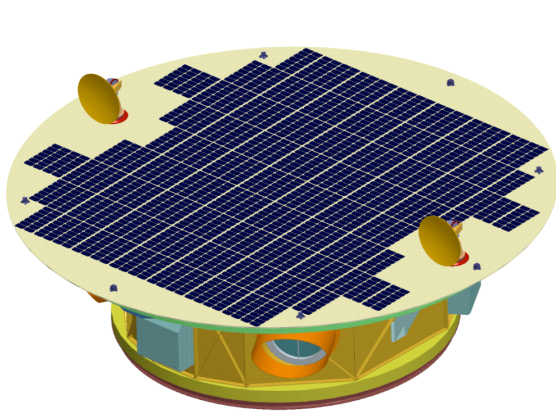
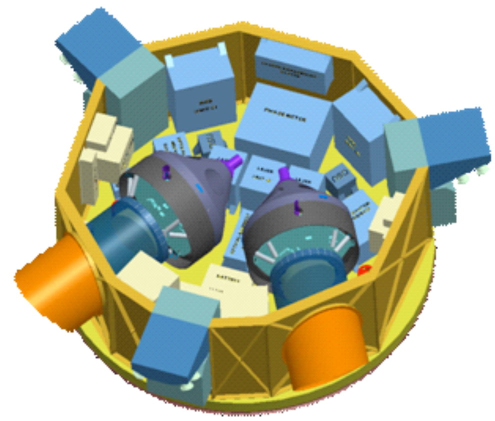
TEAM X SUMMARY for Space-based Gravitational Wave Observatory (SGO):
MID and HIGH
FOR UNLIMITED RELEASE

Title: Team X Study of the SGO-Mid and SGO-High Options

Jet Propulsion Laboratory,
California Institute of Technology

With contributions from the SGO Team

Dr. Jeffrey Livas, NASA
Dr. Robin (Tuck) Stebbins, NASA
Mr. Kenneth Anderson, NASA

Overview

This study was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The goal of this study is to provide a cost estimate and risk assessment for the proposed SGO-Mid mission, which the SGO team referred to as Option 1. The secondary goal was to provide a delta assessment (primarily cost) for the SGO-High concept as Option 2. Here are the key questions that the customer wanted to see addressed: 1) What is the estimated mission cost for each concept, assuming all technologies are at TRL 6 by 2021? 2) What are the key technical drivers for the mission design? 3) What are the key critical technologies that need to be developed to achieve TRL 6 in 2021? These missions are derived from the Laser Interferometer Space Antenna (LISA) concept that was conceived in 1974 and was studied with the European Space Agency (ESA) from 1993 to March 2011. The LISA concept was considered very mature. The first study (Option 1) was SGO-Mid, which was envisioned with a shorter baseline than LISA, smaller telescopes, and shorter lifetime. The SGO-High concept (Option 2) envisioned as LISA with some cost savings from a shortened mission, but with full LISA science performance and redundancy. The costs of both options were estimated.

Baseline Option and Key System Parameters

The high-level scientific objectives of SGO- Mid and SGO-High are essentially the same as for LISA:

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

Both SGO-Mid and SGO-High take the form of triangular shaped constellations. The science instrument for SGO-Mid is a constellation of three “sciencecraft” (SC) arranged as an equilateral triangle with 1 Gm arms. In the case of SGO-High the configuration is the same but with 5 Gm arms. Each SC consists of a tightly integrated scientific payload and spacecraft bus. The three-sciencecraft constellation is essentially the instrument. The orbits passively maintain formation and the three sciencecraft house free-falling test masses and interferometry. The Interferometer Measurement System (IMS) consists of an active transponder, and phase-locked laser ranging system. The phasemeter records the fringe signal. The laser frequency noise correction is by pre-stabilization and post processing. The test masses are part of a disturbance reducing sciencecraft control loop used for disturbance cancellation and inertial positioning. The design is optimized to limit thermal, magnetic, electrostatic, mechanical, and self-gravity disturbances. Due to the need to eliminate vibration and mass movement form each sciencecraft, the sciencecraft are 3-axis controlled using colloidal thrusters rather than conventional chemical propulsion thrusters. For the same reason, they do not have reaction wheels and must maintain attitude solely with the propulsion system. The low thrust of the colloidal thrusters make them well suited for the science operations portion of the mission once the sciencecraft have reached the vertices of the constellation’s triangle, but transporting the sciencecraft to these locations is beyond the capabilities of these thrusters. To position each sciencecraft, a second spacecraft – a propulsion module – is used to carry each sciencecraft to its operational orbit. These modules are identical and carry their own power, ACS, CDS, and telecom systems, and each utilizes a mono-prop propellant system to produce the thrust needed to reach position. Once on orbit, the modules separate, move away from the science craft and shut down. All three sciencecraft/propulsion module vehicles are launched on a single shared vehicle in a stacked arrangement. The baseline parameters are summarized in Tables 1 and 2.

