SGO Lowest: A LISA-Like Concept for the Space-based Gravitational-wave Observatory (SGO) at the Lowest 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

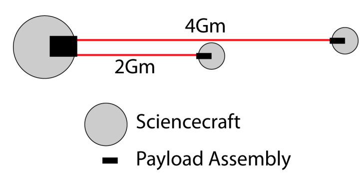
The lowest price-point concept for SGO (SGO Lowest) is based on the LISA concept presented to the Astro2010 Decadal survey. With the SGO lowest concept we aim to consider a candidate for the lowest cost gravitational mission that may achieve some minimal portion of LISA's science objectives. Toward this, the SGO Lowest concept is a further reduction of the SGO Low concept, collapsing the Vee-constellation into a line, replacing the two corner sciencecraft with one corner sciencecraft that is nearly identical. The two interferometer arms are nearly collinear, but unequal in length. This is similar to the SyZyGy concept [1], but with additional cost reductions.

Relative to SGO Low, SGO Lowest reduces the number of sciencecraft, eliminates the need for two optical assemblies at the vertex by putting both end sciencecraft along the same line of sight, and eliminates the need for a propulsion module by using a careful choice of trajectory and an upgraded version of the micronewton thruster for final separation of the sciencecraft.

Concept Description

As described in Appendix B, SGO Lowest differs from SGO Low by:

- Two corner sciencecraft combined into a single one with a single optical assembly using a similar optical bench capable of two outputs.
- 3 sciencecraft instead of 4
- Elimination of the free-space laser link.
- Elimination of propulsion modules.



Gravitational Wave Science Payoffs

SGO Lowest would achieve only a limited portion of the science outlined in the RFI. It would detect only a few massive black hole binaries and only a few tens of galactic binaries (cf. RFI Table 3). It would produce only crude estimates of the astrophysical parameters of those sources. As shown in Appendix C, it would detect no signals from stellar-mass compact objects inspiraling into massive black holes and make no cosmological measurements. The discovery space would be drastically reduced in comparison to LISA.

Cost Estimate

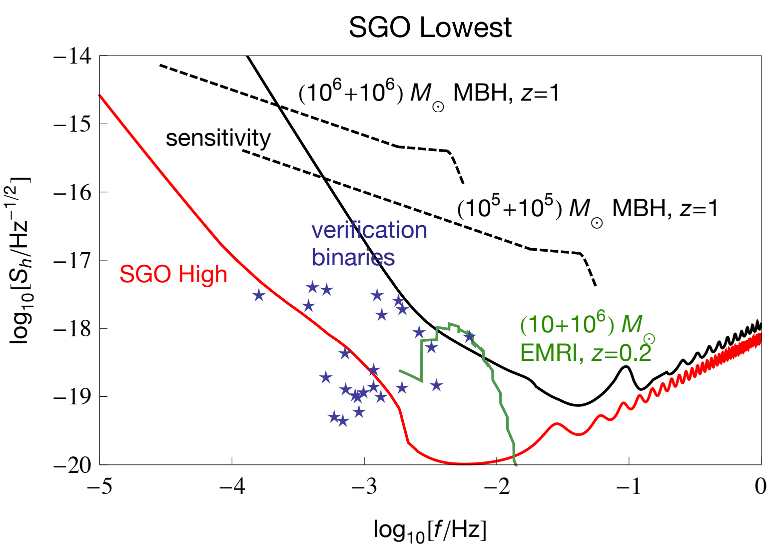
The cost and schedule of SGO Lowest has been estimated using cost information from the LISA cost estimates supplied to the Astro2010 decadal survey and other sources and a scaling model to estimate savings. The total cost is estimated to be $1.19B. A rough schedule is 108 months for Phase A through D, and 42 months of Phases E and F. The cost savings are modest compared to the severe loss of science capability.

Risk

This design benefits from significant risk mitigation through its LISA heritage, but suffers increased risk arising from elimination of redundancy in the payload design, and in the reduction to 4 laser links. Additional risk is associated with novel mission elements including the single-telescope/two-arm measurement concept, the replacement of propulsion modules with enhanced micronewton thrusters, and the need for stationkeeping to maintain stringent alignment requirements. Scientifically, there is a risk that no MBH mergers would be measured by this mission.

