Space-based Gravitational-wave Observatories (SGOs)

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https://www.elisascience.org/
Artist's impression of eLISA satellite. Credit: AEI/MM/exozet/NASA/Henze

IEEE AVFOP Conference: Atlanta, GA 11 Nov 2014
Outline

• Why are SGOs important?
• Basic GW physics
• Science
• Mission description
• How it works – more detail
• Program status
• Summary
Why is this important?

The Gravitational Wave Spectrum

Sources

- Richest set of sources
- ESA L3 (2034 launch)

Wave period

- GW imprint on inflation age of universe
- Stochastic background years
- Compact objects captured by Supermassive Black Holes hours
- Compact Binaries in our Galaxy & beyond sec
- Rotating NS, Supernovae ms

Log(frequency)

- Cosmic microwave background polarization
- Pulsar Timing
- Space Interferometers
- Terrestrial interferometers

Detectors

- BICEP-2/Planck Detection 2018-20?
- Detection 2017-18?

Image credit: NASA
Measurement Challenge

- **Lowest order radiator is a quadrupole**
  - Dipole radiation forbidden by conservation of momentum
  - Simplest quadrupole is a pair of masses rotating around their common center of mass (a “dumbell”)

- **What is to be measured**
  - Time-varying strain ($\Delta L/L$) in spacetime typically $\sim 10^{-21} /\sqrt{\text{Hz}} = 10 \text{ pm}/10 \text{ Gm}/\sqrt{\text{Hz}}$
  - Variations are periodic or quasi-periodic between $10^{-4}$ and 1 Hz, observable for months to centuries

- **Measurement concept**
  - Measure distance changes between free-falling mirrors
    - Test masses are the mirrors
    - Interferometric measurement of distance changes
  - Preferred measurement conditions
    - A long measurement path to make $\Delta L$ large
    - A very quiet place to avoid disturbances to the test masses: SPACE!
Science Overview

\[ \log_{10}(S_n/\text{Hz}^{-1/2}) \]

-14

-5 -4 -3 -2 -1 0

\[ \log_{10}[f/\text{Hz}] \]

(\(10^6 + 10^6\) \(M_\odot\) MBH, \(z=1\))

sensitivity

verification

binaries

SGO High

(\(10^5 + 10^5\) \(M_\odot\) MBH, \(z=1\))

(\(10 + 10^6\) \(M_\odot\) EMRI, \(z=0.2\))
Science Overview

- Formation and growth of massive black holes: galaxy mergers
- Dynamical strong-field gravity
- Merger rates of 10s -100s yr\(^{-1}\) expected

Supermassive Black Hole Mergers

\[(10^6 + 10^6) M_\odot \text{ MBH, } z=1\]

\[(10^5 + 10^5) M_\odot \text{ MBH, } z=1\]

\[(10 + 10^6) M_\odot \text{ EMRI, } z=0.2\]

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Science Overview

- Formation and growth of massive black holes: galaxy mergers
- Dynamical strong-field gravity
- Merger rates of 10s - 100s yr\(^{-1}\) expected

Supermassive Black Hole Mergers
- Population of galactic ultra-compact binaries
- Evolution of ultra-compact binaries
- >10\(^4\) sources expected

Galactic close compact binaries
- Population of galactic ultra-compact binaries
- Evolution of ultra-compact binaries
- >10\(^4\) sources expected

\[(10^6+10^6) \, M_\odot \text{ MBH, } z=1\]

\[(10^5+10^5) \, M_\odot \text{ MBH, } z=1\]

\[(10+10^6) \, M_\odot \text{ EMRI, } z=0.2\]

\[10^\log_{10}[f/\text{Hz}]]
Science Overview

- **Formation and growth of massive black holes: galaxy mergers**
- **Dynamical strong-field gravity**
- **Merger rates of 10s -100s yr\(^{-1}\) expected**

- **Supermassive Black Hole Mergers**
  - Population of galactic ultra-compact binaries
  - Evolution of ultra-compact binaries
  - >10\(^4\) sources expected

- **Galactic close compact binaries**
  - Population of galactic ultra-compact binaries
  - Evolution of ultra-compact binaries
  - >10\(^4\) sources expected

- **Extreme Mass Ratio Inspirals (EMRIs)**
  - Precision tests of GR in strong-field regime
  - Event rates uncertain

![Graph](image-url)
Science Overview

Supermassive Black Hole Mergers
- Formation and growth of massive black holes: galaxy mergers
- Dynamical strong-field gravity
- Merger rates of 10s -100s yr⁻¹ expected

Galactic close compact binaries
- Population of galactic ultra-compact binaries
- Evolution of ultra-compact binaries
- >10⁴ sources expected

Extreme Mass Ratio Inspirals (EMRIs)
- Cosmological gravitational wave background
- Superstring bursts
- Precision tests of GR in strong-field regime
- Event rates uncertain

New Physics / Unexpected Sources
- Cosmological gravitational wave background
- Superstring bursts

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Not just detection...