Table 1: Key Design Features for SGO-Mid.

Domain	Category (unit)		Values with Comments
System	Launch Mass (kg) each (total)		1378 (4553)
	Spacecraft Power (W) each		652 (Science on station with telecomm)
	Total Mission Cost ($B FY12)		1.9
	Radiation TID (krad)		20.7 (behind 100 mil of Aluminum, with an RDM of 2)
Science	Science Goals		Measuring gravitational waves
	Key Measurements		Laser ranging among 3 spacecraft 1M km apart
	Total Data Volume (Gbits)		190
Mission Design	Launch Date		October 10, 2020
	Launch Vehicle		Atlas V 551
	Launch Mass Allocation (kg)		6075
	Trajectory/Orbit Type		Earth trailing, drift away
	Mission Duration (months)		24
	Key Mission Phases		Launch, 17 mos cruise to 9 deg trailing position, 3 mos checkout (inc'g establish laser links), 24 mos science ops, 24 mos Phase F (data analysis)
Instruments	Telescope	Type	Cassegrain
		Size	25 cm
	No. of Instruments		2 per sciencecraft
	Instrument Types		Telescopes, Gravitational Reference Sensor (GRS)
	Payload Mass (kg)		216.6
	Payload Power (W)		233
	Payload Data Rate (Mbps)		0.004
ACS	Pointing Control (arcsec)		2
	Pointing Knowledge (arcsec)		0.7
	Pointing Stability (arcsec/sec)		0.1
	Stabilization Type		3-axis
	Pointing Technologies		Star trackers, sun sensors, colloidal micro-thrusters
CDH	Processor Type		RAD 750
	Redundancy		Dual cold
	Data Storage (Gbytes)		4
Telecom	Bands		X
	Antenna Types		LGA horns (2), 0.35m HGA dish
	Uplink Rate (kbps)		0.1 through LGA, 2 through dish
	Downlink Rate (kbps)		0.1 through LGA, 90 through dish
Power	Solar Array Area (m^2)		5.27
	Solar Array Type		GaAs Triple junction, fixed panel, no articulation
	EOL Power (W)		642
	Battery Storage Size(s) (A-hrs/Ty)		20/ Li-Ion ABSL
Propulsion	No. of Prop Systems		2
	Type(s) of System(s)		Blowdown hydrazine monoprop for Delta V, colloidal microthrusters for Science
	Propellant Mass(es) (kg)		139.5
Structures	Primary Structural Material		Machined aluminum and titanium with metallic honeycomb composite panels
	No. of Mechanisms		1
Thermal	Active/Passive		Sciencecraft is passive, Prop module is active
	Key Operating Temperature(s) (K)		293
	Thermal Stability (K/hr)		Laser stabilization cavity = 10 $\mu K/\sqrt{Hz}$ at 1 mHz Across the GRS ref. housing = 60 $\mu K/\sqrt{Hz}$ at 0.1 mHz
	Thermal Control Technologies		MLI, heaters, radiators190
Ground System	Ground Antenna(s)		BWG ground station, 34m antenna
	Average Pass Duration (hrs)		8=1 link per week per Sciencecraft