2. Science Performance

The Astro2010 decadal survey report highlighted the potential for gravitational-wave (GW) to make revolutionary contributions to astronomy and physics during the next two decades by opening up the source-rich low-frequency GW spectrum, 3×10^{-5} Hz to 0.1 Hz. The Astro2010 whitepapers about low-frequency GW astronomy [2-9] provide a very good picture of its excitement and promise. SGO Lowest is sensitive only in a portion of this range, above 0.001 Hz. SGO Lowest is expected to detect roughly 100 compact binaries in our Galaxy, and is likely to observe GW radiation from a few merging massive black holes (MBHs). Other sources such as compact stellar objects spiraling into MBH in galactic nuclei and more exotic sources are not likely to be measurable. SGO Lowest's measurements would determine the physical parameters



Box 1. The black curve shows SGO Lowest's rms strain noise, in units of $\mathrm{Hz}^{-1/2}$. Roughly speaking, sources above this curve are detectable by SGO Lowest. The blue stars represent the frequencies and strengths of known Galactic binaries (potential "verification binaries"). 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 the observation. The height of the source curve above the strain noise approximates the SNR contributed by each logarithmic frequency interval. See [10, 11] 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 Lowest, the Galactic confusion noise is below the instrumental sensitivity.

of detected sources to reduced precision, limiting the potential to address the high-level science questions highlighted by the decadal survey [10, 11]. In this section we summarize SGO Lowest's key science goals and expected performance.

Sources and Sensitivity

Since SGO Lowest's science objectives are realized through observations of its various source classes, we begin by displaying, in Table 1, the strength of a few fiducial sources compared to strengths, rates, and science yields. To allow reuse of LISA-based analysis codes, the science analysis for SGO Lowest is based on an approximately equivalent equal-arm linear configuration. As the figure indicates, there is significant loss of sensitivity by comparison with LISA, especially at low frequencies.

SGO Lowest assumes position measurement noise 30% larger than the other SGO mission concepts, allowing for some losses in implementing the single telescope measurement concept. A favorable implementation could improve sensitivity by a factor of two, but this would not lead to a qualitative change in the science capabilities.

Massive Black Hole (MBH) Mergers	
Detection Rate	$\sim 2/\text{yr}$ total
Characteristics	• Redshifts: $z \lesssim 10$, $\tilde{z} \sim 4$ • Mass: $10^3 M_\odot \lesssim M \lesssim 10^5 M_\odot$ • Signal Duration: $\sim$ weeks?
Observables	• Masses: $\frac{\sigma_M}{M} \sim 5\%$ @ $z = \tilde{z}$ • Spins: $\sigma_S \gtrsim 50\%$ • Sky Localization: $\sigma_\Omega \gtrsim 10^2$ deg^2
Science Objectives	• Confront General Relativity with observations (5)

Ultra-Compact Binaries	
Detections	$\sim 10^2$ individual sources, no "verification binaries"
Characteristics	Primarily compact WD-WD binaries; mass transferring or detached Orbital periods: $\sim 10^2 - 10^3$ s
Observables	Orbital frequency; Sky location to few degrees; Chirp mass and Distance from $\dot{f}$ for some high-f binaries
Science Objectives	• Discover shortest-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)

Table 1. A summary of SGO Lowest's sources: their characteristics, estimated rates, parameter estimation accuracy, and science pay-offs.

Science Objectives

SGO Lowest can address a subset of the high-level science goals of LISA[2,11]:

- Survey compact stellar-mass binaries and study the structure of the Galaxy
- Confront General Relativity with gravitational wave observations

Other LISA science goals would be *inaccessible* to SGO Lowest.

- Understand the formation of massive black holes
- Trace the growth and merger history of massive black holes and their host galaxies

- Explore stellar populations and dynamics in galactic nuclei
- Probe new physics and cosmology with gravitational waves
- Search for unforeseen sources of gravitational waves

We now consider these in turn.

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. At relatively low masses and high redshifts, these are more challenging massive black hole detections. SGO Lowest would be insensitive to this seed population.

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

SGO Lowest would be likely to detect just a few massive black hole mergers, with a plausible risk that none would be detected. Those mergers which are detected would be biased toward low redshifts $z<5$, though their distances and positions could not be meaningfully estimated. Masses could be estimated to better than 10%, but significant constraints on the other parameters would be unlikely. While some information about recent mergers could be inferred from these measurements, the result would show no trace of the merger history through time.

