Technical Overview of the Gravitational-Wave Mission Concept Study

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Workshop on Gravitational-Wave Mission Concepts

20-21 December 2011

Outline

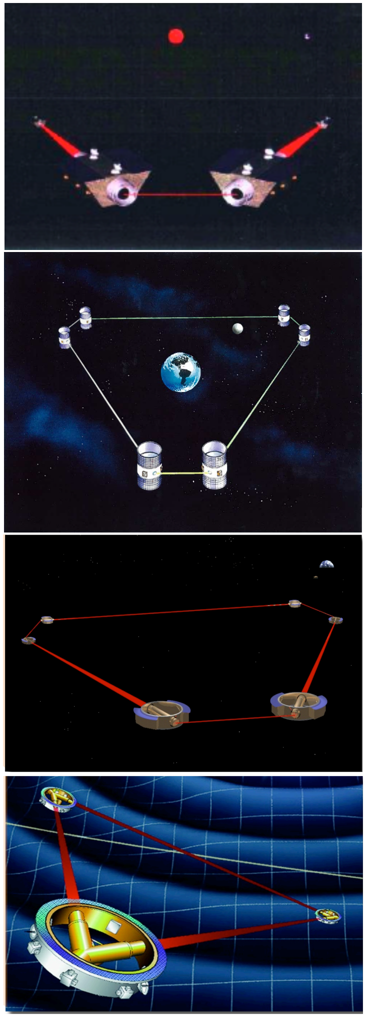
- Goals of the Study
- The context of the Study
- Analysis of mission concepts
- Workshop organization
- After the Workshop

Goals of the Study

- Develop mission concepts that will accomplish some or all of the LISA science objectives at lower cost points.
- Explore alternative mission architectures and technical solutions (e.g., instrument concepts, enabling technologies).
- Assess the technical readiness and risk of the mission concepts, instruments and technologies.
- Report the options for science return at multiple cost points .

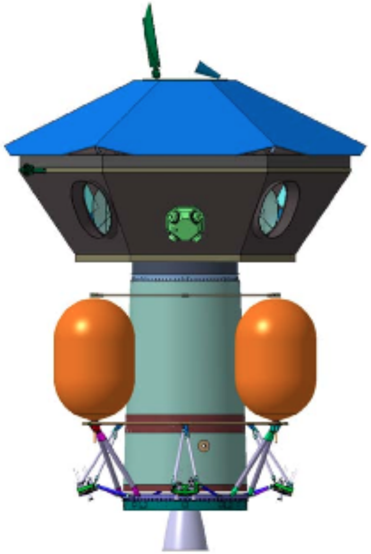
Context of the Study – A Brief History of LISA

- 1972 - A dinner conversation: Weiss, Bender, Misner and Pound
- 1985 – LAGOS Concept (Faller, Bender, Hall, Hils and Vincent)
- 1993 – LISAG - ESA M3 study: six S/C LISA & Sagittarius
- 1997 - JPL Team-X Study: 3 S/C LISA
- 2001-2015 - LISA Pathfinder and ST-7 DRS
- 2001 – NASA/ESA project began
- 2003 – TRIP Review
- 2005 – GSFC AETD Review
- 2007 – NRC BEPAC Review
- 2009 – Astro2010 Review
- 2011 – NASA/ESA partnership ended
- 2011 – New Gravitational-Wave Observer (NGO) started



Context of the Study – Activities in Europe

- LISA Pathfinder
  - Demonstration of space-based GW technology, in late stages of I&T
  - Paul McNamara will describe
- NGO
  - Candidate for ESA's Cosmic Visions L1, decision in April/May 2012, before the end of the Study!
  - Stefano Vitale will describe
- Technology development
  - Inertial sensor electronics, charge control
  - Optical system
  - Laser system
  - Pointing and point-ahead mechanisms



