SGO High: A LISA-Like Concept for the Space-based Gravitational-wave Observatory (SGO) at a High Cost-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 High Cost-Point concept for SGO (SGO High) is based on the LISA concept presented to the Astro2010 Decadal survey. The rationale for the SGO High concept is to reproduce the full LISA performance with all known cost savings. A lower cost launch vehicle and a single agency cost model make it possible to get the full LISA science return for less than $2B (FY12). This concept is submitted for comparison with other RFI responses for SGO Mid, SGO Low and SGO Lowest (see Appendix B).

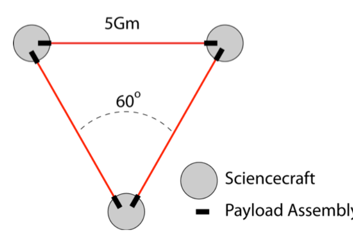
SGO High capitalizes on 20 years of NASA and ESA studies leading to the final LISA concept and the very substantial resources invested in risk reduction, primarily through LISA Pathfinder. Of all the LISA-like concepts, this one has the lowest scientific risk, the lowest technical risk, and the lowest cost risk owing to the many years of study and very substantial technology investments by NASA and ESA.

Extensive LISA documentation can be found at lisa.gsfc.nasa.gov.

Concept Description

SGO High preserves all LISA performance parameters (cf. Appendix B). It differs from LISA by:

- Single agency cost model
- Lower launch costs



Gravitational Wave Science Payoffs

SGO High achieves all of the LISA science objectives because it meets all of the LISA science requirements in Table 3 of the RFI. SGO High will deliver ***all*** of the LISA science endorsed in *NWNH*: measuring massive black hole masses and spins, detecting signals from stellar-mass compact objects inspiraling into massive black holes and discovering unanticipated or exotic sources. As shown in Table 1, SGO High fully achieves ***all*** the science payoffs listed in Table 2 of the RFI.

Cost Estimate

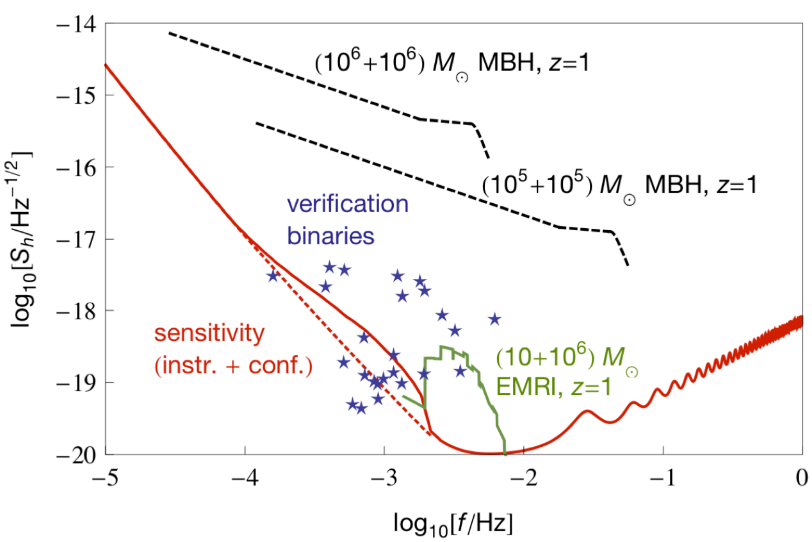
The cost and schedule of SGO High has been estimated using cost information from the LISA cost estimates supplied to the Astro2010 decadal survey and other sources. The total cost is estimated to be $1.66B (FY12 dollars). A rough schedule comprises 108 months for Phase A through D, and 78 months of Phases 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 High 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 High's measurements will determine the physical parameters of many sources to astounding precision, allowing SGO High to address some of the most important questions that face astrophysics and physics today [1, 3]. In this section we summarize SGO High's key science goals and expected performance.

Sources and Sensitivity

Since SGO High's science objectives are realized through observations of its various source classes, we begin by displaying, in Box 1, the strength of a few fiducial sources compared to SGO High's sensitivity curve. A summary of SGO High's sources, along with their expected strengths, rates, and science yields, is given in Table 1.



