Final Report of the Gravitational-Wave Mission Concept Study

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Outline

- Goals, Elements and Activities
- Context
- RFI Responses
- Architecture Choices
- Science Findings
- Risk Findings
- Cost Findings
- Technology Findings
- General Findings

Goals, Elements and Activities

- Goals
  - Develop mission concepts that will accomplish some or all of the LISA science objectives at lower cost points
  - Explore how architectural choices affect science, risk and cost
  - Identify key enabling technologies
- Elements: the research community, Core Team, Community Science Team, Science Task Force, Team X
- Activities
  - RFI, public workshop, open house, 'in-breeding'
  - Core Team analyses, CST analyses, science analyses, Team X studies (4), Study team deliberations, "Abstracting" for the Final Report

Prefatory Material

- LISA science: LIGO and NASA's opportunity
- Context
  - Decades of study and technology development, notably LISA Pathfinder
  - Many NRC reviews that focus on robust science, technical readiness and low risk
  - European intentions
- A primer on gravitational waves

LISA-like Concepts

Acronym	SGO High	SGO Mid	**SGO Low**	**SGO Lowest**	
Lead Author	Stebbins	Livas	**Thorpe**	**Baker**	**Shao**
Novel Idea	LISA with all known cost savings	Smallest LISA-like design with 6 links	Smallest LISA-like design with 4 links	Smallest in-line LISA-like design with 4 links	Formation-flying payload, torsion suspension for test mass
Proposal Type	Concept	Concept	Concept	Concept	Instrument
Cost Estimate (FY12$M)	$1,660	$1,440	$1,410	$1,190	$990
Number of Variants	1	1	1	1	1
Arm length (km)	5.0 x 106	1.0 x 106	1.0 x 10^6	2.0 x 10^6	5.0 x 10^6
Spacecraft/Constellation	3/equilateral triangle	3/equilateral triangle	4/60° Vee	3/In-line	3+3/triangle
Orbit	22° heliocentric, earth-trailing	9° heliocentric, earth drift-away	9° heliocentric, earth drift-away	≤9° heliocentric, earth drift-away	LISA-like
Trajectory	Direct injection to escape with recircularization and out-of-plane boost, 14 months	Direct injection to escape with out-of-plane boosts, 21 months	Direct injection to escape, with out-of-plane boosts, 21 months	Direct injection to escape, with small delta-v for S/C separation, 18 months	LISA-like
Inertial Reference	Two, rectangular	Two, rectangular	Single, rectangular	Single, rectangular	Single, torsion pendulum
Displacement Measurement	3 arms, 6 links	3 arms, 6 links	2 arms, 4 links	2 unequal arms, 4 links	3 arms, 6 links
Launch vehicle	Shared Falcon Heavy	Falcon 9 Block 3	Shared Falcon 9 Heavy	Falcon 9 Block 2	Falcon 9
Baseline/Extended Mission Duration (yrs)	5/3.5	2/2	2/2	2/0	5
Telescope Diameter (cm)	40	25	25	25	LISA-like
Laser power out of telescope, EOL (W)	1.2	0.7	0.7	0.7	LISA-like

All entries "as submitted"

Non-Drag-Free Concepts

Acronym		LAGRANGE
Lead Author	**Folkner**	McKenzie
Novel Idea	Long baseline, no drag-free	No drag-free, geometric reduction
Proposal Type	Concept	Concept
Cost Estimate (FY12$M)	$924	$1,120
Number of Variants	2	2
Arm length (km)	2.6×10^8	2.09 x 107
Spacecraft/Constellation	3/equilateral triangle //4/square	3/isosceles triangle with 164° central angle
Orbit	Heliocentric	Heliocentric/ Earth-Sun L2
Trajectory	Not specified beyond HEO parking, double lunar assist. Solar electric propulsion mentioned.	Direct escape to L2, "drift" of SC1/3 to 8° leading/trailing
Inertial Reference	None	GOCE accelerometer
Displacement Measurement	3 arms, 6 links	2 arms, 4 links
Launch vehicle		Falcon 9 Block 3
Baseline/Extended Mission Duration (yrs)	3	2
Telescope Diameter (cm)	30	20/40
Laser power out of telescope, EOL (W)	1	1.2