Context of the Study – Decadals and NRC Reviews

- 2000 – Astronomy and Astrophysics for the New Millennium
  - LISA ranked as the next new start after GLAST/Fermi in the Moderate Initiatives
- 2003 – Connecting Quarks with Cosmos
  - LISA recommended for "exploring the basic laws of physics"
- 2007 – Beyond Einstein Program Assessment Review
  - LISA "should be the flagship mission of a long-term program addressing Beyond Einstein goals"
- 2010 – New Worlds, New Horizons
  - LISA ranked behind WFIRST and Explorer Augmentation in the Large category
- 2020 – Astro2020

Astro2010 Endorsed LISA Science

- Measurements of black hole mass and spin will be important for understanding the significance of mergers in the building of galaxies.
- Detection of signals from stellar-mass compact stellar remnants as they orbit and fall into massive black holes would provide exquisitely precise tests of Einstein's theory of gravity.
- Potential for discovery of waves from unanticipated or exotic sources, such as backgrounds produced during the earliest moments of the universe or cusps associated with cosmic strings.

Panel on Particle Astrophysics and Gravitation

Table 1. Science Questions and Gravitational Wave Measurements

Science Questions	Measurements Addressing the Questions
How do cosmic structures form and evolve?	Tracing galaxy-merger events by detecting and recording the gravitational-wave signatures
How do black holes grow, radiate, and influence their surroundings?	Using gravitational-wave inspiral waveforms to map the gravitational fields of black holes.
What were the first objects to light up the universe, and when did they do it?	Identifying the first generation of star formation through gravitational waves from core-collapse events.
What are the progenitors of Type Ia supernovae and how do they explode?	Detecting and recording the gravitational wave signatures of massive-star supernovae, of the spindown of binary systems of compact objects, and of the spins of neutron stars.
How do the lives of massive stars end?	
What controls the mass, radius, and spin of compact stellar remnants?	
How did the universe begin?	Detecting and studying very-low-frequency gravitational waves that originated during the inflationary era.
Why is the universe accelerating?	Testing of general relativity—a deviation from general relativity could masquerade as an apparent acceleration—by studying strong-field gravity using gravitational waves in black hole systems, and by conducting space-based experiments that directly test general relativity

Adapted from Panel Reports, New Worlds, New Horizons (NRC 2010, http://www.nap.edu/catalog/12982.html, p. 385)

LISA Science Objectives and Investigations - 1/2

Science Objectives	Science Investigations
Understand the formation and growth of massive black holes	Search for a population of seed black holes at early epochs
	Search for remnants of the first (Pop III) stars through observation of intermediate-mass black hole captures, also at later epochs
Trace the growth and merger history of massive black holes and their host galaxies	Determine the relative importance of different black hole growth mechanisms as a function of redshift
	Determine the merger history of $1x10^4$ to $3x10^5$ $M_\odot$ black holes from the era of the earliest known quasars (*z~6*)
	Determine the merger history of $3x10^5$ to $1x10^7$ $M_\odot$ black holes at later epochs (z<6)
Explore stellar populations and dynamics in galactic nuclei	Characterize the immediate environment of MBHs in z<1 galactic nuclei from EMRI capture signals
	Study intermediate-mass black holes from their capture signals
	Improve our understanding of stars and gas in the vicinity of galactic black holes using coordinated gravitational and electromagnetic observations

LISA Science Objectives and Investigations - 2/2

Science Objectives	Science Investigations
Survey compact stellar-mass binaries and study the morphology of the Galaxy	Elucidate the formation and evolution of Galactic stellar-mass binaries: constrain the diffuse extragalactic foreground
	Determine the spatial distribution of stellar mass binaries in the Milky Way and environs
	Improve our understanding of white dwarfs, their masses, and their interactions in binaries and enable combined gravitational and electromagnetic observations
Confront General Relativity with observations	Detect gravitational waves directly and measure their properties precisely
	Test whether the central massive objects in galactic nuclei are the black holes of General Relativity
	Make precision tests of dynamical strong-field gravity
Probe new physics and cosmology with gravitational waves	Study cosmic expansion history, geometry and dark energy using precise gravitationally calibrated distances in cases where redshifts are measured
	Measure the spectrum of, or set bounds on, cosmological backgrounds
Search for unforeseen sources of gravitational waves	