- Detection already happened (direct + indirect…)
- Study growth of cosmic structure
- Test of GR in strong field limit
- Precise parameter estimation, including distances

<table>
<thead>
<tr>
<th>Number of Sources Observed</th>
<th>Classic LISA</th>
<th>SGO-Mid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massive Black Hole Mergers</td>
<td>108-230</td>
<td>41-52</td>
</tr>
<tr>
<td>Detected @ Z&gt;10</td>
<td>3-57</td>
<td>1-4</td>
</tr>
<tr>
<td>Both mass errors &lt; 1%</td>
<td>67-171</td>
<td>18-42</td>
</tr>
<tr>
<td>One spine error &lt; 1%</td>
<td>49-130</td>
<td>11-27</td>
</tr>
<tr>
<td>Both spin errors &lt; 1%</td>
<td>1-17</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Distance error &lt; 3%</td>
<td>81-108</td>
<td>12-22</td>
</tr>
<tr>
<td>Sky location &lt; 1 deg(^2)</td>
<td>71-112</td>
<td>14-21</td>
</tr>
<tr>
<td>Sky location &lt; 0.1 deg(^2)</td>
<td>22-51</td>
<td>4-8</td>
</tr>
<tr>
<td>Extreme-Mass-Ratio-Inspirals</td>
<td>800</td>
<td>35</td>
</tr>
<tr>
<td>Resolved Ultra Compact Binaries</td>
<td>40,000</td>
<td>7,000</td>
</tr>
<tr>
<td>Interacting UCB’s</td>
<td>1,300</td>
<td>100</td>
</tr>
<tr>
<td>Detached UCB’s</td>
<td>40,000</td>
<td>8,000</td>
</tr>
<tr>
<td>Sky location &lt; 1 deg(^2)</td>
<td>13,000</td>
<td>2,000</td>
</tr>
<tr>
<td>Sky loc &lt; 0.1 deg(^2) + distance error &lt; 10%</td>
<td>8,000</td>
<td>800</td>
</tr>
<tr>
<td>Stochasitc Bkgnd relative to LISA</td>
<td>1.00</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table courtesy Robin T. Stebbins
With assistance from R. Lang, N. Cornish, and S. Larson
SGO Mission Concepts

SGO High

LISA concept with single-agency costing and all know cost reductions.

SGO Mid

Minimum-cost three arm design with acceptable Decadal-survey science return.

SGO Low

Two-arm version of SGO Mid

SGO Lowest

Minimum two-arm mission

Study final report is available here: http://pcos.gsfc.nasa.gov/studies/gravitational-wave-mission.php
How the science instrumentation works

• The Constellation is the instrument
  – Orbits passively maintain formation
  – “Sciencecraft” house test masses and interferometry

• Interferometer Measurement System (IMS)
  – Active transponder, phase-locked laser ranging system
  – Phasemeter records fringe signal
  – Laser frequency noise correction by pre-stabilization and post processing

• Disturbance Reduction System (DRS)
  – Free-falling test masses don’t contact the sciencecraft
  – Drag-free stationkeeping reduces sciencecraft test mass relative motion and force gradients
  – Design to limit thermal, magnetic, electrostatic, mechanical, self-gravity disturbances

\[
\begin{align*}
S_+ &= \frac{\sqrt{3}}{2} X \\
S_x &= \frac{1}{2} (X + 2Y) \\
S_o &= \frac{1}{3} (X + Y + Z)
\end{align*}
\]
Payload Integrated with Bus

Payload systems
- Interferometer Measurement System (IMS)
  - Laser
  - Telescope
  - Optical bench
- Disturbance Reduction System (DRS)
  - Gravitational Reference Sensor (GRS)
  - µN thrusters
  - Control laws

Full Spacecraft Bus

(Note: solar array not shown)

Optical bench mounted in Telescope Assembly

Telescope Assembly

DRS Detail

colloidal µN thrusters

GRS

IMS Detail

Payload systems

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Prop Module/Cruise Configuration