All entries “as submitted”

Geocentric Concepts

Group	Group 3 - Geocentric			
Acronym	**GEOGRAWI**	**GADFLI**	OMEGA	**LAGRANGE**
Lead Author	**Tinto**	**McWilliams**	Hellings	**Conklin**
Novel Idea	Geostationary orbits, single spherical TM	Geostationary orbits, smaller telescope and laser	Novel trajectories, Explorer cost approach	Earth-Moon Lagrange points, spherical test mass, grating
Proposal Type	Concept	Concept	Concept	Concept
Cost Estimate (FY12$M)	$1,122	$1,200	$300	$950
Number of Variants	3	3	1	1
Arm length (km)	7.3×10^4	7.3×10^4	1.04 x 106	6.7 x 105
Spacecraft/Constellation	3/equilateral triangle	3/equilateral triangle	6/equilateral triangle	3/equilateral triangle
Orbit	Geostationary	Equatorial, geostationary	600,000 km geocentric, earth-moon plane (retrograde)	Earth-Moon L3, L4, L5
Trajectory	Not specified	Direct launch together to geostationary, re-phase 2 S/C	Butterfly trajectories to Weak Stability Boundary, 384 days total	Either: direct to WSB, return and lunar fly-by; direct to Trans Lunar Injection, return and lunar fly-by
Inertial Reference	Single, spherical	Two, rectangular	Single, rectangular	Single, spherical
Displacement Measurement	3 arms, 6 links	3 arms, 6 links	3 arms, 6 links	3 arms, 6 links
Launch vehicle		Falcon 9 Block 2	Small Delta or Falcon 9	Falcon 9
Baseline/Extended Mission Duration (yrs)		2	3	5
Telescope Diameter (cm)	Same as LISA	15	30	20
Laser power out of telescope, EOL (W)	Same as LISA	0.7	0.7	1

All entries "as submitted"

Other Concepts

Group	Group 4 - Other		
Acronym	InSpRL		
Lead Author	Saif	Yu	Gulian
Novel Idea	Atom interferometry	Atom inteferometer for inertial sensor	Electrons in superconductor
Proposal Type	Concept	Instrument	Concept
Cost Estimate (FY12$M)	$444/$678		
Number of Variants	2		
Arm length (km)	0.5/500		
Spacecraft/Constellation	1//2/in-line		1
Orbit	1200 km above geostationary	LISA-like	Not specified.
Trajectory	Not specified	LISA-like	Not specified
Inertial Reference	Atom interferometers		Not specified
Displacement Measurement			
Launch vehicle	Falcon		
Baseline/Extended Mission Duration (yrs)			
Telescope Diameter (cm)			
Laser power out of telescope, EOL (W)	10-20		

All entries "as submitted"

Architecture Choices

- Orbits and Trajectories
  - Heliocentric, drift-away, high geocentric, geosync
  - Launch vehicle/time to orbit/delta-v, weak stability boundary, lunar assist
- Inertial Reference
  - Drag-free test mass, force correction, atom interferometry
- Time-of-Flight: laser interferometry, AI phasemeter
- Flight System
  - Unusual requirements on the spacecraft, tight integration
  - Number of designs, number of spacecraft
  - Requirements on-drag-free spacecraft are challenging and not well understood.

Science Findings

- Several mission concepts, including those studied by Team X, were found to be capable of delivering a significant fraction of the LISA science related to massive black hole mergers and galactic binaries.
- The science of compact object captures (EMRI systems) may be at risk due to significantly reduced detection numbers relative to the LISA mission.
- Concepts with three arms significantly improve parameter estimation over two-arm designs for black holes and enhance the ability to detect un-anticipated signals.
- Additional years of science observations produce more science return for very modest expense.
- Gravitational-wave astrophysics and data analysis research has had a major impact on the anticipated science return from gravitational wave missions and has the potential to continue doing so.

