SGO Mid: A LISA-Like Concept for the Space-based Gravitational-wave Observatory (SGO) at a Middle 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.

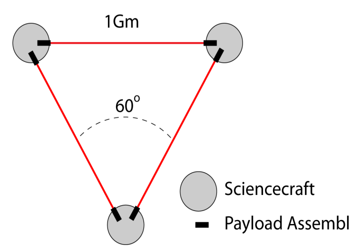
1. Executive Summary

Introduction

The Mid Price-Point concept for SGO (SGO Mid) is based on the LISA concept presented to the Astro2010 Decadal survey. The rationale for the SGO Mid concept is to reduce the LISA concept to the least expensive variant with six laser links, comprising three interferometer arms. Six laser links are critical for simultaneously observing both polarizations of gravitational waves, discriminating between some cosmological sources and instrumental noise, and for redundancy.

Relative to LISA and SGO High, SGO Mid reduces the constellation size, the constellation distance from the Earth, and the length of observation.

Concept Description



SGO Mid differs from LISA by:

- The detector arm length is reduced from 5 Gm to 1 Gm
- The observation period is reduced from 5 to 2 years.
- The nominal starting distance from Earth is reduced by about a factor of 2.5 to a 9-degree trailing orbit.
- The telescope diameter is reduced from 40 to 25 cm, and the laser power out of the telescope is reduced from 1.2 to 0.7 W (end of life).
- In-field guiding is used instead of articulating the entire optical assembly

Gravitational Wave Science Payoffs

SGO Mid will detect fewer sources of all types than LISA and the accuracy with which it will extract astrophysical parameters will typically be a few times worse. Scientifically, the greatest cost of descoping SGO High to SGO Mid comes from the risk that some of our estimated source rates (which generally come from models, not direct observation) could be much smaller than our current best estimates, greatly reducing the science return. SGO Mid has an overall sensitivity a factor of a few worse than LISA, so its potential for serendipitous discovery is correspondingly reduced.

Risk

This design benefits from low technical risk through its LISA heritage. The main science risk is the short lifetime.

Cost Estimate

The cost and schedule of SGO Mid has been estimated using cost information from the LISA cost estimates supplied to the Astro2010 decadal survey and other sources. The total cost is estimated to be $1.40B. A rough schedule is 108 months for Phase A through D, and 46 months of Phases E and F.

2. Science Performance

Gravitational-wave (GW) astronomy is poised to make revolutionary contributions to astronomy and physics during the next two decades. In particular, space-based gravitational-wave detectors will open up the low-frequency GW spectrum, 3×10^{-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. SGO Mid is certain to detect thousands of compact binaries in our Galaxy, and it is strongly expected to observe GW radiation from merging massive black holes (MBHs), compact stellar objects spiraling into MBH in galactic nuclei, and possibly from more exotic sources, such as a stochastic GW background from the early universe or GW bursts from cosmic strings. SGO Mid's measurements will determine the physical parameters of many sources with sufficient precision to allow SGO Mid to address some of the most important questions that today face astrophysics and physics [1, 3]. In this section we summarize SGO Mid's key science goals and expected performance.

Sources and Sensitivity

SGO Mid's science objectives are realized through observations of various source classes. Box 1 shows the strength of a few fiducial sources with respect to the strain sensitivity of SGO Mid. A summary of SGO Mid's sources, along with their expected strengths, rates, and science yields, is given in Table 1.