3. Explore stellar populations and dynamics in galactic nuclei

Unlike LISA and the other SGO concepts, SGO Lowest would not be expected to reliably detect the Extreme Mass-Ratio Inspiral (EMRI) events which provide access to the stellar populations in galactic nuclei.

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

SGO Lowest would survey of the nearby population of short period compact stellar-mass binaries, likely detecting ~100 individual binaries and measuring their orbital periods and sky distribution. These distributions may shed light on the (now) poorly constrained formation mechanisms and evolution of these binaries. The shortest period binaries may provide insight in the physics of tidal interactions and mass transfer, while also revealing the chirp masses and distances for some cases. SGO Lowest would not be sensitive to binaries throughout the Galaxy, thus providing little information about the structure of the Galaxy.

5. Confront General Relativity with Observations

SGO Lowest has the potential for limited tests of General Relativity. Though the strongest currently known compact binary system would be just near SGO Lowest's threshold of detectability, other currently unknown systems would likely be comparable with future electromagnetic observations, though. Directly measured GWs could be tested for consistency with electromagnetic (EM) observations. SGO Lowest would also observe the merger and ringdown of MBH merger. The strongest MBH signals would likely have SNRs comparable to probable observations of stellar-mass black hole binaries with ground-based GW detectors, but may be lack signals from the pre-merger inspiral, which would degrade the quality of constraints that could inferable about strong gravity physics.

6. Probe New Physics and cosmology with gravitational waves and 7. Search for unforeseen sources of gravitational waves

SGO Low, SGO Lowest provides only 4 laser links so that 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. The possibility of distinguishing a stochastic GW background or GW bursts from cosmic superstrings would be remote. Any other unexpected GW sources would have to be perhaps implausibly strong to be confidently detected.

3. Mission Description

The science instrument for SGO Lowest is a constellation of three *sciencecraft (SC)* arranged in a linear array so that the single optical assembly onboard the corner SC can exchange light with the two other SC at the ends of the different-length arms (see Figure 1). Each SC consists of a tightly integrated scientific payload and spacecraft bus. Despite the different function, the payload changes are modest, and all three SC are designed to be maximally similar to avoid additional non-recurring engineering (NRE) expenses. This section describes the elements of the SC, including the scientific payload, and the spacecraft bus.

Scientific Payload

The SGO Lowest concept utilizes the minimum number of classic LISA components **[**12**]** necessary to achieve a functional gravitational wave detector while enforcing the requirement that all three SC be nominally identical. Savings relative to LISA result from removal of components (OATM), relaxed requirements on components (telescope, laser, control laws), and reduced component count per SC (GRS, optical bench, laser, & telescope).

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, 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. 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 Lowest is essentially

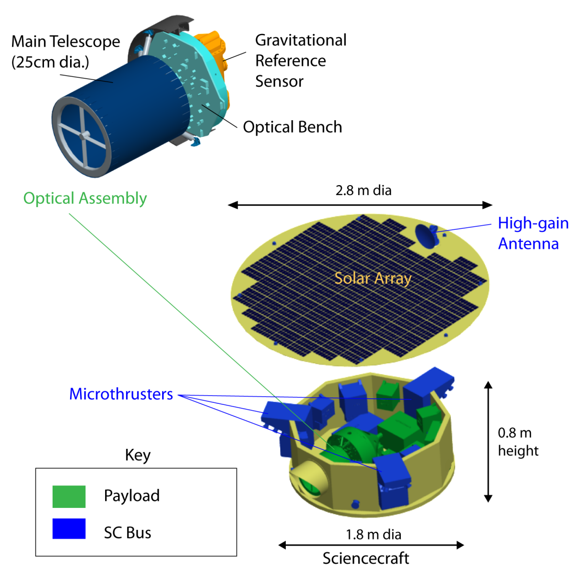


Figure 2: SGO-Lowest configuration showing the optical assembly and spacecraft bus. This is similar to the SGO Low configuration, except with no back link, and a wider field of view telescope.

identical to that which will fly on ESA's upcoming LISA Pathfinder mission [13].

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 constellation arms. A digital phase measurement system (PMS) 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 [14].