Risk Findings

- A three-arm design has lower risk than a similar two-arm design, allowing for graceful degradation.
- Three dual-string spacecraft appear to be more robust than six single-string spacecraft for most mission failures.
- A non-drag-free architecture introduces significant additional risk.
- Overlapping construction of multiple units adds significant schedule risk.

Cost Findings

- In all cases, the Team X estimated costs were found to be well over $1B, thus putting the mission in the flagship class.
- The choice of heliocentric versus geocentric mission designs does not seem to be a significant cost driver.
- Reducing a three-arm design to two arms will not necessarily reduce the cost significantly.
- Eliminating the drag-free inertial reference achieves at most modest savings while incurring additional risk.
- Optimizing the build plan could be a source of modest savings.

Technology Findings

- No new or unproven technology is needed to enable a LISA-like mission such as SGO High or SGO Mid.
- Refinement and enhancement of core LISA technologies could provide cost, risk, or performance benefits that integrate to a moderate effect on the mission as a whole, but will not enable a probe-class mission.
- Coordinated US investment in core LISA technologies will preserve the US research capability and support mission opportunities on a variety of time scales for a variety of partnering arrangements.
- System test beds for drag-free control and interferometric measurement are a good investment, providing an arena in which to develop technologies and an opportunity to gain deep insight into the measurement process.

General Findings

	SGO High	SGO Mid	LAGRANGE/ McKenzie	OMEGA Option 1	OMEGA Option 2
Science Performance					
Massive Black Hole Binaries					
Total detected	108-220	41-52	37-45	21-32	21-32
Detected at $z \geq 10$	3-57	1-4	1-5	1-6	1-6
Both mass errors ≤ 1%	67-171	18-42	8-25	11-26	11-26
One spin error ≤ 1%	49-130	11-27	3-11	7-18	7-18
Both spin errors ≤ 1%	1-17	<1	0	<1	<1
Distance error ≤ 3%	81-108	12-22	2-6	10-17	10-17
Sky location ≤ 1 deg^2	71-112	14-21	2-4	15-18	15-18
Sky location ≤ 0.1 deg^2	22-51	4-8	≤ 1	5-8	5-8
Total EMRIs detected†	800	35	20	15	15
WD binaries detected (resolved)	$4 \cdot 10^4$	$7 \cdot 10^3$	$5 \cdot 10^3$	$5 \cdot 10^3$	$5 \cdot 10^3$
WD binaries w/ 3D location	$8 \cdot 10^3$	$8 \cdot 10^2$	$3 \cdot 10^2$	$1.5 \cdot 10^2$	$1.5 \cdot 10^2$
Stochastic Background Sensitivity (rel. to LISA)	1.0	0.2	0.15*	0.25	0.25
Top Team X Risk	Moderate‡	Low	Moderate	Moderate	High
Top Team X + Core Team Risk	Moderate‡	Low	High	High	High
Team X Cost Estimate (FY12$)	2.1B	1.9B	1.6B	1.4B	1.2B

† Based on median rate; estimates for EMRI rates vary by as much as an order of magnitude in each direction.
* Two-arm instruments such as LAGRANGE/McKenzie lack the "GW null" channel that can be used to distinguish between stochastic backgrounds & instrumental noise, making such measurements more challenging.
‡ The moderate risk for SGO High comes about from the thruster development necessary to demonstrate the required lifetime for 5 years of science operations.

- Scientifically compelling mission concepts can be carried out for less than the full LISA cost. No concepts were found near or below $1B.
- Scaling the LISA architecture with 3 arms down to the SGO Mid concept preserves compelling science, reduces cost and maintains low risk.
- Eliminating a measurement arm reduces costs modestly, reduces science and increases mission risk.
- More drastic changes, such as eliminating drag-free operation or adopting a geocentric orbit, significantly increase risk, and the associated cost savings are uncertain.
- Scientific performance decreases far more rapidly than cost.
- We have found no technology that can make a dramatic reduction in cost.
- There is an urgent need for NASA to prepare for the imminent exploration of the Universe with gravitational waves, leading to revolutionary science. The U.S. needs a sustained and significant program supporting technology development and science studies to participate in the first space-based gravitational-wave mission.