Analysis of Concepts – 1/2

Mission Element	Factors
Concept	Do we understand it? Novel ideas Proposal type, number of concepts
Science	Sensitivity curve (claimed & estimated) Horizons for MBH binaries, EMRIs, compact binaries Number of events of each type Parameter estimation for MBH binaries Error budget Robustness
Payload	Instrument requirements Master Equipment List Mass and power
Spacecraft	How many different ones? Subsystem requirements Master Equipment List Mass and power

Analysis of Concepts – 2/2

Mission Element	Factors
Mission design	Orbits: interior angles of constellation, doppler rates, etc Trajectories: delta-v, cruise time Launch vehicle
Operations	Length of science operations Comm strategy, assets and schedule Downlink budget Science ops, GI program, data analysis, archiving, distribution
Technical readiness	TRLs Technology development
Risk	Science risk Technical development risk Redundancy Programmatic (cost and schedule)
Cost and schedule	Contingency 70% probability of success

Analysis of Concepts

Group	Group 1 (No drag-free)		Group 2 (Geocentric)				Group 3 (LISA-like)					Group 4 (Other)			Instrument Concepts/Technologies		
Proposal Number	**3**	**16**	**4**	**17**	**7**	**10**	**11**	**14**	**15**	**12**	**13**	**5**	**8**	**9**	**6**	**1**	**2**
Lead Author	**Folkner**	**McKenzie**	**Tinto**	**McWilliams**	**Hellings**	**Conklin**	**Shao**	**Stebbins**	**Livas**	**Thorpe**	**Baker**	**Saif**	**Yu**	**Gulian**	**de Vine**	**Fritz**	**McIntyre**
Acronym		**LAGRANGE**	**GEOGRAWI**	**GADFLI**	**OMEGA**	**LAGRANGE**		**SGO High**	**SGO Mid**	**SGO Low**	**SGO Lowest**	**InSpRL**					
Novel Idea	Long baseline, no drag-free	No drag-free, geometric reduction	Geocentric orbit, single spherical TM	Smaller telescope and laser, smaller satellites	Novel trajectories, Explorer cost approach	Earth-Moon Lagrange points, spherical test mass, grating	Formation-flying payload, torsion suspension for test mass	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	Atom interferometry	Atom inteferometer for inertial sensor	Electrons in superconductor	Replace optical bench with photonic integrated circuit		
Proposal Type	Concept	Concept	Concept	Concept	Concept	Concept	Instrument	Concept	Concept	Concept	Concept	Concept	Instrument	Concept	Instrument	Technology	Technology
Cost Estimate (FY12$M)	$924	$1,120	$1,122	$1,200	$300	$950	$990	$1,660	$1,440	$1,410	$1,190	$444/$678			N/A	N/A	N/A
Number of Alternates	2	2	3	3	1	1	1	1	1	1	1	2					
Arm length (km)	2.6 x 10^{8}	2.09 x 10^{7}	7.3 x 10^{4}	7.3 x 10^{4}	1.04 x 10^{6}	6.7 x 10^{5}	5.0 x 10^{6}	5.0 x 10^{6}	1.0 x 10^{6}	1.0 x 10^{6}	2.0 x 10^{6}	0.5/500					
Spacecraft/Constellation	3/equilateral triangle //4/square	3/isosceles triangle	3/equilateral triangle	3/equilateral triangle	6/triangle	3/equilateral triangle	3+3/triangle	3/equilateral triangle	3/equilateral triangle	4/triangle (60-deg Vee)	3/In-line: Folded SyZyGy	1//2/in-line		1			
Orbit	Heliocentric	Heliocentric/ Earth-Sun L2	Geostationary	Equatorial, geostationary	600,000 km geocentric, earth-moon plane (retrograde)	Earth-Moon L3, L4, L5	LISA-like	22° heliocentric, earth-trailing	9° heliocentric, earth drift-away	9° heliocentric, earth drift-away	≤9° heliocentric, earth drift-away	1200 km above geostationary	LISA-like	Not specified.	Comparable to LISA		
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	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		Direct injection to escape with recircularization and out-of-plane boost, 14 months	Direct injection to escape with out-of-plane boost, 21 months	Direct injection to drift away, with out-of-plane boosts, 21 months	Direct injection to escape, with small delta-v for S/C separation, 18 months	Not specified	LISA-like	Not specified			
Inertial Reference	None	GOCE accelerometer	Single, spherical	Two, rectangular	Single, rectangular	Single, spherical	Single, torsion pendulum	Two, rectangular	Two, rectangular	Single, rectangular	Single, rectangular	Atom interferometers					
Displacement Measurement	3 arms, 6 links	2 arms, 4 links	3 arms, 6 links	3 arms, 6 links				3 arms, 6 links	3 arms, 6 links	2 arms, 4 links	2 unequal arms, 4 links						
Launch vehicle		Falcon 9 Block 3		Falcon 9 Block 2	Small Delta or Falcon 9	Falcon 9	Falcon 9	Shared Falcon Heavy	Falcon 9 Block 3	Shared Falcon 9 Heavy	Falcon 9 Block 2	Falcon					
Baseline/Extended Mission Duration	3 arms, 6 links	2		2	3	5	5	5/3.5	2/2	2/2	2/0						
Telescope Diameter (cm)	30	20/40	Same as LISA	15	30	20		40	25	25	25						
Laser power out of telescope, EOL (W)	1	1.2	Same as LISA	0.7	0.7	1		1.2	0.7	0.7	0.7	10-20					
Sensitivity curve	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes			Comparable to LISA		
Residual acceleration (m/s^{2}/$Hz^{1/2}$)	1.0 x 10^{-13}	4.4 x 10^{-14} (0.001/f)^0.75	3.0 x 10^{-15}	3.0 x 10^{-15}	3.0 x 10^{-15}	3.0 x 10^{-15}		3.0 x 10^{-15}	3.0 x 10^{-15}	3.0 x 10^{-15}	3.0 x 10^{-15}						
Displacement sensitivity (m/$Hz^{1/2}$)	550 x 10^{-12}	150 x 10^{-12}	7 x 10^{-12}	8 x 10^{-12}	5 x 10^{-12}	5 x 10^{-12}		8 x 10^{-12}	8 x 10^{-12}	8 x 10^{-12}	8 x 10^{-12}				5 x 10^{-12}		