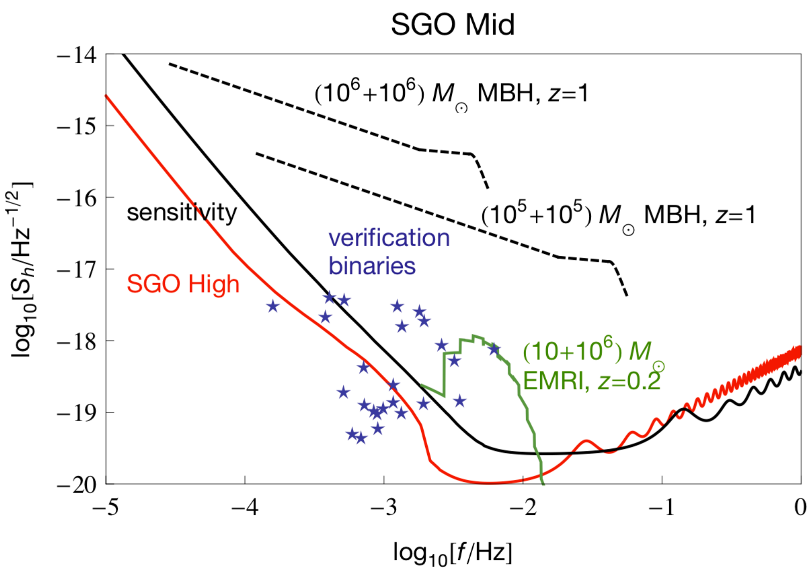
Science Objectives

The high-level scientific objectives of SGO Mid are essentially the same as 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
6. Probe new physics and cosmology with gravitational waves
7. Search for unforeseen sources of gravitational waves

<u>1. Understand the formation of massive black holes</u>

Understanding MBH formation requires determining the origin of the lower-mass BH "seeds" from which the MBHs evolved via accretion and successive mergers. SGO Mid will give statistical information on the growth of intermediate mass black holes (IMBHs) from the seeds by observing inspirals of the IMBHs into larger MBHs after galaxy mergers. The SGO Mid design parameters (e.g., its arm length and displacement sensitivity) provide some sensitivity for observing mergers of IMBHs with roughly 10^4 to 10^5 M_sun MBHs out to high redshifts (z ~ 10), and will measure the MBH masses and spins to ~1% accuracy. SGO Mid's capability to distinguish large seed and small seed formation scenarios is significantly reduced in comparison with SGO High.



Box 1 The black curve shows SGO Mid rms strain noise, in units of $\mathrm{Hz}^{-1/2}$. Roughly speaking, all sources above this curve are detectable by SGO Low. The blue stars represent the frequencies and strengths of known Galactic binaries (SGO Mid's "verification binaries"); their height above the noise curve gives their matched-filtering signal-to-noise ratio (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 Mid'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 Mid, the Galactic confusion noise is almost insignificant.

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

For MBH mergers occurring at the median redshift range (z~5), SGO Mid will measure masses to 1%, spins to 2%, and distances to 3% (limited by weak gravitational lensing). By comparing the observed distribution of masses and spins with merger tree models, constraints on MBH development can be made. For favorable observations, rough sky locations will be determined, allowing for targeted searches for EM counterparts. However the error box on the sky will be typically be ~ 10 times larger than for SGO High, generally making the search for EM counterparts much more challenging. In addition, the observation of captures of stellar-mass objects by MBHs (so-called "extreme mass ratio inspirals," or EMRIs) will provide very precise masses and spins for the nuclear MBH out to z~0.2 for MBHs with masses up to $\sim 10^6\ M_\odot$ [1, 5, 9].

3. Explore stellar populations and dynamics in galactic nuclei

SGO Mid will observe EMRI events with a best-estimate rate of ~100/yr, out to z~ 0.2. The precise rates, and the masses of the stellar-mass black holes, should reveal a good deal about the stellar population in the close vicinity of the MBH. However we emphasize that the event rate is still highly uncertain, and could be two orders of magnitude lower than our best estimate. So with SGO Mid there is some risk that few or no EMRIs would be observed. A fairly large number of events (~50 or more) are required before one can begin to make significant statistical inferences about the underlying stellar population.

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

SGO Mid will detect ~4,000 individual compact binaries in the Galaxy and measure their orbital periods and sky distribution. (The Mock LISA Data Challenges have already demonstrated

Massive Black Hole (MBH) Mergers	
Detection Rate	~ 17/yr total, ~ 1/yr at $z < 2$
Characteristics	• Redshifts: $z \lesssim 14$, $\tilde{z} \sim 5$ • Mass: $10^4 M_\odot \lesssim M \lesssim 3 \times 10^6 M_\odot$ • Signal Duration: hours to months • SNR: $10 \lesssim \rho \lesssim 10^3$, $\rho \sim 70$ @ $z = \tilde{z}$
Observables	• Masses: $\frac{\sigma_M}{M} \sim 1\%$ @ $z = \tilde{z}$; $\frac{\sigma_M}{M} \lesssim 0.1\%$ @ z=1 • Spins: $\sigma_\chi \sim 2\%$ @ $z = \tilde{z}$; $\sigma_\chi \lesssim 0.1\%$ @ z=1 • Luminosity Distance: $\frac{\sigma_{D_L}}{D_L} \lesssim 3\%$ @ $z \lesssim 6$ (limited by weak lensing) • Sky Localization: $\sigma_\Omega \sim 1$ deg^2 @ $z = \tilde{z}$; $\sigma_\Omega \lesssim 0.1$ deg^2 @ z=1
Science Objectives	• Nature of seed black holes at $z \sim 10 - 17$ (1) • Growth and merger history of MBHs (2) • Test General Relativity in strong-field, highly-dynamic regime (5) • Electromagnetic counterparts (6)

