fall along the sensitive axis and within the measurement bandwidth

(MBW), 0.1 mHz < f < 100 mHz. This is accomplished by placing the 4cm gold-platinum TM in an electrode housing that is used to sense its position and orientation. The combination of TM, electrode housing, and structure comprise the Gravitational Reference Sensor (GRS). A set of control laws determines the forces and torques to apply to the TMs and the SC such that TM free-fall, constellation pointing, and solar array pointing are maintained. The TM is actuated via the electrodes while the SC is actuated by the Colloidal Micro-Newton Thrusters (CMNTs). The GRS design for SGO Low is essentially identical to that which will fly on ESA's upcoming LISA Pathfinder mission [13].

Component	**# per S/C**	**Hardware Description**	**TRL**
Disturbance Reduction System (DRS), Residual TM acceleration requirement 3.0 x 10^{-15} m/s^2/Hz$^{1/2}$			
Gravitational Reference Sensor (GRS)	1	LPF hardware design, optimized electronics	6
Attitude Control Laws	N/A	*12-DOF, single TM drag-free in sensitive direction*, SC attitude adjusted for constellation pointing & Sun angle	*6*
Colloidal Micro-Newton Thrusters (CMNT)	3 clusters of 4	ST-7/LPF thrusters, 30 μN max thrust, <0.1 μN/Hz$^{1/2}$ noise (open loop)	6
Optical Assembly Tracking Mechanism (OATM)	*0*	*No OATM: Tracking accomplished with SC attitude*	*N/A*
Charge Management	*1*	*UV-LEDs (240-255 nm) [14][15]*	*6*
Interferometric Measurement System (IMS), Displacement Sensitivity requirement of 18 x 10^{-12} m/Hz$^{1/2}$			
Laser subsystem	*1* *+ 1 spare*	Master oscillator power amplifier (MOPA) design @ 1064nm. Master: 40mW Nd:YAG NPRO with fiber-coupled phase modulator. Amplifier: *0.7W* Yb-doped fiber	6
Optical Bench	*1*	Fused silica components hydroxide bonded to Zerodur bench	6
Main Telescope	*1*	*25 cm*, f/1.5 on-axis Cassegrain.	*6*
Back-link Telescope	*1*	*8 cm on-axis Cassegrain (TBD)*	*3*
Photoreceivers	*4 per bench*	InGAs quadrant photodetectors with transimpedance amplifiers. 35 MHz BW and 1.8 pA/Hz$^{1/2}$ noise	3
Phase Measurement System	1	Digital heterodyne receiver based on GPS technology. 22 channels per SC with ~1 μcycle/Hz$^{1/2}$ noise	5
Laser Frequency Stabilization	0	*Arm-locking [16] w/ 300 Hz/Hz$^{1/2}$ residual noise in MBW (stabilization via science signals, no additional H/W required)*	*5*
Point-Ahead Angle Mechanism	1	Piezo-actuated flex pivot mirror on optical bench. Angular range: 800µrad, angular jitter: 16nrad/Hz$^{1/2}$, piston jitter: 2pm/Hz$^{1/2}$ (open loop)	4

Table 2: Major Scientific Payload Components. Differences from SGO High are highlighted in *blue*. DRS TRL levels from Astro2010 RFI#2, Table 2-8 [17].

The IMS monitors changes in the separation between pairs of TMs on separate SC using continuous-wave (CW) heterodyne interferometry. The GRS is mated with an ultra-stable optical bench and a telescope to form the optical assembly. Light from a frequency- or phase-stabilized laser is fed to the optical bench and used to make heterodyne measurements. The 25cm main telescope is used to both transmit and receive light signals along the 1 Gm constellation arms. An 8cm back-link telescope is used to exchange light along the 10 km corner link. A digital phase measurement system measures the phase of the heterodyne signals with a precision of a few microcycles. Phase measurements from all three SC are combined on the ground to form gravitational wave strain measurements using Time Delay Interferometry (TDI) algorithms [18].

