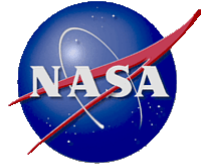




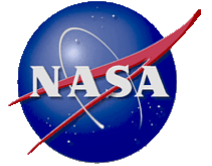
Final Report of the Gravitational-Wave Mission Concept Study

Robin Stebbins, Study Scientist
Astrophysics Subcommittee of the NAC
NASA HQ, 30 July 2012



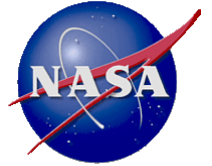
Outline

- 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)	5.0×10^6	1.0×10^6	1.0×10^6	2.0×10^6	5.0×10^6
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	2.09×10^7
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	1.04×10^6	6.7×10^5
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

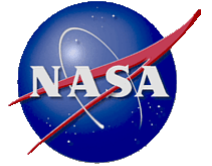
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Other Concepts

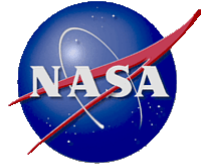
Group	Group 4 - Other		
Acronym	InSpRL		
Lead Author	Saif	Yu	Gulian
Novel Idea	Atom interferometry	Atom inteferometer for inertial sensor	Electrons in superconductor
Proposal Type	Concept	Instrument	Concept
Cost Estimate (FY12\$M)	\$444/\$678		
Number of Variants	2		
Arm length (km)	0.5/500		
Spacecraft/Constellation	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"



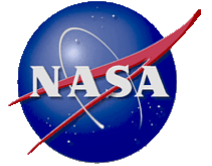
Architecture Choices

- 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.



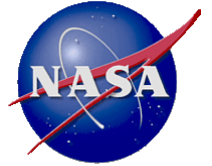
Science Findings

- 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.



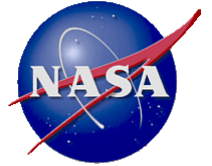
Risk Findings

- 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					
<i>Massive Black Hole Binaries</i>					
<i>Total detected</i>	108-220	41-52	37-45	21-32	21-32
<i>Detected at $z \geq 10$</i>	3-57	1-4	1-5	1-6	1-6
<i>Both mass errors $\leq 1\%$</i>	67-171	18-42	8-25	11-26	11-26
<i>One spin error $\leq 1\%$</i>	49-130	11-27	3-11	7-18	7-18
<i>Both spin errors $\leq 1\%$</i>	1-17	<1	0	<1	<1
<i>Distance error $\leq 3\%$</i>	81-108	12-22	2-6	10-17	10-17
<i>Sky location $\leq 1 \text{ deg}^2$</i>	71-112	14-21	2-4	15-18	15-18
<i>Sky location $\leq 0.1 \text{ deg}^2$</i>	22-51	4-8	≤ 1	5-8	5-8
<i>Total EMRIs detected</i>	800	35	20	15	15
<i>WD binaries detected (resolved)</i>	$4 \cdot 10^4$	$7 \cdot 10^3$	$5 \cdot 10^3$	$5 \cdot 10^3$	$5 \cdot 10^3$
<i>WD binaries w/ 3D location</i>	$8 \cdot 10^3$	$8 \cdot 10^2$	$3 \cdot 10^2$	$1.5 \cdot 10^2$	$1.5 \cdot 10^2$
<i>Stochastic Background Sensitivity (rel. to LISA)</i>	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.