Box 1. The red curve shows SGO High's rms strain sensitivity, in units of $\mathrm{Hz}^{-1/2}$. It includes both instrumental noise (dotted red) and confusion noise from unresolved Galactic binaries, which will dominate instrumental noise between 10^{-4} and 2×10^{-3} Hz. Roughly speaking, all sources above these lines are detectable by SGO High. The stars represent the frequencies and strengths of known Galactic binaries (LISA's "verification binaries"); their height above the noise curve gives their matched-filtering signal-to-noise ratio (SNR) in a one-year integration, for a single SGO High Michelson interferometer; the corresponding strain in the Solar System is shown on the left vertical axis. The two black curves and the green curve represent two SMBH binaries, and an EMRI, respectively, whose frequency evolves upward significantly during observation. The height of the source curve above the strain sensitivity approximates the SNR contributed by each logarithmic frequency interval. See [1, 2] for more details.

Massive Black Hole (MBH) Mergers	
Detection Rate	$15 \sim 30$/yr total, $1 \sim 2$/yr at $z < 2$
Characteristics	• Redshifts: $z \lesssim 17$, $\tilde{z} \sim 5$ • Mass: $10^4 M_\odot \lesssim M \lesssim 10^7 M_\odot$ • Signal Duration: hours to years • SNR: $10 \lesssim \rho \lesssim 10^4$, $\rho \sim 500$ @ $z = \tilde{z}$
Observables	• Masses: $\frac{\sigma_M}{M} \sim 0.2\%$ @ $z = \tilde{z}$; $\frac{\sigma_M}{M} \lesssim 0.1\%$ @ z=1 • Spins: $\sigma_\chi \sim 0.3\%$ @ $z = \tilde{z}$; $\sigma_\chi \lesssim 0.1\%$ @ 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
Captures of Stellar Mass Compact Objects by MBH	
Detection Rate	Best estimate: ~ 750/yr; Pessimistic: ~ 10/yr
Characteristics	• Compact Object: mostly BH with $M \sim 10 M_\odot$ possibly some NSs and WDs • MBH Mass: $10^4 - 5 \times 10^7 M_\odot$ • Redshift Range: $z \lesssim 1$ • Orbital Period: $10^2 - 10^3$ 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: $\frac{\sigma_{D_L}}{D_L} \sim 1\%$ @ $z = 0.5$ (limited by weak lensing)
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	• $\sim 2 \times 10^4$ individual sources, including ≈ 10 known "verification binaries" • Diffuse galactic background at $f \lesssim 2\,\mathrm{mHz}$
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	• $\sim 100-$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 $\Omega_{gw} \gtrsim 10^{-10}$ will be detectable over foreground from Galactic WD/WDs
Science Payoffs	• 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: $h(t) \propto \lvert t - t_c \rvert^{1/3}$
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 HIGH's sources: their characteristics, estimated rates, parameter estimation accuracy, and science objectives.

Science Objectives

The high-level scientific objectives of SGO High 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 identification of lower-mass BH "seeds" from which the MBHs evolved via accretion and successive mergers. SGO High will search for this seed population. The SGO High design (e.g., its arm length) was chosen to provide good sensitivity for lower-mass ($\sim10^4$–10^5 $M_\odot$) MBH mergers out to high redshift (z > 10) [1, 4], and will measure their masses and spins to ~1% accuracy. SGO High will also search for remnants of the first stars; it is sensitive to the captures of intermediate mass BHs (IMBHs, $\sim10^2$–10^3 $M_\odot$) by MBHs out to high redshifts [4].