Captures of Stellar Mass Compact Objects by MBH	
Detection Rate	Best estimate: ~ 100/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: $z \lesssim 0.2$ • Orbital Period: $10^1 - 10^3$ s • Signal Duration: $\sim$ years
Observables	• Masses: $\frac{\sigma_M}{M} \sim 0.01\%$ @ $z = 0.1$ • Spins: $\sigma_\chi \sim 0.1\%$ @ $z = 0.1$ • Luminosity Distance: $\frac{\sigma_{D_L}}{D_L} \sim 10\%$ @ $z = 0.1$
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	$\sim 4 \times 10^3$ individual sources, including ≈ 8 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	• $\sim 20-$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)

Early Universe Stochastic Backgrounds	
Possible Sources	Early universe 1st-order phase transition at $kT \sim 1TeV$ (e.g., electro-weak transition); Brane oscillations in large extra dimensions; Cosmic (super-)strings
Observables	Any early-universe background with $\Omega_{gw} \gtrsim 10^{-9}$
Science Objectives	• Amplitude and spectral shape of $\Omega_{gw}(f)$ (6,7) •Early universe physics (6)

Cosmic (Super-)String Bursts	
Characteristics	String loops generically develop "cusps" once per oscillation; these produce highly beamed GW bursts with universal profile: $h(t) \propto \|t - t_c\|^{1/3}$
Observables	Sky positions, amplitudes, overall rate
Science Objectives	• Possible experimental proof of string theory (6,7) • constrain string phenomenology (6,7)

Table 1. A summary of SGO Mid's sources: their characteristics, estimated rates, parameter estimation accuracy, and science objectives.

algorithms that can do this.) 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. Of all the science objectives, this one is probably the least affected by the descope from SGO High to Mid.

5. Confront General Relativity with Observations

SGO Mid will test General Relativity in several ways [1, 8]. First, SGO Mid will use specific compact binaries known from electromagnetic observations to measure GWs directly and confirm that their properties are consistent with the amplitude, orbital period, phase, and other characteristics determined from electromagnetic (EM) observations. Second, SGO Mid 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 or boson stars. Third, SGO Mid will observe the inspiral, merger, and ringdown of MBH merger. The strongest MBH signals will have SNRs of order hundreds, allowing quite close comparisons between the SGO Mid measurements and the predictions of numerical relativity. Again, the risk to this science lies in the poorly constrained event rates, and therefore the possibility that no MBH mergers or EMRIs are seen. Observing only one or two events would make it difficult to draw robust conclusions.

6. Probe New Physics and cosmology with gravitational waves

While in electromagnetic astronomy, distance measurements generally depend on empirically determined relationships (such as the brightness-period relation for Cepheids or the Tully-Fisher relation for spiral galaxies), in GW astronomy distances come from fundamental physics—the two-body problem in GR. Although GWs do not encode the source's redshift, several mechanisms have been suggested that could lead to detectable electromagnetic counterparts to MBH mergers, allowing astronomers to determine the redshift of the host galaxy. With even a handful of mergers at $z < 1$ with EM counterparts, SGO Mid will be able to determine the Hubble constant to ~1%, in a manner independent of conventional methods [1, 10]. But compared to SGO High, the chance of this cosmological science coming to fruition is significantly reduced, since i) there are fewer sources, and ii) for each source, the much larger error boxes on the source's location makes the search for a counterpart impractical. In addition, SGO Mid has unique abilities to detect and quantify a remnant isotropic GW background from the early universe. It will be especially sensitive to GWs from phase transitions at the TeV scale. This includes the electro-weak phase transition and potentially the phase transitions associated with brane dynamics in large extra dimensions [1, 11]. SGO Mid will also be highly sensitive to GWs from cosmic (super-)strings: it may observe both a stochastic background from their large-scale oscillations, and individual highly beamed GW bursts from the cusps that develop generically on the strings [1, 11]. Indeed, SGO Mid could perhaps provide experimental verification of string theory!