Organization of the Workshop

- Goal: identify 3 concepts for Team-X studies from 15 instrument and mission concept submissions.
- Concepts should explore the design space.
- Concepts arranged in 4 groups
  - Group 1: Non-drag-free concepts (2)
  - Group 2: Geocentric orbits (4)
  - Group 3: LISA-like (5)
  - Group 4: Other (3)
- Strategy (implemented in the agenda)
  - Hear about each in a group
  - Select the best of each group
  - Pick three from the Final Four

After the Workshop

- Progress reports at AAS in Austin and April APS in Atlanta. Final report at AAS in Anchorage.
- Core Team and the CST analyze concepts, prepare for Team-X studies
- Team-X studies in March
- Final report in June
  - Survey the design choices
  - Evaluate the cost and science trade-offs
  - Three Team-X studies with costing

Team-X

- A cross-functional multidisciplinary team of engineers utilizes concurrent engineering methodologies to complete rapid design, analysis and evaluation of mission concept designs.
- Experienced flight-project engineers are co-located in the Project Design Center to perform architecture, mission, and instrument design studies in real time.
- The Project Design Center is a state-of-the-art facility consisting of networked workstations, a supporting data management infrastructure, large interactive graphic displays, computer modeling and simulation tools, historical data repositories and a shared project model that the design team updates.

Summary

- Studying architecture choices and science and cost consequences to find lower alternate mission concepts.
- In the context of
  - The long history of LISA
  - The activities taking place today in Europe and the U.S., notably LISA Pathfinder
  - Decadals, NRC studies and reviews, past and future
  - The near term funding prospects
- The Core Team, CST and Team-X will extensively analyze candidate mission concepts.
- This Workshop will set the direction for the remainder of the study.

Backup

Concept Characteristics

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