<u>2. Trace the growth and merger history of massive black holes and their host galaxies</u>

Just as facilities such as JWST and ALMA will study the evolution and growth of galaxies out to high redshift, SGO High will undertake the complementary study of MBH evolution and growth back to very early times, even before the epoch of re-ionization [1, 4]. SGO High will measure the masses, spins, distances, and rates of MBHs undergoing inspiral and merger. For the most energetic events, merger times and sky locations will be determined from the inspiral well in advance of the actual merger, allowing for simultaneous targeted searches for EM counterparts. In addition, the observation of captures of stellar-mass objects by MBHs (so-called "extreme mass ratio inspirals," or EMRIs) will provide precise masses and spins for the nuclear MBH out to z~1. SGO High's sensitivity down to a frequency of $\sim3\times10^{-5}$ Hz will provide the ability to observe MBH with masses up to 10^7 $M_\odot$, while its excellent sensitivity at a few mHz will allow precision measurements with EMRIs [1, 5, 9].

<u>3. Explore stellar populations and dynamics in galactic nuclei</u>

SGO High will observe EMRI events with a best-estimate rate of ~750/yr. There are two main reasons why this estimate is significantly higher than the estimate ~50/yr given to the Astro2010 Decadal Committee. Most significantly, the smaller rate was based on a purposely conservative assumption regarding the threshold SNR required for detection, as limited by realistic computing power. Based on experience from the Mock LISA Data Challenges, we are now adopting a threshold which is ~1.6 times lower, which increases the detection rate by $\sim 1.6^3 = 4$. Also, our best estimate of the event rate per galaxy has increased, but we emphasize that it is still uncertain by two orders of magnitude. Most detected EMRIs will be stellar-mass BH captures, but SGO High also expects to see neutron star (NS) and white dwarf (WD) captures [1, 4, 9]. The event rates and mass distribution will help characterize the immediate environments of the MBHs in galactic nuclei. SGO High will follow these capture events over ~10^5 highly relativistic orbits, allowing measurement of the spin and mass of the central MBH, the mass of the compact object (particularly interesting for determining the mass spectrum of stellar BHs), and the eccentricity of the orbit, all to a precision of ~0.01%.

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

SGO High will detect ~20,000 individual compact binaries in the Galaxy and measure their orbital periods and sky distribution. (The Mock LISA Data Challenges have already given a demonstration of the algorithms that 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. In addition, at frequencies below 1 mHz, SGO High will map the diffuse background from millions of unresolved compact binaries in the Galaxy. See [1,6,7,9] for additional information.

5. Confront General Relativity with observations

SGO High will test General Relativity in several ways [1, 8]. First, SGO High 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 High 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 High will observe the inspiral, merger, and ringdown of MBH mergers. The strongest MBH signals will have SNRs in the thousands (two orders of magnitude higher than will be possible for ground-based GW detectors), allowing exquisitely precise comparisons between the SGO High measurements and the predictions of numerical relativity.

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 the source redshift is not encoded in the GW signal, 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. (We note that SGO HIGH will have reasonably good angular and distance resolution; e.g., for roughly a quarter of the observed mergers, the error box will have $\Delta\Omega < 10\,\deg^2$ and $\Delta D_L / D_L < 10\%$.) With even a handful of mergers at z <1 with EM counterparts, SGO High will be able to determine the Hubble constant to ~1%, in a manner independent of conventional methods [1, 10]. In addition, SGO High 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 High will be also 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 High could perhaps provide experimental verification of string theory!

7. Search for unforeseen sources of gravitational waves

As emphasized by Astro2010, SGO High has tremendous discovery potential. It covers 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 High is a constellation of three sciencecraft (SC) arranged as an equilateral triangle with 5 Gm arms. Each SC consists of a tightly integrated scientific payload and spacecraft bus (Fig. 2). This section describes the elements of the SC, including the scientific payload, the spacecraft bus, and the propulsion module.

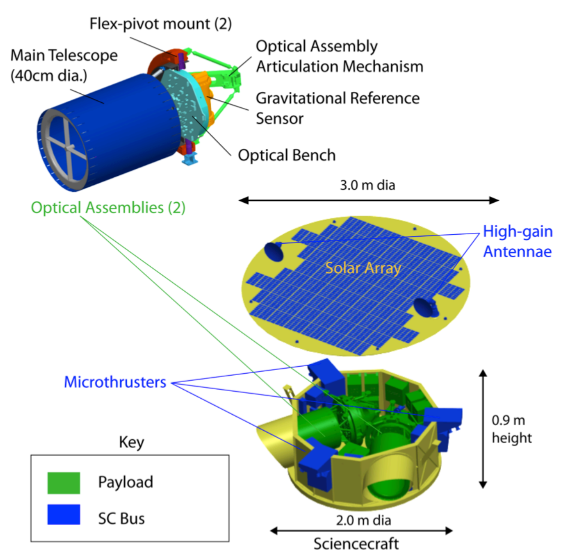


Figure 2: SGO High configuration showing scientific payload and SC bus. See Appendix E for propulsion module and launch vehicle interface.