7. Search for unforeseen sources of gravitational waves

SGO Mid has tremendous discovery potential. It covers nearly four decades of the GW frequency spectrum with high sensitivity, and it is capable of detecting individual sources out to very high redshift ($z > 15$). The history of astronomy strongly suggests that opening such a wide and qualitatively new observational window should yield very significant surprises, revealing new objects and phenomena that would otherwise remain invisible to us [3].

3. Mission Description

The science instrument for SGO Mid is a constellation of three sciencecraft (SC) arranged as an equilateral triangle with 1 Gm arms. Each SC consists of a tightly integrated scientific payload and spacecraft bus, shown in Figure 2. This section describes the elements of the SC, including the scientific payload, the SC bus, and the propulsion module.

Scientific Payload

The payload for the mid-price point SGO option is similar to the payload for the classic LISA baseline mission [12]. 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 masses (TMs) into inertial free-fall along the sensitive axes and within the measurement bandwidth, 0.1 mHz < f < 100 mHz. This is accomplished by placing each 4cm gold-platinum TM in an electrode housing that is used to sense its position and orientation. The TM, housing, electronics, and charge management system form the Gravitational Reference Sensor (GRS) subsystem. A set of control laws determines the forces and torques to apply to the two TMs and the SC such that TM free-fall, constellation pointing, and solar array pointing are maintained. The TMs are actuated via the electrodes while the SC is actuated by the Colloidal Micro-Newton Thrusters (CMNTs). The GRS design for SGO Mid is essentially identical to that which will fly on ESA's upcoming LISA Pathfinder mission [13]. One exception is the replacement of the UV lamps with UV LEDs in the charge management system. The GRS, together with a set of CMNTs, the SC, and a set of control laws form the DRS.

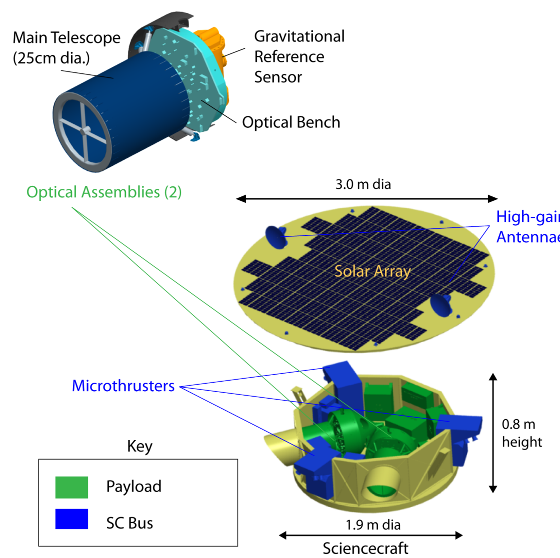


Figure 2: SGO-Mid configuration showing the major components of the scientific payload and the SC bus.

The IMS monitors changes in the separation between pairs of TMs on separate SC using continuous-wave (CW) heterodyne interferometry. Each GRS is mated with an ultra-stable optical bench and a telescope to form an optical assembly. Light from a frequency- or phase-stabilized laser is fed to the optical bench and used to make heterodyne measurements. The telescope is used to both transmit and receive light signals along the 1 Gm constellation arms. The shortening of the arms relative to SGO High allows both a reduction in the laser power and a reduction in the telescope diameter while increasing the peak shot-noise limited strain sensitivity (although the peak sensitivity occurs at a higher Fourier frequency). It also reduces the coupling of angular jitter, allowing a relaxation on those requirements. The laser power and telescope diameter parameters chosen for SGO Mid represent one point in this trade space. Further optimization may yield additional cost reductions and/or science benefits.

Component	# per SC	Hardware Description	TRL
Disturbance Reduction System (DRS), Residual TM acceleration requirement of 3.0 x 10^{-15} m/s^2/Hz$^{1/2}$			
Gravitational Reference Sensor (GRS)	2	LPF hardware design, optimized electronics	6
Attitude Control Laws	N/A	18-DOF, each 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
In-Field Guiding	2	*Replaces OATM from classic LISA. S/C tracking accomplished with steering mirror in aft optics. Angular range of ~20^o, angular jitter of 0.2nrad/Hz$^{1/2}$, piston jitter: 2pm/Hz$^{1/2}$ (open loop).*	6
Charge management	2	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	2 + 2 spare	Master oscillator power amplifier (MOPA) design @ 1064nm. Master: 40mW Nd:YAG NPRO with fiber-coupled phase modulator. Amplifier: *0.7W* Yb-doped fiber amp.	6
Optical Bench	1	Fused silica components hydroxide bonded to Zerodur bench	6
Telescope	1	25 cm, f/1.5 on-axis Cassegrain.	6
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. ~20 channels per SC with ~1 μcycle/Hz$^{1/2}$ noise	5
Laser Frequency Reference	1	Heterodyne Mach-Zehnder (LPF) or Fabry-Perot cavity. 300 Hz/Hz$^{1/2}$ residual noise in MBW	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 representative specifications)	4