Table 2: Key Design Features for SGO-High

Domain	Category (unit)		Values with Comments
System	Launch Mass (kg) each (total)		1641 (5822)
	Spacecraft Power (W) each		689 (Science on station with telecomm)
	Total Mission Cost ($B FY12)		2.1
	Radiation TID (krad)		35 (behind 100 mil of Aluminum, with an RDM of 2)
Science	Science Goals		Measuring gravitational waves
	Key Measurements		Laser ranging among 3 spacecraft 5M km apart
	Total Data Volume (Gbits)		473
Mission Design	Launch Date		October 10, 2020
	Launch Vehicle		Atlas V 551
	Launch Mass Allocation (kg)		6075
	Trajectory/Orbit Type		Earth trailing, drift away
	Mission Duration (months)		81
	Key Mission Phases		Launch, 18 mos cruise to 22 deg trailing position, 3 mos checkout (inc'g establish laser links), 81 mos science ops, 24 mos Phase F (data analysis)
Instruments	Telescope	Type	Cassegrain
		Size	40 cm
	No. of Instruments		2 per sciencecraft
	Instrument Types		Telescope with Gravitational Reference Sensor (GRS)
	Payload Mass (kg)		260
	Payload Power (W)		256
	Payload Data Rate (Mbps)		0.004
ACS	Pointing Control (arcsec)		2
	Pointing Knowledge (arcsec)		0.7
	Pointing Stability (arcsec/sec)		0.1
	Stabilization Type		3-axis
	Pointing Technologies		Star trackers, sun sensors, colloidal micro-thrusters
CDH	Processor Type		RAD 750
	Redundancy		Dual cold
	Data Storage (Gbytes)		4
Telecom	Bands		X
	Antenna Types		LGA horns (2), 0.35m HGA dish
	Uplink Rate (kbps)		0.1 through LGA, 2 through dish
	Downlink Rate (kbps)		0.1 through LGA, 90 through dish
Power	Solar Array Area (m^2)		7.43
	Solar Array Type		GaAs Triple junction, fixed panel, no articulation
	EOL Power (W)		689
	Battery Storage Size(s) (A-hrs)		20 L-Ion ABSL
Propulsion	No. of Prop Systems		2
	Type(s) of System(s)		NTO/ hydrazine biprop for Delta V, colloidal microthrusters for Science
	Propellant Mass(es) (kg)		299.4
Structures	Primary Structural Material		Machined aluminum and titanium with metallic honeycomb composite panels
	No. of Mechanisms		1
Thermal	Active/Passive		Sciencecraft is passive, Prop module is active
	Key Operating Temperature(s) (K)		293
	Thermal Stability (K/hr)		Laser stabilization cavity = 10 $\mu K/\sqrt{Hz}$ at 1 mHz Across the GRS ref. housing = 60 $\mu K/\sqrt{Hz}$ at 0.1 mHz
	Thermal Control Technologies		MLI, heaters, radiators190
Ground System	Ground Antenna(s)		BWG ground station, 34m antenna
	Average Pass Duration (hrs)		8 =1 link per week per Sciencecraft.

Technical Findings

With the original approach and mass and equipment list (MEL), SGO-Mid converges to meet the launch vehicle constraints of the Atlas V 551, the largest launch vehicle on the current NASA Launch Services (NLS) contract. The concept of placing the sciencecraft inside of the load bearing propulsion module appears to be very viable. The drawback is that to save cost, the mass structure of the stack of 3 spacecraft is not optimized. A trade should be done to study a side-by-side launch configuration or alternately a stacked configuration with propulsion modules' structures optimized for their position in the stack. The latter approach may result in a stack that would fit in a smaller launch vehicle.

The SGO-High option was not able to meet the Atlas V 551 launch vehicle mass constraints with sufficient mass margin necessary for this stage of development. The combination of larger telescopes, more Delta V and the resulting impact on stacked structures mass led to a design spiral which placed it outside the L/V launch mass capability for NLS.

The risk for both missions at this stage seemed to be very low.

Design Assumptions

1. *Class B mission*
2. *Costs in FY2012$*
3. *Total mass margin of 53%of dry mass CBE*
4. *Cost reserves of 30% (excluding launch vehicle) on Phase A through E*
5. *JPL's Design Principle margins elsewhere*
6. *NLS II launch vehicles and L/V costs*
7. *TRL 6 at technology for 2015*
8. *All three flight systems are identical for both options.*

Technical Details for SGO-Mid and High

- **ACS** – Three axis stabilization for both options. Attitude control hardware on the sciencecraft: colloidal thrusters with a thrust range of 4 to 150 μN. Attitude control hardware on the SGO-Mid and High prop module: hydrazine thrusters.

- **Structure** – The materials utilized to construct the Primary Structure of the sciencecraft for both the Mid and High options were a combination of machined aluminum and titanium with flat panels constructed of metallic honeycomb composite. The Propulsion Stage for the Mid option were constructed of a combination of machined aluminum and metallic honeycomb composite panels. Due to the stacked launch configuration, additional material has to be added for all propulsion stages.

.

- **Telecom** – The nominal design from the customer had a Ka-Band downlink for the science data and X-Band communications via LGAs for cruise and low rate engineering data. The science data rate is only 90 kbps – Ka-Band is not needed. To save money, the design was changed to remove the Ka-Band equipment as well as the second HGA.

- **CDH** – The C&DH subsystems for both options (SGO-Mid and SGO-High) are identical. The sciencecraft includes redundant RAD 750 computers, 4GB NVM, telecom and power interface cards. It supports 1553 and RS-422 buses. The propulsion modules' CD&H subsystems are the same as the sciencecraft but single string.

