Gravitational wave detectors and detection in the year 2012

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Goals and Outline

- Goal: anticipate spectrum of detector sensitivities when LISA becomes science operational

- Outline
  - Resonant Acoustic Detectors
  - Interferometers
  - Pulsar Timing Arrays
  - Conclusions
Resonant Acoustic Detectors

- How they work
- Where they’re going
Detecting Gravitational Waves: “Bar” Detectors

Auriga “Bar” Detector, Italy
Bar Detectors Worldwide

- ALLEGRO (USA)
- Nautilus (Italy)
- Explorer (Italy)
Principal technical challenge: *in situ* low-noise amplifiers

- On-resonance mechanical response larger than off-resonance response
- Ratio signal to (amplifier) noise larger for on resonance gravitational wave power than for off resonance power
- Leads to effective narrowing of response
- Current best sensitivity
  - $\sim 10^{-22}$ in 1 Hz bandwidth near 900 Hz

Measured strain noise spectral density of ALLEGRO and the various noise contributions which are predicted from the noise model of the detector.
- Measured total noise,
- antenna brownian,
- transducer brownian,
- transducer electrical loss,
- SQUID white noise,
- SQUID back action.
Spherical Detectors

• Why spherical? “Omni”:
  – Equal sensitivity to waves from any incident direction
  – Equal sensitivity to either wave polarization
  – Ability to discern incident wave polarization, direction

Kamerlingh Onnes Laboratory, Leiden University
“Dual” spheres for increased bandwidth

- Sphere inside a shell
  - Different resonant frequencies for inner sphere, outer shell

- Incident wave with characteristic frequency between resonant frequencies
  - Inner sphere, outer shell respond *out of phase*
  - Increased sensitivity in band between resonant frequencies

- Cf. Cerdonio et al., PRL 87 (2001) 082003
Interferometric Detectors

• How they work
• Where they’re going
Detecting Gravitational Waves: Laser Interferometry
LIGO: The Laser Interferometer Gravitational-wave Observatory

- United States effort funded by the National Science Foundation
- Two sites
  - Hanford, Washington & Livingston, Louisiana
- Construction from 1994-2000
- Commissioning from 2000 - 2002
- Operations: now!
Laser Interferometer Detectors Worldwide

- Virgo: Italy & France (3 Km arms)
- GEO: Germany & UK (600m arms)
- TAMA: Japan (300m arms)
What limits LIGO’s sensitivity?

• Initial LIGO detectors:
  – Different $f$, different limit
  – $< \sim 50\text{Hz}$: seismic noise
  – 50 - 200Hz: thermal noise
  – $> 200\text{Hz}$: “shot” noise

• Facility limits
  – Gravity gradients
  – Stray light
  – Residual gas
Building a better interferometer: Advanced LIGO

- Seismic isolation
- Thermal noise mitigation; high power optics
- High power lasers
- Tuning ifo response
High frequencies: improving photon counting statistics

- More photons, better statistics
  - Higher laser power
  - Greater light storage time in cavity
- Higher laser power
  - Initial LIGO: 6 W input to IFO
  - Advanced LIGO: 125 W input to IFO
- Greater light storage time
  - Initial LIGO: 0.84ms light storage time; 30 KW on test masses
  - Advanced LIGO: 5.0ms light storage time; 800 KW on test masses
Thermal noise contributions

- **Suspensions:**
  - $kT$ energy in taut suspension wire violin modes

- **Test masses:**
  - Normal modes: $kT$ energy in mirror modes
  - Thermoelastic: Temperature fluctuations and thermal expansion coefficient
Thermal noise mitigation: suspensions

- Noise proportional to mechanical losses: reduce losses
  - Initial LIGO: mirrors rest on cylindrical wires
  - Advanced LIGO: mirrors bonded to fused silica ribbons

- Coupling proportional to ratio wire/mirror mass
  - Initial LIGO: 11 Kg mass
  - Advanced LIGO: 40 Kg mass
Thermal noise mitigation: test masses

- Material properties problem
  - Normal modes:
    - Increase Young’s modulus: less motion for same thermal energy
  - Thermoelastic:
    - Decrease coefficient thermal expansion: less motion for same thermal fluctuations
  - Goal: single crystal sapphire
- Laser spot diameter, profile
  - Fluctuations averaged over effective spot area
  - Increase area, reduce effective fluctuation

- Initial LIGO: 25cm
- Advanced LIGO: 35cm
Seismic isolation

- Initial LIGO
  - Passive isolation: lossy springs
- Advanced LIGO
  - Active isolation
    - External hydraulic actuators
    - Suspension platform fine control
  - Multiple pendulum suspension
    - Mirrors at bottom of chain
    - Orientation forces applied at reaction masses
Sensitivity improvements: high power optics

- Radiation pressure: photons bouncing off mirrors
  - High power: high light pressure
- Mitigation: increased mirror mass
  - Smaller acceleration for same force
  - Initial LIGO: 11Kg
  - Advanced LIGO: 40Kg
Sensitivity improvements: high power optics

• More laser power, greater mirror heating
  – Differential heating changes mirror shape: “thermal lensing”
• Mitigation: bring face to constant temp.
  – Heat optic radiatively with suspended heating element
Tuning the detector response

- Undisturbed interferometer operates on dark fringe
  - Response to gravitational waves is light at output port
- Introduce partially reflecting mirror at output port
  - Make resonant cavity with rest of interferometer
  - Resonance enhances power at output port for excitation at resonant frequency
  - Higher power: lower shot noise
- Mitigate shot noise in narrow band
Advanced LIGO sensitivity goals
LISA: Laser Interferometer Space Antenna

• Three spacecraft in equilateral triangle configuration
  – 5x10^6 Km arm length
  – Solar orbit 20 deg behind Earth

• Constellation tracks changes in separation on

Courtesy Rutherford Appleton Laboratory, UK
LISA: critical technologies

- Space laser interferometry
  - Track fringes to establish separation changes with 10pm accuracy

- Inertial sensing
  - Sense deviations from inertial (geodesic) trajectories

- Micro-newton thrusters
  - Mitigate against deviations from inertial trajectories owing to, e.g., acceleration noise from solar wind
LISA technology tests

- ESA LISA Test Package (LTP), NASA Disturbance Reduction System (DRS)
  - Technology validation of space interferometry & inertial sensors, thrust technologies for drag-free flight
  - Flies on ESA SMART-2 August 2006
Conclusions, or What does this all mean?

- Ground-based “ifos” on-track for
  - Stochastic background sensitivity $\Omega h^2 < 10^{-9}$@ 100Hz
  - NS/NS binary inspiral sensitivity to $\sim 400$ Mpc
  - 2$x10$ $M_{\text{sol}}$ BH/BH binary inspiral sensitivity to $z \sim 0.5$
  - Pulsars: $\varepsilon < 10^{-6}$@ 100 Hz, $10^{-7}$@ 300 Hz, $10^{-8}$@ 1 KHz in 1 yr

- Resonant acoustic detectors
  - Could be competitive in $\sim 100$Hz bandwidth near 1 KHz

- LISA
  - Stochastic background sensitivity $\Omega h^2 < 10^{-10}$ @ 0.01Hz
  - Sensitive to galactic binaries with orbital $f > 10^{-3.5}$ Hz
  - Massive ($> 10^3 M_{\text{sol}}$) black hole binary inspiral anywhere
  - Massive ($10^{4.5} M_{\text{sol}} < M < 10^7 M_{\text{sol}}$) black hole coalescence anywhere

Gravitational Wave Astronomy!

24 April 2003

Astrophysics of Gravitational Wave Sources