Scientific Payload

The payload for the SGO High option is essentially the same as the payload for the classic LISA baseline mission **[**12**]**. The scientific payload (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 4 cm gold-platinum TM in an electrode housing that is used to sense its position and orientation. 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 Sun angle are maintained. The TMs are actuated via the electrodes while the SC is actuated by the Colloidal Micro-Newton Thrusters (CMNTs) and the Optical Assembly Tracking Mechanism (OATM). The SGO High design for the Gravitational Reference Sensor (GRS), the TM and supporting subsystems, is essentially identical to that which will fly on ESA's upcoming LISA Pathfinder mission [13]. The GRS, the SC, the CMNTs and the control laws together form the DRS.

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 (Fig. 2). 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 5 Gm constellation arms. An optical fiber is used to exchange light between the two optical benches aboard each SC. A digital phase measurement system (PMS) measures the phase of the heterodyne signals relative to the local 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 [16].

Component	# per SC	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)	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
Optical Assembly Tracking Mechanism (OATM)	2	OA mounted on flex pivot through GRS axis. Piezo inchworm angle actuator. ~1^{o} dynamic range, ~8 nrad/Hz$^{1/2}$ angular jitter (closed loop)	6
Charge management	2	UV lamps [14]	6
Interferometric Measurement System (IMS), Displacement Sensitivity requirement: 18 x 10^{-12} m/Hz$^{1/2}$			
Laser subsystem	2 + 2 spare	Master oscillator power amplifier (MOPA) design @ 1064nm. Master: 40 mW Nd:YAG NPRO with fiber-coupled phase modulator. Amplifier: 1.2 W Yb-doped fiber amp.	6
Optical Bench	2	Fused silica components hydroxide bonded to Zerodur bench	6
Telescope	2	40 cm, f/1.5 on-axis Cassegrain.	6
Photoreceivers	6 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. ~60 channels per SC with ~1 μcycle/Hz$^{1/2}$ noise	5
Laser Frequency Stabilization	2	Heterodyne Mach-Zehnder (LPF) or Fabry-Perot cavity. 300 Hz/Hz$^{1/2}$ residual noise in MBW	5
Point-Ahead Angle Mechanism	2	Piezo-actuated flex pivot mirror on optical bench. Angular range: 800 μrad, angular jitter: 16 nrad/Hz$^{1/2}$, piston jitter: 2pm/Hz$^{1/2}$(open loop representative specs)	4

Table 2: Major Scientific Payload Components. TRL levels from Astro2010 RFI#2 [15].

Spacecraft Bus

The SGO High spacecraft bus is designed to meet the requirements of the payload: in particular low levels of mechanical and thermal disturbances in the mHz range. The bus design will be very similar to the classic LISA design [19] with a few minor changes.

Thermally stability of better than 10^{-6} °K/Hz$^{1/2}$ for the payload is achieved with passive thermal isolation. In addition to housing the payload, the bus structure also contains 2 HGAs and 2 omnidirectional antennas for the Communications Subsystem, 12 Coarse Sun Sensors (CSSs) and 2 Star Tracker systems for the Attitude control Subsystem (ACS). All 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 High is essentially LISA; all of the previous orbit and trajectory analysis pertains [19]. During normal mission science, the constellation forms an equilateral triangle with arms of length L = ~ 5 Gm. The center of the triangle follows a circular orbit about the Sun, with radius of 1 A.U. It is located 22° behind the mean Earth, i.e., ~ 58 Gm away. The normal to the triangle plane is tilted away from the Sun by 30°. The triangle rotates about its center at 1 revolution per year.