- **Power** – Array: driving power mode - Science on station with telecommunications. For the batteries: driving power mode – launch and separation. Redundancy met with use of ABSL design with its inherent series/parallel design. Allowing for additional strings. Electronics: redundant boards

- **Propulsion** - Sciencecraft Options 1 and 2 have a colloidal propulsion system based on ST7 design and heritage. Propulsion stage Option 1, blowdown hydrazine monopropellant system, 49.9 kg CBE including 53% contingency. On option 2, Team X switched to a biprop approach to save mass.

- **Thermal** - Passive design is necessary due to strict stability requirements. Active heaters cycling on and off would disturb the system. Environment is steady, with the 60 degree inclination resulting in one revolution per year for the sciencecraft.

A number of commercial bus manufacturers would be able to construct the spacecraft, but for uniformity in assumptions across all SGO studies, Team X assumed a JPL built bus as the baseline.

Key Trades or Options studies in Team X

Several key Options and trades were examined as part of the Team X studies. The most significant trades were:

- **Option 1 SGO-Mid.** Three Earth trailing spacecraft in an equilateral triangle formation consisting of a sciencecraft and propulsion module: together they are called the cruisecraft. The 3 spacecraft incorporate a 1 million km baseline with 2 years in science formation. They arrive on-station 6/1/2022 with a launch ~18 months prior. The three sciencecraft incorporate 45 months for Phase E.

- **Conclusions**: The design closes comfortably. The concept of placing the sciencecraft inside of the load bearing Propulsion Module appears to be very viable. To save cost, the mass structure of the stack of 3 spacecraft was not optimized.
  - An ATLAS 551 can comfortably launch the entire cruisecraft stack of three flight systems. There was 26% additional margin over and above the 53% contingency/margin applied to the total launch mass.

Option 2 SGO-High: Essentially the same concept as SGO-Mid but incorporated larger sciencecraft and instruments (twin 40-cm telescopes with lasers) into a helio-centric, Earth-trailing, stable orbit. As opposed to a 1 million kilometer baseline there is 5 million km spacing between each sciencecraft. SGO-High allowed for 81 months for Phase E.

- **Conclusions**: Option 2 did not converge to fit within the LV mass constraints. The SGO-High design is too massive for the largest launch vehicle in the NLS II database. This design cannot converge within the given constraints. However if relaxed non-NLS launch vehicle were allowed, or a smaller mass contingency coupled with propulsion module structures tailored for their positions in the stack were utilized, it might be possible to close the design.

- Team X proceeded with design as though an appropriately sized launch vehicle existed. Each sciencecraft is 797.1 kg. Each Prop Stage with sciencecraft is 1641 kg dry. The propulsion modules require 299.4 kg NTO/ Hydrazine propellant to achieve 483 m/s delta V which is below the approximately 1100 m/s needed for the 5 million km baseline

- Total launch mass for 3-stack is 5938 kg including the adapter. Cost of mission is $2.1B (assumed launch vehicle cost equaled that of an Atlas V 551)

Cost Estimate Interpretation Policy

The cost estimates summarized in this document were generated as part of a Pre-Phase-A preliminary concept study, are model-based, and do not constitute a cost commitment on the part of JPL or Caltech.

Table 3: Cost Estimate

Item	SGO-Mid Option 1 Cost ($M 2012)	SGO- High Option 2 Cost ($M 2012)
Management, Systems Engr., Mission Assurance	$93	$97
Payload System	$383	430
-- Science Compliment	$383	430
Flight System	$546	574
-- Mgmt, Sys Engr	$48	48
-- Sciencecraft	$358	355
-- Prop Stage	$126	157
-- Test Beds	$15	15
Mission Ops Preparation/ Ground Data System	$103	127
Launch vehicle	$247	247
Assembly, Test, Launch Operations	$81	81
Science	$44	84
Education and Public Outreach	$16	18
Mission Design	$11	11
Reserves	$379	421
Total Project Cost	**$1,903**	**$2,090**

Table 4: Phase Cost profile – Costs are in $M FY2012

	Phase A	Phase B	Phase C/D	Phase E/F	Total
Option 1 Cost - SGO Mid	15.0	102.7	1659.6	125.3	1903
Option 2 Cost - SGO High	15.0	105.5	1760	209.7	2090

Technology Costing

Team X does not provide technology development costing. Models are based on the assumption of achieving TRL 6 by the end of Phase B.