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

Unlike SGO High, the telescope for SGO Mid has a sufficiently large field of view that an Optical Assembly Articulation Mechanism (OATM) is not needed to maintain pointing to the far SC as the constellation interior angle varies. An optical fiber is used to exchange light between the two optical benches aboard each SC. A digital phase measurement system measures the phase of the heterodyne signals with a precision of a few microcycles relative to the SC clock. 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 Spacecraft bus design will be very similar to the classic LISA design [19] with a few changes but is slightly smaller due to elimination of the OATM in favor of in-field guiding. The propulsion module is lighter and smaller than that for SGO high due to reduced propellant requirements for achieving final orbit (9 degree heliocentric earth-trailing drift away orbit and the reduction of arm length to 1 Gm).

All avionics components will be fully redundant including the Command and Data Handling, Power Supply Electronics, Attitude Control and Telecommunications. One 20 Ah battery will be used for LEOP, cruise, and Propulsion Module separation requirements.

Flight S/W will be developed using the Core Flight Executive Architecture, which provides extreme flexibility with respect to design, modification, and testing.

All of the Bus hardware is at TRL 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

SGO Mid is essentially LISA, 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 ($\Delta L/L$, Δv, $\Delta\alpha$) = ~ (±0.6%, ±1.8 m/s, ±0.6°). The look-back to look-ahead angle is decreased by a factor of 5; i.e., (ω 2L/c) = ~ 1.3 μ-radians.

The HGA azimuthal range is still 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 its 21°, 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, becoming 126 m/s and 30 m/s, respectively. 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: (1) let the drift-away rate be determined by the Earth anomaly at launch, or (2) 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 and 7°/year translates into launch window anomaly range of ±(123° to 139°) and a C3 range of 0.10 to 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 ground segment includes the Deep Space Network (DSN), the Mission Operations Center (MOC), the Science Operations and Data Processing Centers (SODPC), and a distributed team of science investigators.

The distributed team of investigators accesses the data through public networks, and performs focused investigations of specific sources and phenomena. Results are returned to the Science Data Processing Facility for archival and use in further data reduction.

The SGO Mid mission can be divided into the following phases: Launch through entry into an Earth-escape trajectory; Early Operations: Initial spacecraft checkout; Cruise through interplanetary space to the operational orbits; Commissioning (when the constellation is initialized and propulsion modules ejected); Science operations (the bulk of the mission, during which the measurements are made); De-commissioning at the end of the mission.

The launch and initial maneuvers will place SGO Mid onto a constant drift away from Earth at 6°/year. Maneuvers during and at the end of the cruise at 9° trailing Earth (18 months after launch) will put the three into a LISA triangular configuration with 1Gm arm lengths. The propulsion modules will be ejected, starting drag-free operations. During Science Operations, the constellation will be stable by virtue of initial conditions without any maintenance maneuvers, with the only propulsion being micro-Newton thrust levels to control spacecraft attitude and to have each spacecraft follow its test masses. For SGO Mid, science operations will last two years at 9°-21° heliocentric, continuing to drift at 6°/year, trailing the Earth.

6. Launch Vehicle

The launch vehicle for the SGO Mid must accommodate the mass and size of the three sciencecraft, three propulsion modules and the launch vehicle adapter.

The wet mass of each of SGO Mid sciencecraft and propulsion module is 1190 kg, a savings of 536 kg over the SGO High configuration. The estimated mass of the launch vehicle adapter is 189 kg. The total mass for three sciencecraft, three propulsion modules and the launch adapter is 3759 kg, a savings of 1703 kg over SGO High.

As an illustrative example, the minimum launch vehicle for placing the SGO Mid into heliocentric orbit, C3 = 0.08 $(km/sec)^2$, is an Atlas V (411) or a Falcon 9 (Heavy). A Falcon 9 (Block 3) would require a mass reduction of ~ 8% to meet the launch mass with zero margin.