Propulsion Module:
- Bi-prop design
- $\Delta v \sim 200$ m/sec capability
- 6 coarse sun sensors
- 2 star tracker heads
- 2 omni antennas
Mission Timeline

Falcon Heavy EELV

Cruise Trajectories

Science Orbits

Doppler/Arm length changes

Stack in Falcon 5 m PLF

Acquisition

Mission Timeline

24 months science operations: orbits optimized for 48 months
Inter-Spacecraft Distance Measurement

- Test-mass to test-mass measured in 3 parts:
  - $2 \times$ test-mass to spacecraft measurements (short-arm: LPF tests this)
  - $1 \times$ spacecraft to spacecraft interferometer (long-arm)

$$d_{12} = 1 \times 10^9 \text{ m}$$
Interferometry Measurement System

Seed laser with LPF heritage  Cavity pre-stabilization  Same noise with tuning  TDI demonstrated with realistic delays using electronic signals

Optical bench with LPF heritage  Low noise quad detector  LISA Phasemeter development meets multiple requirements

Pointing mechanisms tested  Prototype telescope spacer demonstrates dimensional stability and for studying scattered/stray light
Front-end Phasemeter Architecture

100 pW from far spacecraft
100 μW from local oscillator

- Low noise quad photodiode* serves two functions
  - Differential wavefront sensing of quadrant pairs determines S/C pointing
  - Sum is main science signal

Weak Light Phase Locking

SGO received power budget:
θ ~ 2.4 λ/D ~ 13 µradian

\[ \lambda = 1064 \text{ nm} \]
\[ D = 20 \text{ cm} \]

\[ \frac{20 \text{ cm}}{13 \text{ km}} \approx 2.5 \times 10^{-10} \]

\[ P_{TX} = 0.5 \text{ W} \rightarrow P_{RX} \approx 125 \text{ pW} \]

- Phase lock Successful at lower power than requirements
  - Master Oscillator = 1 mW vs 3-10 mW
  - Slave laser power = 13pW vs ~ 100 pW
  - Laser power step attenuated– not variable

- Shot noise limit for 13pW = 1.3x10^{-4} rad/√Hz

Paul W McNamara 2005 Class. Quantum Grav. 22 S243-S247
Frequency Noise Suppression: Time Delay Interferometry (TDI)

- An interferometer arm length mismatch $\Delta L$ will allow frequency noise to mimic a displacement noise, $\delta x$.
- A sensitivity requirement of $\delta x < 10 \text{ pm}/\sqrt{\text{Hz}}$ implies that the interferometer arm lengths must be equal to better than 100 m.
- LISA arm lengths may differ by as much as 1% or 10,000 km!

\[
\delta x = \frac{\delta \nu \Delta L}{v}
\]

1. Unequal-arm Michelson interferometer
   - Output corrupted by laser frequency noise
2. Equal-arm (Sagnac) interferometer (TDI combination X)
   - Output immune to laser frequency noise: synthesized equal arms
3. Constant spacecraft velocity introduces an arm length mismatch to the synthesized interferometer.
   - $\Delta L \sim 20 \text{m/s} \times 6.7 \text{ s} \sim 130 \text{ m}$
   - Output immune to laser frequency noise: synthesized equal arms

Laser frequency noise can be reduced with margin

- Laser frequency noise suppression of \( \sim 10^9 \)
- Clock noise suppression of \( \sim 6 \times 10^4 \)

Mitryck, et al. PRD 86, 122006 (2012) testbed with electronic delays

Laser frequency noise can be reduced with margin

de Vine, et al. PRL 104, 211103 (2010) static test bed
Inter-Sciencecraft Signaling:
Clock noise and ranging

- **Requirement 1:**
  - **Implementation:** clock-coherent side tone
    - 8 GHz nominal sidetones (~2 MHz offsets in send vs receive)
    - 1% of power in sidebands
    - Sideband-sideband beat detection
- **Requirement 2:**
  - **Implementation:** inter-spacecraft comm
    - 1% modulation on main science beam (carrier)
    - Manchester encoding (2 Mchips/s)
    - 13-bit Gold code yields 2 m range accuracy
  - ~100 bps required (400 kbps capable)

Phase modulator supports clock noise rqmts

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**Diagram:**
- Ultra-stable oscillator (USO) modulated onto main science beam
- Sideband-sideband beatnote from far sciencecraft recovered by phasemeter
- Laser
- Fiber-coupled electro-optic modulator (EOM)