Spacecraft Bus

The SGO Low SC bus design will be somewhat similar to the classic LISA design [19] with changes as follows:

- Four SCs are required for the SGO Low configuration, all having the same design to reduce the NRE costs.
- The propulsion module (P/M) will be based on the LISA P/M design [20] with reductions in volume and mass resulting from reduced propellant requirements to achieve final orbit.
- Reduction in power requirements allow shrinking the solar array diameter to 2.8 m as compared to SGO High's 3.0 m.

As with the baseline LISA design, thermally stability of better than 10^{-6} K/Hz$^{1/2}$ for the payload is achieved with passive thermal isolation in combination with the orbits. In addition to housing the payload, the SC bus also contains 1 High-Gain Antenna (HGA) and 1 omni-directional antenna for the Communications Subsystem, 12 Coarse Sun Sensors (CSSs) and 2 Star Tracker systems for the Attitude Control Subsystem (ACS). Three clusters of Colloidal Micro-Newton Thrusters (CMNTs) provide onboard propulsion and fine control for the DRS.

Flight S/W will be developed using the Core Flight Executive Architecture that provides extreme flexibility with respect to design, modification, and testing.All of the SC bus hardware is at a TRL of 6 or better. A complete Master Equipment List (MEL) is provided in Appendix D.

4. Mission Design

The final operational orbits and trajectories for accessing them are described in this section.

Orbits

The SGO Low constellation is similar to the classic LISA constellation [21], with shorter arms, shorter lifetime, and the constant trailing angle replaced with a drift-away orbit. The constellation center semi-major axis and period for the drift-away orbit are (1.0111 AU, 1.0167 year). Optimization of the mission orbits for a two-year life on a drift-away orbit yield $(\Delta L/L, \Delta v, \Delta\alpha) = \sim (\pm 0.6\%, \pm 1.8 \text{ m/s}, \pm 0.6°)$. The point-ahead angle is decreased by a factor of 5 due to the reduction in armlength, L; i.e., $(\omega\, 2L/c) = \sim 1.3$ μ-radians.

The HGA azimuthal range is 360°. The elevation range at the start of science would be ~ [2.1°, 12.9°] when the constellation is at 9° behind the mean Earth. The elevation range becomes ~ [9.0°, 13.7°] by the time the constellation reaches 21°, the end-of-life location.

Trajectories

With a drift-away orbit, judicious selection of launch date allows direct insertion into the selected drift orbit. This is done by launching when Earth is 1.0111 AU from the Sun, i.e., with mean anomaly of ~ ±131°. The required launch vehicle C3 for this is ~ 0.09 (km/s)^2. Using such immediate drift-away, no breaking maneuver is required. One still needs the out-of-plane inclination change burn and in-plane eccentricity changing burn(s). These burns scale as L, and are 126 m/s and 30 m/s, respectively for L = 1Gm. A straight sum yields a total delta-V of ~ 156 m/s; an optimized combination would yield something closer to the root-sum-square value of ~ 130 m/s.

A one-day launch window with two possibilities per year is rather restrictive. There are two options for widening the window: let the drift-away rate be determined by the Earth anomaly at launch or allow sufficient extra propulsion module delta-V to compensate for launch shift. The former requires a modification to required launch vehicle C3, but no change to the post-release delta-V. For economy on the propulsion vehicle side, the former approach would be best. A range of drift-away rates between 5^{o} and 7°/year translates into launch window anomaly range of ±[123°, 139°] and a C3 range of [0.10, 0.075] $(km/s)^{2}$. In contrast, if we allow the launch window to extend up to Earth aphelion and use the propulsion modules to acquire the 6°/year drift, the required C3 drops to 0.023 $(km/s)^{2}$ and the additional delta-V is 44 m/s.

5. Operations

The SGO Low mission can be divided into the following phases: launch and cruise (18 months total), commissioning (4 months), science operations (24 months), and de-commissioning.

The four SC-P/M pairs will share a single launch (see section 6) into Earth-escape orbit and will each cruise to their respective positions in the constellation. During this cruise phase, some initial check out of the SC will be performed, although a number of systems (e.g. CMNTs, GRS, long-arm interferometry) cannot be fully activated until after the SC has separated from the P/M. At the end of the cruise phase, the P/Ms will be ejected, leaving the SC with CMNTs for propulsion during commissioning and science operations. No station keeping is required. An extended mission will be limited by constellation degradation (e.g. increased inter-SC Doppler shifts and larger angular variations) as well as reduced communication bandwidth, CMNT fuel supply, and component lifetimes.