The Atlas V (411) is not on the launch manifest, but the next EELV up in the series, the Altas V (521) has an estimated launch margin of 411kg, or about 11%. This is short of the customary margin goal of 30%. The Atlas V (531) has an estimated launch margin of 31%, which is adequate. The Falcon 9 (Heavy) has an estimated launch margin of 9700kg, or about 2.6 times the mass of the SGO Mid launch stack.

The Falcon 9 (Heavy) is substantially the same cost as the Atlas V (531) and has a much larger launch margin. The large margin allows for the possibility of launch sharing with another spacecraft to reduce project launch costs. A shared launch is typically 60% of the single launch cost, which will reduce the up-front launch costs but perhaps require additional cost for coordination, timing, and logistics with the launch partner.

The SGO Mid constellation can be easily accommodated in the Space-X 5 meter fairing or the Altas 4 m fairing. Additional space will likely become available once the P/M is optimized. (See Figure E1).

7. Cost Estimate

The cost estimate for SGO Mid 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, 22], 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 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.

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 (SVLCM) a top-level model based the NASA/Air Force Cost Model (NAFCOM) [23]. 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].

SGO High estimate	**1.66**
Launch vehicle savings	-0.03
Payload mass or redundancy reduction	-0.11
Mission duration reduction	-0.12
SGO Mid total	**$1.40B**

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

Our cost model estimates that SGO Mid would cost $1.40B 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, respectively. Note that SGO Mid's Phase E has an 18 month transfer trajectory, 4 months of commissioning, and 24 months of science observation.

References

[1] T. Prince et al., "LISA: Probing the Universe with Gravitational Waves", LISA-LIST-RP-436 (March 2009) http://lisa.gsfc.nasa.gov/Documentation/LISA-LIST-RP-436_v1.2.pdf

[2] LISA International Science Team, "LISA Science Requirements Document" LISA-ScRD-004 (September 2007). http://lisa.gsfc.nasa.gov/Documentation/LISA-ScRD_v4.1a.pdf

[3] T. Prince, "The Promise of Low-Frequency Gravitational Wave Astronomy", Astro2010 WP (2009)

[4] P. Madau et al., "Massive BH Across Cosmic Time", Astro2010 WP (2009)

[5] C. Miller et al., "Probing Stellar Dynamics in Galactic Nuclei", Astro2010 WP (2009)

[6] G. Nelemans et al., "The Astrophysics of Ultra-Compact Binaries", Astro2010 WP (2009)

[7] G. Nelemans, arXiv:0901.1778 (2008)

[8] B. Schutz et al., "Will Einstein Have the Last Word on Gravity?", Astro2010 WP (2009)

[9] S. Phinney, "Finding and Using Electromagnetic Counterparts of Gravitational Wave Sources", Astro2010 WP (2009)

[10] C. Hogan et al., "Precision Cosmology with Gravitational Waves", Astro2010 WP (2009)

[11] C. Hogan and P. Binetruy., "GW from New Physics in the Early Universe", Astro2010 WP (2009)

[12] O. Jennrich, "LISA Technology & Instrumentation", C&QG 26 153001 (2009).

[13] P. McNamara and G. Racca, "Introduction to LISA Pathfinder" LISA-LPF-RP-0002 (March 2009). http://lisa.gsfc.nasa.gov/Documentation/LISA-LPF-RP-0002_v1.1.pdf

[14] K. Sun, B.A. Allard, R.L. Byer, & S. Buchman, "Charge management of electrically isolated objects via modulated photoelectric charge transfer", US patent US20080043397

[15] K. Sun, N. Leindecker, S. Higuchi, J. Goebel, S. Buchman & R. L. Byer, "UV LED operation lifetime and radiation hardness qualification for space flights" *J. Phys.: Conf. Ser.* **154(1)** 012028 (2009).

[16] K. McKenzie, R.E. Spero, and D.A. Shaddock "The performance of arm-locking in LISA" PRD **80** 102003 (2009).

[17] R. Stebbins, et al., "Astro2010 RFI#2 Space Response", (Aug. 2009). http://lisa.gsfc.nasa.gov/Documentation/Astro2010_RFI2_LISA.pdf

[18] J.W. Armstrong, F.B. Estabrook, and M. Tinto, "Time-delay interferometry for space-based gravitational wave searches" Ap.J. 527 (1999) 814-826.