A key difference from the other SGO concepts is that the payload on the corner SC must be capable of extracting the signals from both end sciencecraft. The ability of the PMS to simultaneously track multiple heterodyne phases in a single analog signal enables such a

Component	**# per SC**	**Hardware Description**	**TRL**
Disturbance Reduction System (DRS), Residual TM acceleration of 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	*Advanced version of* ST-7/LPF thrusters, *1000* μN max thrust, <0.1 μN/Hz$^{1/2}$ noise (open loop)	*3*
Optical Assembly Tracking Mechanism (OATM)	*0*	*Tracking accomplished with SC attitude, quasi-linear constellation, & large telescope FOV*	*N/A*
Charge Management	2	UV-LEDs (240-255 nm) [15, 16]	6
Interferometric Measurement System (IMS), Displacement sensitivity req. 24 x 10^{-12} m/Hz$^{1/2}$			
Laser subsystem	*1 + 1 spare Master*	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, *field of view > 3X LISA.*	6
Photoreceivers	*2 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 end SC,32 per corner* with ~1 μcycle/Hz$^{1/2}$ noise	5
Laser Frequency Stabilization	0	*Arm-locking **[17]** w/ 1 kHz/Hz$^{1/2}$ residual noise in MBW (stabilization via science signals, no additional H/W required)*	5
Point-Ahead Angle Mechanism	2	Piezo-actuated flex pivot mirror on optical bench. Angular range: TBD, angular jitter: 16nrad/Hz$^{1/2}$, piston jitter: 2pm/Hz$^{1/2}$ (open loop)	*N/A*

Table 2: Major Scientific Payload Components. Differences from SGO High are highlighted in *blue*. DRS TRL levels from Astro2010 RFI#2, Table 2-8 [18].

configuration. Another major change is the adoption of next-generation CMNTs capable of providing higher thrusts that enable periodic station-keeping maneuvers to maintain the constellation's linear geometry. Additional cost savings might be found by degrading the GRS performance, which will have less impact on the science performance of SGO Lowest than for the other SGO variants.

Spacecraft Bus

The SGO Lowest bus design is somewhat similar to the classic LISA design (LISA-SC-DD-0001) but with the minimum size needed to contain just one optical assembly. As such it is similar the SGO Low configuration, but without the backlink telescope.

Since there is no PM, the SC would need some sort of mounting structure that may also function as a launch vehicle adapter, but which has not yet been designed in detail. A simple concept would be to use a variant that is similar to the shell of a PM but just large enough to contain the SC bus. See Appendix E for a sketch.

Minimal redundancy would be employed within the designs of all avionics components including the Command and Data Handling, Power Supply Electronics, Attitude Control. and Telecommunications. One 20 A/H battery would be used for LEOP, cruise, and Propulsion Module separation requirements.

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

A complete Master Equipment List (MEL) is provided in Appendix D. The SGO Lowest configuration would launch as a stack aboard a Falcon 9, Block 2 or 3 ELV.

4. Mission Design

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

Orbits

The details of the SGO Lowest mission orbits are laid out in Appendix F. The SGO Lowest constellation is formed as a line: SC-1, SC-2, SC-3, with nearly equal distance L from SC-1 to SC-2 and from SC-2 to SC-3. SC-1 and -3 have the same orbital radius, with SC-2 slightly lower by a fractional amount $dR/R = 0.5\ (L/R)^2$, where R is the constellation orbital radius The constellation mean position follows the same drift-away orbit discussed for SGO Mid.

Science life-time is governed by the constraint $\theta_{max} = (9\pi^2 / 32)\ (T)^2\ (L/R)^3$, where θ_{max} is the maximum permitted angle between SC-2 and SC-3 as seen from SC-1 (essentially the telescope field-of-view size), T is the mission life time (in years). For LISA the telescope FOV is $\theta_{max} \approx$ 10 μ-rad. For this analysis we *optimistically* suppose that this FOV can be expanded by perhaps a factor of 3 at no additional cost. Ignoring the perturbative effects of the Earth-Moon system on the orbits, we find that, with arm lengths of 3, 2.5, 2 and 1.5 Gm, the configuration survives for 1.2, 1.5, 2.1, and 3.3 years, respectively. We have assumed a nominal 2-year mission concept with 2-Gm arm length.