The ground segment includes the Deep Space Network (DSN), the Mission Operations Center (MOC), the Science Operations and Data Processing Centers (SODPC), and the distributed team of science investigators. The MOC performs command sequencing, health and safety monitoring, navigation and anomaly investigation; other aspects of SGO Low operations are autonomous. The SODPC will generate the TDI observables and use this data stream to identify and characterize strong signals. These sources can then be subtracted from the TDI data stream to reveal underlying weaker signals. The resulting data output will be a catalog of sources with estimated parameters (see Section 2 for likely sources and parameter accuracy) that is periodically updated as additional data is processed.

The communications data volume during science operations will be roughly constant, with the constellation generating 1.7 Gbit/day. The frequency of DSN contact will be once every six days per SC, but the duration will vary from 1.3 hours at 9^{o} behind Earth to 8 hours when at 21^{o} behind Earth. The DSN will downlink data from the two vertex SC simultaneously. Key SC operations are re-pointing of the HGAs and switching of laser frequencies, both of which interrupt science operations and will be coordinated to minimize outage times.

6. Launch Vehicle

The SGO Low configuration will launch as a stack of four SC – P/M pairs. The SC will nest inside the P/M (see Appendix E), allowing the launch loads for the stack to be transmitted through the outer shell of the propulsion module rather than through the SC itself.

The launch vehicle for SGO Low must accommodate the mass and size of the four SC, four propulsion modules, and the launch vehicle adapter. The wet mass of each SC – P/M pair is 1021 kg. The estimated mass of the launch vehicle adapter is 200 kg. The total mass for four pairs and the launch adapter is 4284 kg. For a C3 of 0.08 $(km/s)^2$, two example EELVs are the Atlas V (531) with a mass margin of 656 kg and the Falcon 9 (Heavy) with a margin of 9216 kg. A large margin allows for the possibility of launch sharing with another spacecraft to reduce project launch costs by approximately 60%. We assume shared launch as a baseline for the purposes of computing the cost. Appendix E demonstrates that the SGO Low launch stack can easily be accommodated in the Space-X 5 meter fairing while leaving space for a shared payload.

7. Cost Estimate

The cost estimate for SGO Low is developed by reference to our SGO High cost, which is based on a combination of LISA Project cost estimates from several sources: the responses to Astro2010 RFI 1 and 2 [17, 21], a GSFC Mission Design Lab run, ESA LISA Pathfinder costs and launch vehicle cost data. These costs assume sufficient contingencies for 70% probability of success probability and 20% additional management reserves, and have been converted to 2012 dollars. Changes for SGO High from LISA include launch cost reductions and increased contingency for LPF technologies developed in Europe.

SGO High estimate	**1.66**
Launch vehicle savings	0.00
Optical assembly count reduction	-0.03
Payload mass or redundancy reduction	-0.10
Mission duration reduction	-0.12
SGO Low total	**$1.41B**

Table 3: Estimated cost savings from design changes in SGO Low compared to SGO High.

The cost impact of mission design variations was derived using a scaling model, based on the mass and number of major subsystems, and lifetime scaling in phase E. A significant fraction of the first flight unit (72% for science payload and 87% for S/C bus and P/M) was assumed to be non-recurring development expenses. Cost of additional copies was based on recurring expenses discounted by a learning curve at 85% per count doubling. Fractional cost savings from reductions in each unit were scaled at 60% of the fraction mass reductions. These specific NRE and mass-scaling rates are derived from SGO High estimates using the Spacecraft/Vehicle-Level Cost Model [23], a top-level model based the NASA/Air Force Cost Model (NAFCOM) (see Costs in phase E and 10% of payload cost were scaled by the operational lifetime. Launch service cost estimates are based on informal discussions with a NASA launch specialist [24].

Our cost model estimates that SGO Low would cost $1.41B in FY12 dollars.