Perturbations due to Earth's gravity cause constellation breathing that grows over time, eventually distorting the constellation beyond usability. Satellite positions and velocities at just before science initialization must be set so as to minimize constellation distortion over the selected 5-year mission lifetime. Optimization for a typical LISA mission example (cf. [19]) shows $(\Delta L/L, \Delta v, \Delta\alpha) = \sim(\pm 1\%, \pm 13 \text{ m/s}, \pm 0.8°)$, where $v = dL/dt$, and α is the angle between two satellites as seen from the third.

Due to constellation rotation and the finite speed of light, each outgoing laser beam must be aimed ahead relative to the corresponding incoming beam by $[\omega \, 2L/c] \approx 7$ μradians, where ω is the rotation rate of the constellation and c is the speed of light.

HGA range is determined by the rotation of the constellation and the rise and fall of the Earth relative to the plane of the constellation due to eccentricity of the Earth's orbit. The azimuthal range is 360°; the elevation range is [8.8°, 13.7°].

Trajectories

Detailed, optimized trajectories from post-launch/escape to start of science have been determined for a number of hypothetical launch dates (cf. [19]). The bottom line is that the launch vehicle deploys the constellation with a post-escape C3 of ~0.3 $(\text{km/s})^2$, the trajectory flight to the science orbit requires ~13 months, and the total post-release delta-V for each satellite is ~1000 to 1100 m/s (distributed in 3 or 4 burns during the flight). A propulsion module [18] that is separated from the sciencecraft at the operational orbit provides the required delta-V.

Heuristically, one can imagine the delta-V broken into three logical components: (a) an in-plane breaking burn at perihelion (~430 to 490 m/s, depending on launch date), (b) an out-of-plane, inclination changing burn at what will thereafter be a node crossing (~630 m/s), and (c) a pair of burns at what will be perihelion and aphelion to adjust the eccentricity (~150 m/s). A straight sum of these parts yields ~1210 to 1270 m/s. Optimized construction reduces those results by ~15 to 20%.

5. Operations

The ground segment includes the Deep Space Network (DSN), the Mission Operations Center (MOC) at JPL, the Science Operations and Data Processing Centers (SODPC), and a distributed team of science investigators.

The three DSN 34-meter X-band antennae communicate with each of the SC directly via a gimbaled High Gain Antenna (HGA). The MOC performs command sequencing, health and safety monitoring, navigation and anomaly investigation. A schedule for DSN passes, HGA positioning, and laser frequency changes is generated for each spacecraft and transferred to the DSN for uplink. Passes are nominally scheduled every other day. Other aspects of SGO Low operations are autonomous, and consist largely of continuously running control loops and self-recovery from detected faults.

The MOC sends the science data and required engineering data to the SODPC where the instrument performance and data quality are assessed. 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 science centers will also provide a higher level of quality assurance for overall instrument performance and may periodically request engineering tests or configuration changes of the constellation or one SC. These requests will be negotiated with the MOC for assessment and disposition.

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 SODPC for archival and use in further data reduction.

The SGO High mission can be divided into the following phases: launch and cruise (14 months total), commissioning (4 months), science operations (60 months), and de-commissioning.

The four SC/prop module pairs will share a single launch (§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 propulsion module. At the end of the cruise phase, the propulsion modules will be ejected, leaving the SC with CMNTs for attitude control and drag-free operations. The test masses will be placed into drag-free flight and the six 5 Gm links will be established. During science operations, the constellation will be stable by virtue of initial conditions without any maintenance maneuvers. For SGO Low, science operations will last two years. 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.

The communications data volume and operations will be consistent during science operations, with the constellation generating 1.3 Gbit/day, and requiring each sciencecraft to have an 8-hour DSN contact every 6 days. Key operations are re-pointing high gain antennas and switching laser frequencies, both of which interrupt science operations and which will be coordinated to minimize outage times.

6. Launch Vehicle

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

As shown in the Master Equipment List (MEL) in Appendix D, the wet mass of each of the SGO High sciencecraft and propulsion module pair is 1726 kg. The estimated mass of the launch vehicle adapter is 284 kg. The total launch mass for three sciencecraft, three propulsion modules and the launch adapter is 5462 kg.