**Equations:**
\[ f_{LSS} = f_{Doppler} + (f_{mod} - f'_{mod}) \]
\[ f_{USS} = f_{Doppler} - (f_{mod} - f'_{mod}) \]

**Figure:**
- Graph showing phase vs frequency
- Three unique frequencies for \( f_{mod} \neq f'_{mod} \)
- Using sideband-sideband beatnotes (instead of carrier-sideband) allows high modulation frequency and low photoreceiver BW
Instrument Performance

• The instrument performance is determined by:
  – Displacement noise from the Interferometric Measurement System (IMS)
  – Acceleration noise from the Disturbance Reduction System (DRS)
  – Arm Length \(1 \times 10^6\) km

• The arm length also determines the instrument response function and is optimized for the science requirements.

Summary of DRS Subsystem allocations

<table>
<thead>
<tr>
<th>Effect</th>
<th>Total per group</th>
<th>Per group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Acceleration noise Budget</td>
<td>30.0</td>
<td></td>
</tr>
<tr>
<td>Total of subsystem allocations</td>
<td>19.5</td>
<td></td>
</tr>
<tr>
<td>Disturbance Groups</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrostatics</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>Brownian</td>
<td>9.1</td>
<td></td>
</tr>
<tr>
<td>Spacecraft magnetic</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>Spacecraft coupling</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>Spacecraft cross coupling</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Interplanetary Magnetic</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>Mise small effects</td>
<td>4.0</td>
<td></td>
</tr>
</tbody>
</table>

Summary of IMS subsystem noise allocations

<table>
<thead>
<tr>
<th>Effect</th>
<th>Total per group (pm/√Hz)</th>
<th>Sub-Noise Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total IMS Error/Noise Budget</td>
<td>12.0</td>
<td></td>
</tr>
<tr>
<td>Total of subsystem allocations</td>
<td>11.7</td>
<td></td>
</tr>
<tr>
<td>Subsystem Allocations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shot noise</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>Pathlength noise</td>
<td>7.0</td>
<td></td>
</tr>
<tr>
<td>Pointing Errors</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>Telescope pathlength stability</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Optical bench pathlength stability</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Measurement noise</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>Photoreceiver errors</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Residual laser frequency noise</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Residual clock frequency noise</td>
<td>3</td>
<td></td>
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<tr>
<td>Phasemeter noise</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Intensity noise</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Phase reconstruction</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>straylight</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
Instrument Performance

- The instrument performance is determined by:
  - Displacement noise from the Interferometric Measurement System (IMS)
  - Acceleration noise from the Disturbance Reduction System (DRS)
  - Arm Length (1 x 10^6 km)

- The arm length also determines the instrument response function and is optimized for the science requirements.

LISA Pathfinder to validate noise model
LPF Status

- Propulsion module complete
- Spacecraft bus near complete
  - cold-gas thruster system currently being integrated
- Major system tests complete
  - thermal
  - electro-magnetic
  - vibration/shock
- On-track for July 2015 launch
  - Lissajous orbit around L1
  - 90 days LTP Ops
  - 90 days DRS Ops
Summary

• Space-based gravitational-wave work continues
  – Science receives top ratings in reviews
  – LPF is progressing for launch in July 2015
  – Issue is funding, not technology

• Current opportunity is partnership with ESA on an L3 mission for 2034 launch
  – 20+ year scientific collaboration on both sides of the Atlantic

• Successful LISA Pathfinder technology demo required

• US technology development targeted at TRL-5 level for ~ 2020 for key technologies
Context and Status of SGO-Mid

• No official project office at NASA
  – Study team under Physics of the Cosmos Program office

• No LISA International Science Team (LIST)
  – University engagement is critical
  – Community engagement through PhysPAG

• Technology development for L3 mission contribution
  – laser -- photoreceiver
  – telescope -- micro-newton thruster
  – phasemeter

• Participation on LPF science team
  – ST-7 experiments -- mission data analysis operations

• Developing a reference mission and science case
SGO-High vs Mid (vs LISA baseline)

**SGO High differs from LISA by:**
- Preserves all LISA performance parameters
- Single agency cost model (not joint mission)
- Lower cost launch vehicle (shared launch on a Falcon Heavy)
- Demonstrated improvements in photoreceiver performance
- More economical trajectories to the operational orbits