A rough schedule is taken from the LISA RFI 1 submitted to Astro2010 [22]. Phases A, B, C/D and E/F are expected to last 12, 30, 66 and 46 months, respectively. Phase E consists of an 18 month transfer trajectory, 4 months of commissioning, and 24 months of science observation.

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List of Acronyms

ALMA	Atacama Large Millimeter Array	**LPF**	LISA Pathfinder
AU	Astronomical Unit	**MBH**	Massive Black Hole
BH	Black Hole	**MBW**	Measurement Bandwidth
BW	Bandwidth	**MEL**	Master Equipment List
CMNT	Colloidal Micro-Newton Thruster	**MOC**	Mission Operations Center
CW	Continuous-Wave	**MOPA**	Master Oscillator Power Amplifier
DOF	Degree of Freedom	**NPRO**	Non-Planar Ring Oscillator
DRS	Disturbance Reduction System	**NS**	Neutron Star
DSN	Deep Space Network	**OATM**	Optical Assembly Articulation Mechanism
EELV	Evolved Expendable Launch Vehicle	**P/M**	Propulsion Module
EM	Electromagnetic	**S/C**	Space craft (sciencecraft bus)
EMRI	Extreme Mass Ratio Inspiral	**S/W**	Software
ESA	European Space Agency	**SC**	Sciencecraft
Gm	Gigameter, 1Gm = 1 x 10^9 m	**SGO**	Space-Based Gravitational-Wave Observatory
GRS	Gravitational Reference Sensor	**SNR**	Signal-to-Noise Ratio
GW	Gravitational Wave	**SODPC**	Science Operations and Data Processing Center
HETO	Heliocentric Earth-Trailing Orbit	**TDI**	Time-Delay Interferometry
HGA	High-Gain Antenna	**TM**	Test Mass
IMBH	Intermediate Mass Black Hole	**TRL**	Technology Readiness Level
IMS	Interferometric Measurement System	**UV**	Ultra Violet
JWST	James Webb Space Telescope	**WD**	White Dwarf
LED	Light-Emitting Diode		
LEOP	Launch & Early Operations		
LISA	Laser Interferometer Space Antenna		

Appendices

A. SGO Core Concept Team

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B. Configurations of LISA-Like Missions

Parameter	LISA Concept	SGO High	SGO Mid	SGO Low	SGO Lowest
Arm length (meters)	5×10^9	5×10^9	1×10^9	1×10^9	2×10^9
Constellation	Triangle	Triangle	Triangle	Triangle (60-deg Vee)	In-line: Folded SyZyGy
Orbit	22° heliocentric, earth-trailing	22° heliocentric, earth-trailing	9° heliocentric, earth drift away	9° heliocentric, earth drift-away	≤9° heliocentric, earth drift-away
Trajectory	Direct injection to escape, 14 months	Direct injection to escape, 14 months	Direct injection to escape, 21 months	Direct injection to escape, 21 months	Direct injection to escape, 18 months
Interferometer	3 arms, 6 links	3 arms, 6 links	3 arms, 6 links	2 arms, 4 links	2 unequal arms, 4 links
Launch vehicle	Medium EELV (e.g., Atlas V 431)	Medium EELV (e.g., Falcon Heavy shared launch)	Medium EELV (e.g., Falcon 9 Block 3)	Medium EELV (e.g., Falcon 9 Heavy shared launch)	Medium EELV (e.g., Falcon 9 Block 2)
Baseline/Extended Mission Duration (years)	5/3.5	5/3.5	2/2	2/2	2/0
Telescope Diameter (cm)	40	40	25	25	25
Laser power out of telescope end of life (W)	1.2	1.2	0.7	0.7	0.7
Measurement system modifications	Baseline/Reference	Baseline/Reference (Same as LISA Concept)	In-field guiding, UV-LEDs, no pointing	4 identical spacecraft with one telescope each, In-field guiding, free space backlink, UV-LEDs, arm locking	3 spacecraft with one telescope each, episodic thrusting, in-field guiding, next gen micronewton thrusters, no prop module
Motivation:	science performance, dual agency	LISA performance with all known economies	lowest cost 6 links	Lowest cost with viable science return	Lowest Cost
Approximate Cost ($B)	1.82	1.66	1.40	1.41	1.19
residual acceleration requirement ($m/s^2/Hz^{1/2}$)	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}
displacement sensitivity requirement ($m/s/Hz^{1/2}$)	18×10^{-12}	18×10^{-12}	18×10^{-12}	18×10^{-12}	24×10^{-12}