Several EELV-class launch vehicles are capable of launching SGO High into its escape trajectory with C3 = 0.3 $(km/sec)^2$.

The Atlas V (541) and the Falcon Heavy are illustrative examples. The Atlas V (541) has a launch margin of 103 kg. The Falcon Heavy has a launch margin of 8,071 kg, far more than the total SGO High launch mass. The Falcon Heavy is cheaper and is capable of launching two such payloads and still have a launch margin of 2,609 kg. Therefore, the baseline is a shared Falcon Heavy launch to further reduce costs. A shared launch introduces additional constraints and risk, which could have a cost impact.

The SGO High launch stack can easily be accommodated in either the Atlas 4 m fairing, or in the Space-X 5 m fairing (See Appendix E).

7. Cost Estimate

The cost estimate for SGO High is based on a combination of LISA Project cost estimates from several sources: the responses to Astro2010 RFI 1 and 2 [20, 15], 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. Launch service cost estimates are based on informal discussions with a NASA launch specialist [21].

Our cost model estimates that SGO High would cost $1.66B in FY12 dollars.

A rough schedule is taken from the LISA RFI 1 submitted to Astro2010 [20]. Phases A, B, C/D and E/F are expected to last 12, 30, 66 and 78, respectively.

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(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 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**	Spacecraft bus
EMRI	Extreme Mass Ratio Inspiral	**S/W**	Software
ESA	European Space Agency	**SC**	Sciencecraft
Gm	Gigameter, 1Gm = 1×10^9 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. 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 High		# 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**	**376.180**	**30%**	**489.03**	**326.90**	**30%**	**467.00**
Structures and Mechanisms					**143.1**		**186.03**			
Primary Structure	105.00	1	1		105		136.50			
Secondary Structure	21.00	1	1		21		27.30			
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					**37.1**		**48.23**	**40.6**		**58**
Solar Array (5.3 m^2)	9.60	1	0		9.6		12.48			
Battery (Lithium Ion 20 AH)	6.20	1	1		6.2		8.06			
Power System electronics	21.30	1	1		21.3		27.69			
Command and Data Handling		1			**29.2**		**37.96**	**57.4**		**82**
C&DH	29.20	1	1		29.2		37.96			
Telecom					**42.2**		**54.86**	**78.4**		**112**
Transponder (X/Ka)	3.10	2	1		6.2		8.06			
RFDU	2.40	1	0		2.4		3.12			
TWT (with EPC)	7.00	2	1		14		18.20			
HG Antenna	2.30	2	0		4.6		5.98			
LG Antenna	1.00	2	0		2		2.60			
Cabling	3.00	1	0		3		3.90			
X-Band Power Amp's	2.50	2	1		5		6.50			
HGAD Electronics	2.50	2	1		5		6.50			
Attitude Control					**8.1**		**10.50**	**26.6**		**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					**45.6**		**59.28**	**91.7**		**131**
Micronewton Thrusters	15.20	3			45.6		59.28			
Thermal Control					**15.9**		**20.67**	**32.2**		**46**
MLI Blankets	0.60	3			1.8		2.34			
Heaters	0.04	32			1.28		1.66			
Thermistats	0.03	64			1.92		2.50			

Thermistors	0.03	150			4.5		5.85			
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	35			0.7		0.91			
Cable and Harnessing					**55.0**		**71.50**			
Cables and Harness	55.00	1			55		71.50			
Propulsion Module (Dry)		**3**	**0**	**1**	**292.800**	**30%**	**380.64**	**157.5**	**30%**	**225.0**
Structure					**198.8**		**258.44**			
Primary Structure	161.70	1			161.7		210.21			
Secondary Structure	15.30	1			15.3		19.89			
Lightband (PM to PM)	21.80	1			21.8		28.34			
Command and Data Handling					**9.1**		**11.83**	**28.0**		**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**	**28.0**		**40.0**
Misc. Thermal Hardware	11.40	1			11.4		14.82			
Propulsion					**71.5**		**92.95**	**101.5**		**145.0**
Hz Fuel Tanks	13.61	1			13.61		17.69			
NTO Tank	6.80	2			13.6		17.68			
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**	**548**	**0%**	**548**			
Propellant	548.0	1			548		548			
Scientific Complement		**3**	**0**	**1**	**237.0**	**30%**	**308.0**	**236.6**		**338.0**