The effects of Earth's gravitational perturbations are actually not trivial relative to the θ_{max} limit. Periodic orbit adjustments during the science phase would be required to cancel out at least the differential (gravity gradient) perturbations. The mean force required to do so near the start-of-science (9° trailing) location is ~ 234 (L/2 Gm) (m_S/1000 kg) μN. Next generation colloidal thrusters being developed at JPL are anticipated to be able to provide force of ~ 1000 μN, so should be adequate to provide the required force with an orbit maintenance time fraction of ~ 10 to 20%, depending on the mass of the satellites.

The constellation members are subject to the look-back to look-ahead angle effect due to rotation about the Sun. The result for L = 2 Gm is (ω 2L/c) = ~ 2.7 μ-radians.

The high-gain antenna HGA can be essentially fixed in azimuth, but would require elevation variation fairly similar to that of SGO Mid due to the eccentricity of Earth's orbit. However, since the satellites are not tilted relative to the Sun (and assuming that the HGA "horizon" plane is that of the solar arrays), we don't need to compensate for a constellation tilt. The elevation range is ~ [2.1°, 14.9°] at the beginning of science life (9° trailing), and ~ [10.4°, 15.8°] at the end of science life.

Trajectories

Launch is done with mean Earth anomaly of ~ ±131°. Just as for SGO Mid, there would be no breaking delta-V required for the SGO Lowest satellites. There is also no out-of-plane delta-V required for inclination change, nor an in-plane delta-V required for eccentricity change. There are small delta-Vs required to separate SC-1 and SC-3 from SC-2. This is done by decreasing SC-1's semi-major axis slightly and increasing SC-3's semi-major axis slightly, and then reversing the effect one year later. The required delta-V for each burn is ~ 22 m/s (L/2Gm); the total Delta-V is 44 m/s, but only for SC-1 and SC-3. Unlike the other SGO concepts, SGO Lowest does not include propulsion modules. These small burns would be accomplished with the CMNT, requiring maximum thrust near 1 mN. This is beyond the range of the LPF thrusters, but within expectation for next generation colloidal thrusters.

5. Operations

For SGO-Lowest, 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 the distributed team of science investigators.

The three DSN 34-meter X-band antennae communicate with each of the science-craft directly via a gimbaled High Gain Antenna (HGA). The MOC performs command sequencing, health and safety monitoring, navigation and anomaly investigation. Schedules for DSN passes, high-gain antenna positioning, and laser frequency changes are generated for each spacecraft and transferred to the DSN for uplink. Passes are scheduled approximately every other day. Other aspects of SGO-Lowest 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 spacecraft data to the SODPC. The performance of the instruments and the data quality is assessed. The time-series of phase measurements is processed here to identify and match strong signals, and to build up a catalog of known sources. The science centers would also provide a higher level of quality of assurance over overall instrument performance, and may periodically request engineering tests or configuration changes of the constellation or one spacecraft. These requests would 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 Science Data Processing Facility for archival and use in further data reduction.

The SGO-Lowest 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 place SGO-Lowest onto a constant drift away from Earth at 6°/year. Over the course of the 18 months, the two end satellites execute delta-Vs to separate them from the middle satellite, each to a distance from the middle of L = 2 Gm. The third, middle spacecraft maneuvers to a lower heliocentric orbit to establish the linear, in-plane arrangement. During Science Operations, the constellation would require low thrust maneuvers periodically to offset being pulled apart by gravity gradients from the Earth-Moon system, which may be cold gas or milli-Newton thrusters. There must also be micro-Newton thrust levels to control spacecraft attitude and to have each spacecraft follow its test masses. For SGO-D, science operations would last two years at 9°-21° heliocentric, continuing to drift at 6°/year, trailing the Earth. During that time, the two SC1 to SC2 links are 2Gm in length, and the SC1 to SC3 links are 4 Gm, and there is no link between SC2 and SC3. After two years, the constellation geometry rapidly degrades. The links will fail once SC1 can no longer keep both SC2 and SC3 in its telescope FOV so there is no possibility of an extended mission.

The communications data volume and operations would be roughly constant, with the constellation generating 1.3 Gbit/day, and requiring each sciencecraft to have an 8-hour DSN contact every 6 days. Key SC operations are re-pointing of the HGAs, switching of laser frequencies, and stationkeeping maneuvers, all of which interrupt science data collection and would be coordinated to minimize outage times.