Science evaluation residual acceleration ($m/s^2/Hz^{1/2}$)	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}	3.0×10^{-15}
Science evaluation displacement sensitivity ($m/s/Hz^{1/2}$)	18×10^{-12}	12×10^{-12}	12×10^{-12}	12×10^{-12}	24×10^{-12}

Note: Science evaluation displacement sensitivity is the displacement requirement minus contingency and chosen to match NGO's evaluation.

C. SGO Comparative Science Performance

Comparison of Science Performance for different versions of SGO				
Concept	SGO High	SGO Mid	SGO Low	SGO Lowest
Nominal Lifetime	5 yrs	2 yrs	2 yrs	2 yrs
MBH mergers				
Total # Detections	$70 \sim 150$	$25 \sim 35$	$25 \sim 35$	~ 4
Median Redshift	$\tilde{z} \sim 5$	$\tilde{z} \sim 5$	$\tilde{z} \sim 5$	$\tilde{z} \sim 4$
Mass Precision @ $z = \tilde{z}$	$\frac{\sigma_M}{M} \sim 0.2\%$	$\frac{\sigma_M}{M} \sim 1\%$	$\frac{\sigma_M}{M} \sim 1\%$	$\sim 3\%$
Spin Accuracy @ $z = \tilde{z}$	$\sigma\chi \sim 0.3\%$	$\sigma\chi \sim 2\%$	$\sigma\chi \sim 3\%$	-
Distance Accuracy @ $z = \tilde{z}$	$\frac{\sigma_{D_L}}{D_L} \sim 3\%$ (WL)	$\frac{\sigma_{D_L}}{D_L} \sim 3\%$ (WL)	$\frac{\sigma_{D_L}}{D_L} \sim 20\%$	-
Sky Localization @ $z = \tilde{z}$	$\sim 1\ \mathrm{deg}^2$	$\sim 1\ \mathrm{deg}^2$	$\gtrsim 100\ \mathrm{deg}^2$	-
# Detections @ $z < 2$	~ 7	$1 \sim 2$	$1 \sim 2$	< 1
Mass Precision @ $z = 1$	$\frac{\sigma_M}{M} \lesssim 0.1\%$	$\frac{\sigma_M}{M} \lesssim 0.1\%$	$\frac{\sigma_M}{M} \lesssim 0.3\%$	-
Spin Accuracy @ $z = 1$	$\sigma\chi \lesssim 0.1\%$	$\sigma\chi \lesssim 0.1\%$	$\sigma\chi \lesssim 1\%$	-
Sky Localization @ $z = 1$	$\lesssim 0.1\ \mathrm{deg}^2$	$\lesssim 0.1\ \mathrm{deg}^2$	$\lesssim 10\ \mathrm{deg}^2$	-
EMRIs				
# Detections	$40 \sim 4000$, to $z \sim 1.0$	$2 \sim 200$, to $z \sim 0.2$	$\lesssim 40$, to $z \sim 0.15$	0
Mass Accuracy	$\frac{\sigma_M}{M} \sim 0.01\%$	$\frac{\sigma_M}{M} \sim 0.01\%$	$\frac{\sigma_M}{M} \sim 0.01\%$	–
MBH Spin Accuracy	$\sigma\chi \sim 0.01\%$	$\sigma\chi \sim 0.01\%$	$\sigma\chi \sim 0.01\%$	–
Compact Binaries				
# Verification binaries	10	8	7	0
# Resolvable binaries	$\sim 20,000$	$\sim 4,000$	$\sim 2,000$	~ 100
Discovery Space				
Detects early-universe Ω_{gw}	$\gtrsim 10^{-10}$	$\gtrsim 10^{-9}$	–	–
Can Detect+Verify Bursts?	✓	✓	–	–