Instrument Electronics					**44.5**		**57.85**	**164.5**		**235**
LASER Unit Assembly	6.00	3			18		23.40			
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**			**128.8**		**167.4**	**65.1**		**93.0**
Telescope					**35.8**		**46.58**			
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) + Adapter	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**	**218.0**	**30%**	**284.0**			
Adapter (5% launch mass)	218.0	1			218.0		66.0			
Subtotal - Cruisecraft Dry					**906.0**	**30%**	**1178.0**			
Total - GW Cruisecraft Wet (w/o L/V Adapter)					**1454.0**	**30%**	**1726.0**			
Total - GW Launch Stack (incl L/V adapter)					**4581.0**		**5462.0**			
Total - GW Cruise Power								**491.40**		**702.00**
Total - GW Operational Power								**563.50**		**805.00**

E. Launch Stack Accommodation

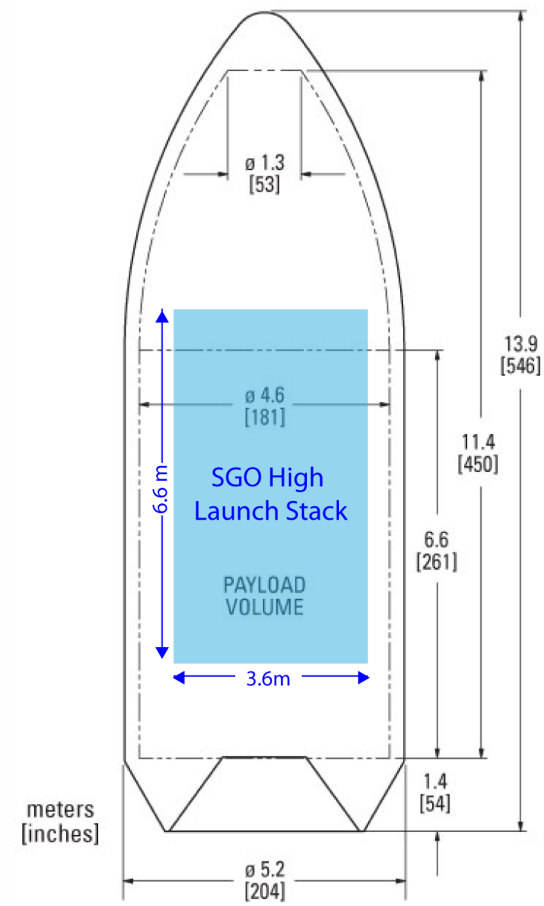

Figure F-1. The Space-X 5 m fairing will accommodate the SGO High launch stack as shown above.

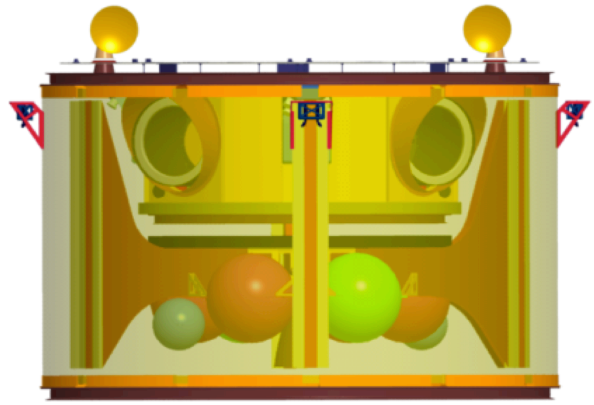

Figure F-2. Each of the three SM will be nested inside of a P/M as shown below, with the three P/Ms stacked as a column inside the launch vehicle payload fairing. The stack is designed to carry the launch loads through the Propulsion Module's outer shell, thereby isolating each of the S/C from the direct launch load inputs.