6. Launch Vehicle

The launch vehicle for the SGO Lowest must accommodate the mass and size of the three sciencecraft and the launch vehicle adapter. A propulsion module is not required.

The wet mass of each of SGO Lowest sciencecraft is 609 kg. The estimated mass of the launch vehicle adapter is 122 kg. The total mass for three sciencecraft and the launch adapter is 1950 kg.

Several launch vehicles options may be considered as illustrative examples capable of placing the SGO-Lowest into heliocentric orbit with C3 = 0.08. The Atlas V (401) provides a launch margin of 1065 kg, or about 55%. The Falcon 9 (Block 2)) would have a margin of 498kg, or about 25%. Shaving 29kg, or about 5%, from the mass of each sciencecraft would comfortably meet the 30% standard launch margin. The Falcon 9 (Block 3) allows a launch margin of 1515kg, or about 78%.

The SGO Lowest constellation can be easily accommodated in, for example, the Space-X 5 meter fairing. (See Figure E1)

7. Cost Estimate

The cost estimate for SGO Lowest 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 [18, 19], 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	-0.01
Optical assembly count reduction	-0.13
Payload mass or redundancy reduction	-0.11
Mission duration reduction	-0.11
Propulsion module elimination	-0.11
SGO Lowest total	**$1.19B**

Table 3: Estimated cost savings from design changes in SGO Lowest 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 the spacecraft bus and propulsion module) 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) [20]. 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 [21].

Our cost model estimates that SGO Lowest would cost $1.19B in FY12 dollars.

A rough schedule is taken from the LISA RFI 1 submitted to Astro2010 [ref]. Phases A, B, C/D and E/F are expected to last 12, 30, 66 and 42, respectively. Note that SGO Lowest’s Phase E has the 18 month transfer trajectory, and 24 months of science observation. Commissioning is expected to take up to 4 months from this total, and may be split between the two phases.

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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
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 Lowest		# 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)	Contin-gency [%]	Total Power [W] (MEV)
Spacecraft Bus		**3**	**0**	**1**	**242.950**	**30%**	**315.84**	**247.7**	**30%**	**322**
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**	**34.6**		**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**	**15.4**		**20**
C&DH	15.10	1	1		15.1		19.63			
Telecom					**18.7**		**24.31**	**66.1**		**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	1	0		2.3		2.99			
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			
Launch Mounting Structure		**3**	**0**	**1**	**97.800**	**30%**	**127.14**	**0.0**	**30%**	**0.0**
Structure					**95.8**		**124.54**			
Primary Structure	65.00	1			65		84.50			
Secondary Structure	9.00	1			9		11.70			
Lightband (PM to PM)	21.80	1			21.8		28.34			
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			
Propellant		**1**	**0**	**0**	**0.000**	**0%**	**0.00**			
Propellant	0.00	1			0		0			
Scientific Complement		**3**	**0**	**1**	**127.87**	**30%**	**166.22**	**203.1**		**264.0**
Instrument Electronics					**24.5**		**31.85**	**138.5**		**180.0**
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			
Optical Sub-Assembly		**1**			**53.81**		**69.95**	**56.9**		**74.0**
Telescope					**25.2***		**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) + 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**	**7.7**		**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					**8.9**		**11.52**			
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	0			0		0.00			
Launch Lock Device Rotation complete	1.00	0			0		0.00			
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			
L/V Adapter		**1**	**0**	**0**	**94.000**	**30%**	**122.20**			
Adapter (5% launch mass)	94.00	1			94.00		28.20			
Subtotal - Cruisecraft Dry					**468.62**	**30%**	**609.20**			
Total - GW Cruisecraft Wet (w/o L/V Adapter)					**468.62**	**30%**	**609.20**			
Total - GW Launch Stack (incl L/V adapter)					**1499.85**		**1949.80**			
Total - GW Cruise Power								**255.4**		**332.0**
Total - GW Operational Power								**450.7**		**586.0**