D. Master Equipment List

GW Flight System SGO Low		# OF UNITS			FLIGHT HARDWARE MASSES			FLIGHT HARDWARE POWER		
Subsystem / Component	Unit Mass [kg] (CBE)	Flight	Flight Spare	EM & Prototype	Total Mass [kg] (CBE)	Contingency [%]	Total Mass [kg] (MEV)	Total Power [W] (CBE)	Contingency [%]	Total Power [W] (MEV)
Spacecraft Bus		**3**	**0**	**1**	**245.250**	**30%**	**318.83**	**326.90**	**30%**	**332.0**
Structures and Mechanisms					**115.5**		**150.15**			
Primary Structure	82.00	1	1		82		106.60			
Secondary Structure	16.40	1	1		16.4		21.32			
HGAD Mechanism	0.50	2	1		1		1.30			
Launch Locks, misc.	0.25	10	1		2.5		3.25			
Lightband (SM to PM)	13.60	1	1		13.6		17.68			
Power					**24.1**		**31.33**	**40.6**		**45**
Solar Array (5.3 m^2)	9.60	1	0		9.6		12.48			
Battery (Lithium Ion 20 AH)	4.50	1	1		4.5		5.85			
Power System electronics	10.00	1	1		10		13.00			
Command and Data Handling		1			**15.1**		**19.63**	**57.4**		**30**
C&DH	15.10	1	1		15.1		19.63			
Telecom					**21.0**		**27.30**	**66.15**		**86**
Transponder (X/Ka)	2.50	2	1		5		6.50			
RFDU	2.40	1	0		2.4		3.12			
TWT (with EPC)	7.00	0	0		0		0.00			
HG Antenna	2.30	2	0		4.6		5.98			
LG Antenna	1.00	2	0		2		2.60			
Cabling	2.00	1	0		2		2.60			
X-Band Power Amp's	0.00	0	0		0		0.00			
HGAD Electronics	2.50	2	1		5		6.50			
Atitude Control					**8.1**		**10.50**	**8.5**		**11**
Gyro's	0.75	2	1		1.5		1.95			
Star Tracker Assemblies										
SC Optical Head	0.50	5	1		2.5		3.25			
SC Electronics	0.60	2	1		1.2		1.56			
Coarse Sun Sensors	0.16	18			2.88		3.74			
Propulsion					**38.4**		**49.92**	**92.3**		**120**
Micronewton Thrusters	12.80	3			38.4		49.92			
Thermal Control					**10.1**		**13.09**	**30.76**		**40**
MLI Blankets	0.60	2			1.2		1.56			
Heaters	0.04	15			0.6		0.78			
Thermistats	0.03	24			0.72		0.94			
Thermistors	0.03	90			2.7		3.51			
Radiators	0.30	1			0.3		0.39			
Coatings (Gold Paint, etc.)	0.20	12			2.4		3.12			
Coatings (Black Paint)	0.15	13			1.95		2.54			

I/F Material (Nusil, cho-therm)	0.02	10			0.2		0.26			
Cable and Harnessing					**13.0**		**16.90**			
Cables and Harness	13.00	1			13		16.90			
Propulsion Module (Dry)		**3**	**0**	**1**	**224.190**	**30%**	**291.45**	**107.7**	**30%**	**140.0**
Structure					**143.8**		**186.94**			
Primary Structure	113.00	1			113		146.90			
Secondary Structure	9.00	1			9		11.70			
Lightband (PM to PM)	21.80	1			21.8		28.34			
Command and Data Handling					**9.1**		**11.83**	**23.0**		**30**
Propulsion Module RIU	9.10	1			9.1		11.83			
Telecom					**2.0**		**2.60**			
LG Antenna	1.00	2			2		2.60			
Attitude Control					**0.0**		**0.00**			
Coarse Sun Sensor	0.20	0			0		0.00			
Thermal					**11.4**		**14.82**	**23.0**		**30**
Misc. Thermal Hardware	11.40	1			11.4		14.82			
Propulsion					**57.9**		**75.26**	**61.5**		**80**
Hz Fuel Tanks	6.80	1			6.8		8.84			
NTO Tank	3.40	2			6.8		8.84			
22N Hz Thruster	0.77	8			6.16		8.01			
Hz Valve		1			0		0.00			
NTO Valve		1			0		0.00			
Injector Heater		1			0		0.00			
45N Main Engine	5.20	1			5.2		6.76			
Hz Valve		1			0		0.00			
NTO Valve		2			0		0.00			
Injector Heater		2			0		0.00			
Regulator	0.84	2			1.68		2.18			
Latch valves, check valves, filters, etc.	31.25	1			31.25		40.63			
Propellant		**1**	**0**	**0**	**225.000**	**0%**	**225.00**			
Propellant	225.00	1			225		225			
Scientific Complement		**3**	**0**	**1**	**143.17**	**30%**	**186.11**	**203.1**		**264.0**
Instrument Electronics					**24.5**		**31.85**	**138.46**		**180**
LASER Unit Assembly	3.00	2			6		7.80			
Ultra Stable Oscillator	0.50	2			1		1.30			
Phasemeter Unit (incl. harness)	8.00	1			8		10.40			
Charge Management Unit	2.00	1			2		2.60			