[19] LISA Project Team, "LISA Spacecraft Description", LISA-SC-DD-0001 (January 2009). http://lisa.gsfc.nasa.gov/Documentation/LISA-SC-DD-0001.pdf

[20] LISA Project Team, "LISA Propulsion Module Description", LISA-SC-DD-0002 (January 2009). http://lisa.gsfc.nasa.gov/Documentation/LISA-SC-DD-0002.pdf

[21] T. Sweetzer, "LISA Mission Description" v2.1, LISA Project Internal Report (2005).

[22] R. Stebbins, et al., ""Laser Interferometer Space Antenna (LISA): A Response to the Astro2010 RFI for the Particle Astrophysics and Gravitation Panel", (Apr. 2009). http://lisa.gsfc.nasa.gov/Documentation/Astro2010_RFI_LISA.pdf

[23] Spacecraft/Vehicle-Level Cost Model, http://cost.jsc.nasa.gov/SVLCM.html

[24] Larry Phillips, Private Communication

(Astro2010 WP = white paper submitted to the National Research Council's 2010 Decadal Survey of Astronomy and Astrophysics. LISA-related white papers are available at http://lisa.gsfc.nasa.gov/documentation)

List of Acronyms

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

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 configuration	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. 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 @ $z = \tilde{z}$	~ 1 deg^2	~ 1 deg^2	$\gtrsim 100$ 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 @ $z = 1$	$\lesssim 0.1$ deg^2	$\lesssim 0.1$ deg^2	$\lesssim 10$ 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 Mid		# OF UNITS		FLIGHT HARDWARE MASSES				FLIGHT HARDWARE POWER		
Subsystem / Component	Unit Mass [kg] (CBE)	Flight	Flight Spare	EM & Proto-type	Total Mass [kg] (CBE)	Contin -gency [%]	Total Mass [kg] (MEV)	Total Power [W] (CBE)	Conti n-genc y [%]	Total Power [W] (MEV)
Spacecraft Bus		**3**	**0**	**1**	**293.0**	**30%**	**381.0**	**358.8**	**30%**	**467.00**
Structures and Mechanisms					**128.0**		**166.40**			
Primary Structure	92.00	1	1		92		119.60			
Secondary Structure	18.90	1	1		18.9		24.57			
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					**33.1**		**43.03**	**44.3**		**58**
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	19.00	1	1		19		24.70			
Command and Data Handling		1			**29.2**		**37.96**	**63.07**		**82**
C&DH	29.20	1	1		29.2		37.96			
Telecom					**28.0**		**36.40**	**86.15**		**112**
Transponder (X/Ka)	2.50	2	1		5		6.50			
RFDU	2.40	1	0		2.4		3.12			
TWT (with EPC)	7.00	1	1		7		9.10			
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	2	1		0		0.00			
HGAD Electronics	2.50	2	1		5		6.50			
Atitude Control					**8.1**		**10.50**	**29.23**		**38**
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**	**100.7**		**131**
Micronewton Thrusters	12.80	3			38.4		49.92			
Thermal Control					**13.3**		**17.23**	**35.4**		**46**
MLI Blankets	0.60	3			1.8		2.34			
Heaters	0.04	20			0.8		1.04			
Thermistats	0.03	40			1.2		1.56			
Thermistors	0.03	115			3.45		4.49			

Radiators	0.30	1			0.3		0.39			
Coatings (Gold Paint, etc.)	0.20	12			2.4		3.12			
Coatings (Black Paint)	0.15	20			3		3.90			
I/F Material (Nusil, cho-therm)	0.02	15			0.3		0.39			
Cable and Harnessing					**16.0**		**20.80**			
Cables and Harness	16.00	1			16		20.80			
Propulsion Module (Dry)		**3**	**0**	**1**	**239.5**	**30%**	**311.47**	**134.5**	**30%**	**175.0**
Structure					**159.2**		**206.96**			
Primary Structure	127.40	1			127.4		165.62			
Secondary Structure	10.00	1			10		13.00			
Lightband (PM to PM)	21.80	1			21.8		28.34			
Command and Data Handling					**9.1**		**11.83**	**30.76**		**40.0**
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**	**30.76**		**40.0**
Misc. Thermal Hardware	11.40	1			11.4		14.82			
Propulsion					**57.9**		**75.26**	**73.07**		**95.0**
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**	**210.0**	**30%**	**273.0**	**244.7**		**318.1**
Instrument Electronics					**38.5**		**50.05**	**180.7**		**235**
LASER Unit Assembly	4.00	3			12		15.60			
Ultra Stable Oscillator	0.50	2			1		1.30			