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

Appendix E: Launch Vehicle Accommodation

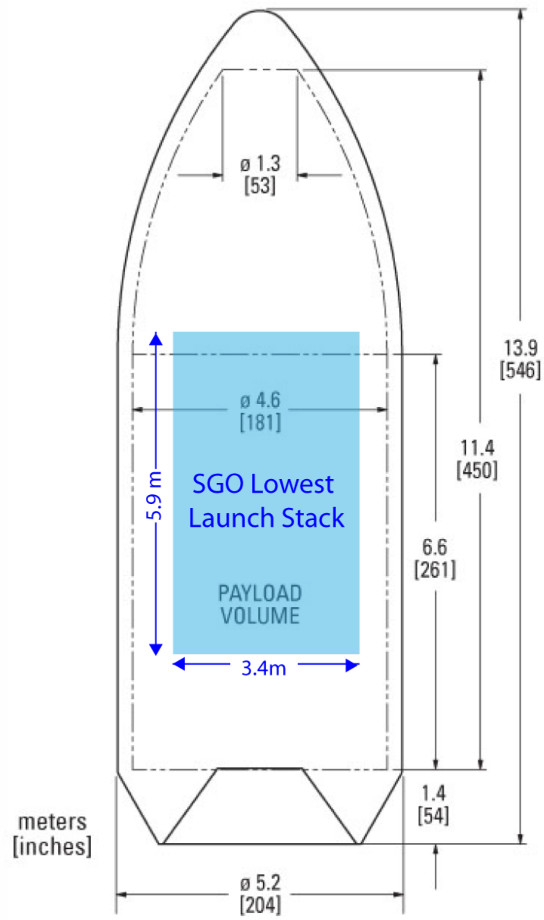

Figure E1

The standard Space-X 5m fairing will easily accommodate the SGO Lowest, particularly since the height can be optimized since there is no P/M.

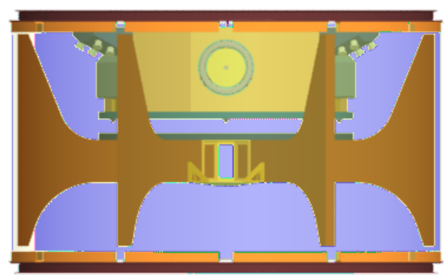

Figure E2

The SGO Lowest configuration does not have a Propulsion Module. It will require a Launch Mounting Structure (LMS) to allow all three S/C to be stacked for launch, as well as a Launch Vehicle Adapter. It may be possible to combine the L/V Adapter and the LMS. Figure E2 shows a P/M shell as an example of a possible LMS, but no attempt has been made to optimize the height.

Appendix F. SGO Lowest Orbits

Here we consider a simplified orbital analysis, circular heliocentric orbits. We assume the two end spacecraft are at the same distance R = 1 AU from the Sun, requiring, for a linear configuration that the center spacecraft is slightly closer to the Sun at $R - dR \approx R - L^2/(2R)$, assuming $L \ll R$. (See Figure F-1 for notation.)