Caging System Electronics	4.00	1			4		5.20			
Diagnostic Driver Electronics	1.50	1			1.5		1.95			
Optical Assembly Mechanism Electronics	1.50	0			0		0.00			
Optical Assembly Electronics	2.00	1			2		2.60			
Moving Optical Sub-Assembly		**1**			**53.81**		**69.95**	**56.9**		**74**
Telescope					**25.2***		**32.76**			
Primary Mirror	8.00	1			8		10.40			
M1 Support Ring	1.27	1			1.27		1.65			
CFRP - Isostaticmount Primary Mirror	0.07	3			0.21		0.27			
Telescope spacer	2.11	1			2.11		2.74			
M2 Support Ring	0.52	1			0.52		0.68			
Secondary Mirror (M2) + Aadapter	0.10	1			0.1		0.13			
Optical Truss Interferometer	0.20	0			0		0.00			
Isomount Telescope Subassy	0.26	3			0.78		1.01			
Focusing Mechanism	0.20	1			0.2		0.26			
I/F Ring Optical Bench	0.95	1			0.95		1.24			
Outer CFRP - Isostaticmount Optical Bench	1.62	1			1.62		2.11			
CFRP-Isostaticmount Optical Bench	0.10	3			0.3		0.39			
TI-Bracket 3 complete (to HRM)	0.26	2			0.51		0.66			
Launch Lock device (MOSA)	0.42	2			0.84		1.09			
CFRP-Rear Cover	1.52	1			1.52		1.98			
TI-Drive and HDRM Adapter	0.30	1			0.3		0.39			
Optical Bench Subsystem	12.60	1			12.6		16.38			
Optical Payload	4.00	1			4		5.20			
Gravitational Reference Sensor					**28.6**		**37.14**			
GRS Head	19.00	1			19		24.70			
GRS Support Frame	2.82	1			2.82		3.67			
Isostatic mounts GRS Head	0.25	3			0.75		0.98			
GRS Head Harness	1.00	1			1		1.30			
GRS Front-End Electronics	5.00	1			5		6.50			
MOSA Thermal Control Hardware		2			**2.0**		**2.6**	**7.0**		**10.0**
CFRP-Substrat between M1 a.OB	0.10	1			0.1		0.13			
MLI Telescope Spacer	0.50	1.436			0.718		0.93			
MLI M2 Support Ring	0.50	0.2			0.1		0.13			
MLI between M1 and OB	0.50	0.26			0.13		0.17			
MLI Rear Cover	0.50	0.76			0.38		0.49			
Stand Off's	0.00	60			0.12		0.16			
Structure					**12.2**		**15.81**			
Static Frame	4.50	1			4.5		5.85			
TI Mountingbracket LLD MOSA	0.42	0			0		0.00			