**SGO Mid differs from LISA by:**
- Detector arm length reduced from 5 Gm to 1 Gm
- Science operations reduced from 5 to 2 years.
- Nominal starting distance from Earth is reduced by about a factor of 2.5 to a 9-degree trailing orbit.
- Telescope diameter is reduced from 40 to 25 cm, and the laser power out of the telescope is reduced from 1.2 to 0.7 W (end of life).
- In-field guiding is used instead of articulating the entire optical assembly
# LISA vs SGO-high vs SGO-mid

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LISA Concept</th>
<th>SGO High</th>
<th>SGO Mid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm length (meters)</td>
<td>$5 \times 10^9$</td>
<td>$5 \times 10^9$</td>
<td>$1 \times 10^9$</td>
</tr>
<tr>
<td>Constellation</td>
<td>Triangle</td>
<td>Triangle</td>
<td>Triangle</td>
</tr>
<tr>
<td>Orbit</td>
<td>22° heliocentric, earth-trailing</td>
<td>22° heliocentric, earth-trailing</td>
<td>Heliocentric, earth-trailing, drifting-away 9°- 21°</td>
</tr>
<tr>
<td>Trajectory</td>
<td>Direct injection to escape, 14 months</td>
<td>Direct injection to escape, 14 months</td>
<td>Direct injection to escape, 18 months</td>
</tr>
<tr>
<td>Interferometer configuration</td>
<td>3 arms, 6 links</td>
<td>3 arms, 6 links</td>
<td>3 arms, 6 links</td>
</tr>
<tr>
<td>Launch vehicle</td>
<td>Medium EELV (e.g., Atlas V 431)</td>
<td>Medium EELV (e.g., Falcon Heavy shared launch)</td>
<td>Medium EELV (e.g., Falcon 9 Block 3)</td>
</tr>
<tr>
<td>Baseline/Extended Mission Duration (years)</td>
<td>5/3.5</td>
<td>5/3.5</td>
<td>2/2</td>
</tr>
<tr>
<td>Telescope Diameter (cm)</td>
<td>40</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>Laser power out of telescope end of life (W)</td>
<td>1.2</td>
<td>1.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Measurement system modifications</td>
<td>Baseline/Reference</td>
<td>Baseline/Reference (Same as LISA Concept)</td>
<td>In-field guiding, UV-LEDs, no pointing</td>
</tr>
<tr>
<td>Motivation:</td>
<td>Science performance, two agencies</td>
<td>LISA performance with all known economies</td>
<td>Lowest cost 6 links</td>
</tr>
<tr>
<td>Approximate Cost (FY12 $B)</td>
<td>1.82</td>
<td>1.66</td>
<td>1.40</td>
</tr>
</tbody>
</table>
Orbits/trajectory

- **2 year drift-away**
  - ~ 6 deg/year drift rate starting at 9 degrees
  - 2 year end of mission similar to nominal SGO-high orbital station (but orbit optimized for 4 years)
  - EOL communications requirements similar to SGO-high

- **Stable constellation geometry simplifies measurement**
  - $\Delta L/L \sim 0.010$, relative to $10^6$ km
  - $\Delta \alpha \sim +/- 0.6^\circ$ relative to 60°
  - $\Delta v \sim +/- 1.6$ m/s
  - Point ahead ~ +/- 0.55 urad out of plane
  - Point ahead ~ +/- 0.004 urad in plane, relative to ~ -0.3 urad

- **18 month trajectory from escape**
  - For shared launch, second stage has 2 restarts
  - Drop off shared package at GTO, then go to escape
  - Optimized $\Delta V \sim 130$ m/s (each), ~ 200 m/s for extended launch window and margin
Operations / Science Data

• Simple Operations
  – No instrument pointing or scheduling of observation time
  – LISA observes “all the sky, all the time”
    o Scheduled interruptions approximately every 2 weeks for HGA re-pointing and to switch laser offset frequencies

• Routine Communications Strategy
  – Ka-Band downlink every 2 days with one spacecraft (6 days for the constellation)
  – Up to 8-hr contacts with DSN 34m at 90 kbps (allows downlink of 6 days telemetry generated at 5 kbps)
  – Special merger events may require more frequent contact and continuous operation for up to ~ 4 days to preempt schedule interruptions and com

• Science Data
  – 5 kbps = 1 kbps science data + 4 kbps science housekeeping and engineering data, 15 kbps total for the constellation
  – No on-board science processing
  – Mission Ops Team forwards downlinked data to Science Data Centers
Countering Solar Radiation Pressure

Drag-free control

Thrusters

Satellite

Position sensor

Test mass

Control loop

Courtesy K. Danzmann