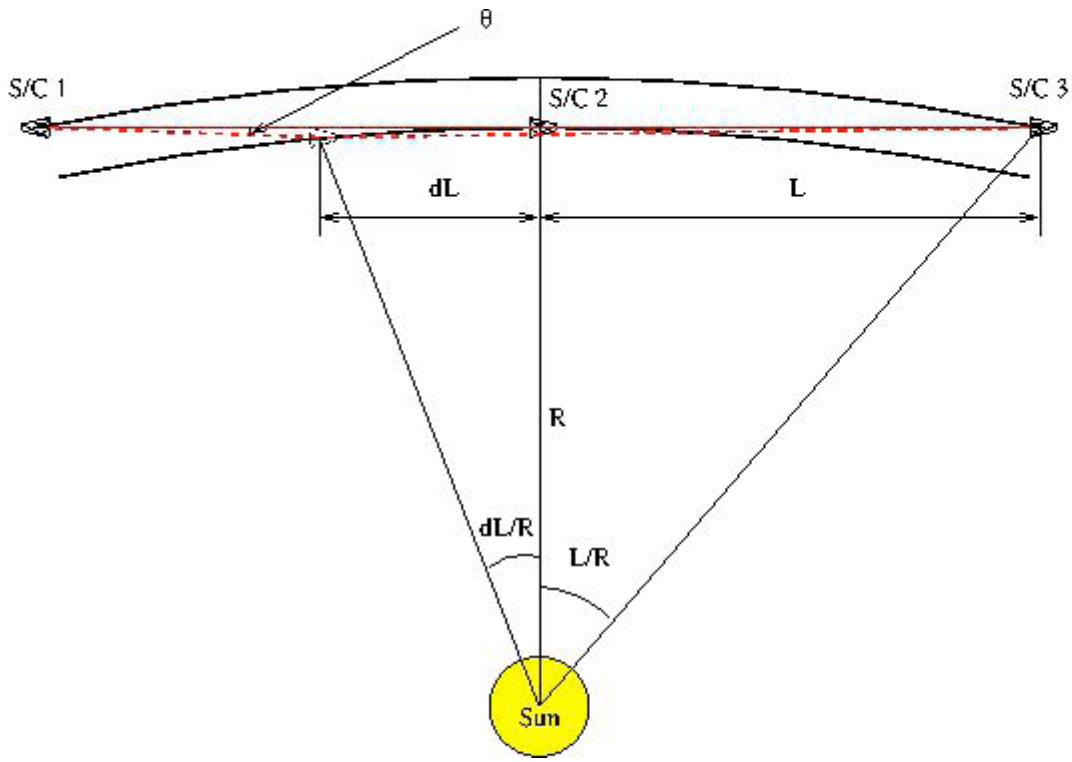

Figure F-1 – SGO Lowest orbit configuration: linear gravitational-wave detector. The measurement is conducted at SC-1, on the left, while SC-2 and SC-3 only echo back the light. Because the center spacecraft SC-2 is closer to the Sun, it must have a shorter period, unavoidably drifting from the center (at the midpoint of mission life) by distance dL toward the SC. The FOV of the telescope on SC-1 sets a limit for how large the angle θ can grow, thus limiting the lifetime of the mission.

The orbital period for the central spacecraft, $P_2 = P - dP$, is shorter than that for the end spacecraft ($P_1 = P_3 = P \approx 1$yr). For Keplerian orbits, $dP/P \approx 3/2\ dR/R \approx 3/4\ (L/R)^2$. This sets a fundamental limit on the lifetime of the configuration. Concretely the lifetime is limited by growth of the angle $\theta \approx (dL)^2 / (2RL)$ (using $dL \ll L \ll R$) between the rays toward SC-2 and SC-3 at SC-1. This angle must be smaller than the functional field of view θ_{max} of the telescope on SC-1. If the spacecraft begin in exact alignment, with SC-2 in the exact center, then after time t, the center spacecraft will have drifted by $dL \approx 3\pi/2\ (t/P)\ (L/R)^2\ R$. Thus the maximum drift time t_{max} becomes is limited by $\theta_{max} = [dL(t_{max})]^2/(2RL)$. If we start S/C 2 at position -dL, then the maximum mission lifetime is $T = 2\ t_{max}$. Then the separation, maximum mission lifetime and field of view are related by $\theta_{max} = (9\pi^2 / 32)\ (T/P)^2\ (L/R)^3$.

The effects of Earth's gravitational perturbations are actually not trivial relative to the θ_{max} limit. Numerical simulations (with GMAT) using L = 1 Gm indicate that maximum variation of over a 2-year period would be ~ 500 μ-rad. We will need periodic orbit adjustments to keep the satellite alignments reasonably tuned. To completely cancel the Earth force at the 9°, start-of-science distance would require a *continuous* force of ~ 700 (m_S/1000 kg) μN, where m_S is the mass of each satellite. However, the mean effect of the Earth's field would be to cause the cause the constellation as a whole to increase its orbital distance from the Sun, slightly increasing the drift-away rate. That's of no real concern. It is the differential (gravity gradient) effect that would be disruptive; its magnitude over the constellation is down by a factor of 4L/D, where D is the distance back to Earth. The required compensation force from the thrusters becomes ~ 234 (L/2Gm)(m_S/1000 kg) μN. This is high relative to current micro-thruster capacity, but the JPL colloidal thruster team is anticipating being able to provide colloidal thruster with ~ mN capacity within a few years. This suggests that periodic orbit maintenance with the thrusters on ~ 1/10 of the time should be adequate if next generation (JPL) colloidal thrusters are used. More thorough analysis would be required if this concept were to go forward.