Phasemeter Unit (incl. harness)	12.00	1			12		15.60			
Charge Management Unit	2.00	1			2		2.60			
Caging System Electronics	5.00	1			5		6.50			
Diagnostic Driver Electronics	1.50	1			1.5		1.95			
Optical Assembly Mechanism Electronics	1.50	2			3		3.90			
Optical Assembly Electronics	2.00	1			2		2.60			
Moving Optical Sub-Assembly		**2**			**107.6**		**139.9**	**57.0**		**74.0**
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			**3.1**		**4.02**	**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					**23.0**		**29.95**			

Static Frame	11.80	1			11.8		15.34			
TI Mountingbracket LLD MOSA	0.42	4			1.68		2.18			
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	0.95	2			1.9		2.47			
Lower Support Struts Main frame	0.65	2			1.3		1.69			
CFRP-Front mount cone	0.95	2			1.9		2.47			
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			
L/V Adapter		**1**	**0**	**0**	**145.27**	**30%**	**188.5**			
Adapter (5% launch mass)	145.27	1			145.27		43.5			
Subtotal - Cruisecraft Dry					**743.47**	**30%**	**966.52**			
Total - GW Cruisecraft Wet (w/o L/V Adapter)					**967.0**	**30%**	**1190.0**			
Total - GW Launch Stack (incl L/V adapter)					**3047.0**		**3759.0**			
Total - GW Cruise Power								**500.7**		**651.0**
Total - GW Operational Power								**563.5**		**785.1**

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

E. Launch Vehicle Accommodation

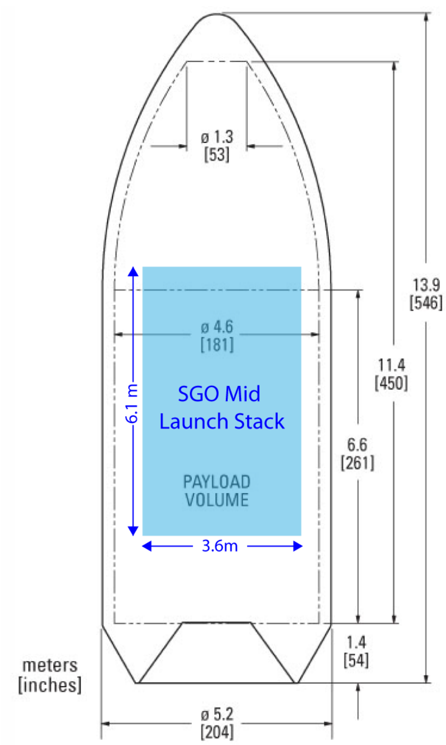

Figure E1
The standard Falcon 9 5-meter fairing will accommodate the SGO Middle Launch stack as shown above.

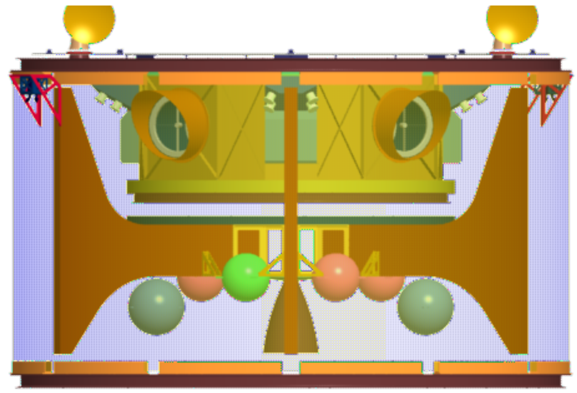

Figure E2

Each of the three sciencecraft (SC) will be nested inside of a propulsion module (PM) as shown above, with the three PMs stacked as a column inside the launch vehicle payload fairing. The stack is designed to carry the launch loads through the PM's outer shell, thereby isolating each of the SC from the direct launch load inputs. The SGO Mid SC is very close to the same size as the SGO High/baseline LISA. It is 0.1 m lower in height, and the lower deck is 0.1 m smaller in diameter. However, neither the SC nor the PM have been optimized for the SGO Mid configuration.