N214 Actuator complete with bracket	1.15	2			2.3		2.99			
Launch Lock Device Rotation complete	1.00	1			1		1.30			
Upper Support Struts Main frame	0.50	2			1		1.30			
Lower Support Struts Main frame	0.50	2			1		1.30			
CFRP-Front mount cone	0.60	2			1.2		1.56			
TI Bracket 2 (Front Isomount)	0.28	1			0.28		0.36			
TI Bracket (Rear Isomount)	0.44	2			0.88		1.14			
Thermal H/W Mainframe					**3.2**		**4.16**			
MLI Front mount cone	0.50	0.2			0.1		0.13			
MLI for Main Support struts	0.50	0.42			0.21		0.27			
Contamination Control Cover	0.50	3.3			1.65		2.15			
Substructure CCC	1.00	1			1		1.30			
Stand Off's	0.00	120			0.24		0.31			
Harness	31.40	1			31.4		40.82			
Standard Parts	3.00	1			3		3.90			
Back Telescope Assembly					**12.0**		**15.60**			
Back Telescope	12.00	1			12		15.60			
L/V Adapter		**1**	**0**	**0**	**201.000**	**30%**	**261.30**			
Adapter (5% launch mass)	201.00	1			201.00		60.30			
Subtotal - Cruisecraft Dry					**609.0**	**30%**	**792.0**			
Total - GW Cruisecraft Wet (w/o L/V Adapter)					**834.0**	**30%**	**1017.0**			
Total - GW Launch Stack (incl L/V adapter)					**3539.0**		**4331.0**			
Total - GW Cruise Power								**370.8**		**482.0**
Total - GW Operational Power								**458.5**		**596.0**

* - Telescope mass is scaled by the square of the ratio of the 25 cm to 40 cm telescope diameter.

E. Launch Vehicle Accommodation

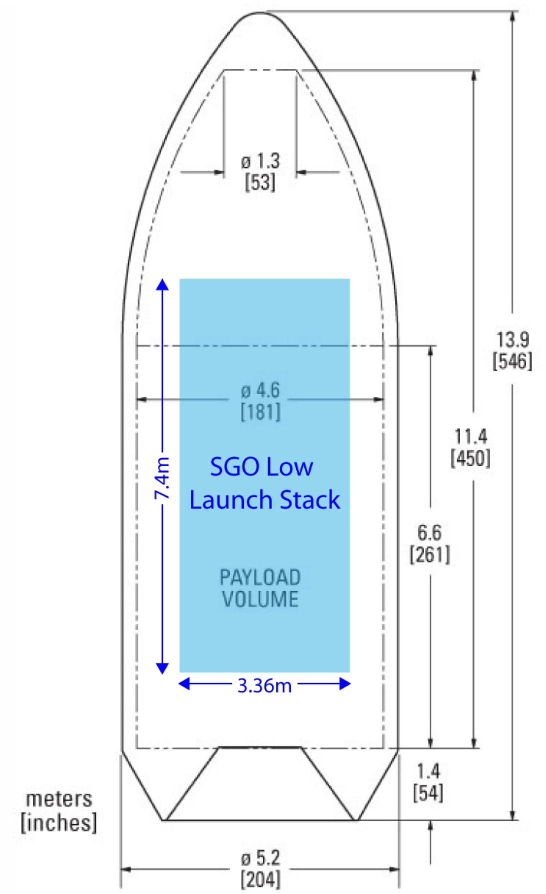

Figure E1

The standard Falcon 9 Fairing will accommodate the SGO Low launch stack (w/o launch adapter). Note that there are 4 SC-P/M pairs in the stack, and there is additional space available for a shared launch.

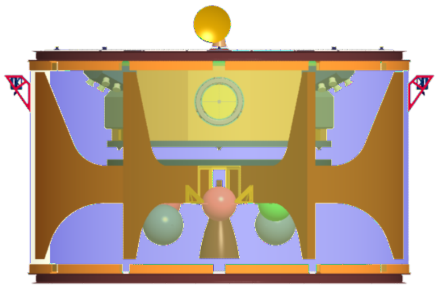

Figure E2

Each of the four SCs will be nested inside of a propulsion module (P/M) as shown above, with the four SC – P/M pairs stacked as a column inside the launch vehicle payload fairing. The stack is designed to carry the launch loads through the P/M's outer shell, thereby isolating each of the SC from the direct launch load inputs. The solar array diameter is 2.8m, the SC upper deck diameter is 2.4 m, and the SC lower deck diameter is 1.8 m. The SC is 0.8 m high. The P/M height and structure has not yet been optimized.