Laser Interferometer
Gravitational-Wave Detectors

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Outline

► Interferometers as gravitational wave detectors
► Existing and planned detectors
► Instrumentation details (with focus on LIGO)
  ► Vacuum system
  ► Laser
  ► Optical layout
  ► Mirrors
  ► Vibration isolation
  ► Servo controls
► Interferometer operation
Demonstration Interferometer

- Laser pointer
- Diverging lens
- Mirror
- Beam splitter
- Steerable mirror
- Steerable mirror
- Screen
A Laser Interferometer as a Gravitational-Wave Detector

Measure *difference* in effective arm lengths to a fraction of a wavelength

Strain $h = \Delta L / L$

Responds to one polarization projection
Antenna Pattern of a Laser Interferometer

Directional sensitivity depends on polarization of waves

“A” polarization

“+” polarization

RMS sensitivity

A broad antenna pattern

⇒ More like a microphone than a telescope
Comparison with Resonant Gravitational-Wave Detectors

Interferometers…

► can be made larger
► are not so limited by thermal noise
► are sensitive over a wider frequency band, including low frequencies
► cost more to build and operate
Existing and Planned Detectors

- Advanced LIGO: operational ~2015
- Advanced VIRGO: operational ~2015
- GEO HF
- CLIO 100 m
- LCGT
- AIGO ?
LIGO Hanford Observatory

Located on DOE Hanford Nuclear Reservation north of Richland, Washington

Two separate interferometers (4 km and 2 km arms) coexist in the beam tubes.
LIGO Livingston Observatory

Located in a rural area of Livingston Parish east of Baton Rouge, Louisiana

One interferometer with 4 km arms
GEO 600

British-German project, located among fields near Hannover, Germany
VIRGO

French-Italian project, located near Pisa, Italy

3 km arms
LCGT (Large-scale Cryogenic Gravitational-wave Telescope)

Planned to be constructed inside Kamioka mine

Funding being requested from Japanese government
Current Sensitivities for Gravitational-Wave Strain

- Virgo (Mar 15 2007)
- GEO (3 Jun 2006)
- LHO 2km (18 Jun 2006)
- LHO 4km (13 Mar 2006)
- LLO 4km (04 Jun 2006)
Design Requirements

Even with 4-km arms, the length change due to a gravitational wave is very small, typically \( \sim 10^{-18} - 10^{-17} \) m

Wavelength of laser light = \( 10^{-6} \) m

Need a more sophisticated interferometer design to reach this sensitivity

- Add partially-transmitting mirrors to form resonant optical cavities
- Use feedback to lock mirror positions on resonance

Need to control noise sources

- Stabilize laser frequency and intensity
- Use large mirrors to reduce effect of quantum light noise
- Isolate interferometer optics from environment
LIGO Beam Tube

Stainless steel, ~1 m in diameter, welded into 2 km lengths
Serrated baffles installed inside to disperse scattered light
Baked to drive off adsorbed water vapor
Vacuum System

Hanford shown (Livingston only has one interferometer)
Vacuum System
Pre-Stabilized Laser

Based on a 10-Watt Nd:YAG laser (infrared)

Uses additional sensors and optical components to locally stabilize the frequency and intensity

Final stabilization uses feedback from average arm length
Input optics stabilize laser frequency & intensity, and select fundamental mode.

Main interferometer has three additional semi-transparent mirrors to form optical cavities.

- Pre-Stabilized Laser
- Mode cleaner
- Recyling mirror
- Beam splitter
- “Reflected” photodiode
- “Antisymmetric” photodiode
- “Pick-off” photodiode
- End mirror
No Fabry-Perot cavities, but dual recycling
Mirrors

Made of high-purity fused silica

Largest mirrors are 25 cm diameter, 10 cm thick, 10.7 kg

Surfaces polished to ~1 nm rms, some with slight curvature

Coated to reflect with extremely low scattering loss (<50 ppm)
A Mirror *in situ*
Handling High Laser Power

Use multiple photodiodes to handle increased light
   And fast shutters to protect photodiodes when lock is lost!

Compensate for radiation pressure in control software

Correct thermal lensing of mirrors by controlled heating
Vibration Isolation

Optical tables are supported on “stacks” of weights & damped springs

Wire suspension used for mirrors provides additional isolation
Active Seismic Isolation at Livingston

Hydraulic external pre-isolator (HEPI)

Signals from sensors on ground and cross-beam are blended and fed into hydraulic actuators

Provides much-needed immunity against normal daytime ground motion at Livingston
Optical cavities must be kept in resonance
   Need to control lengths to within a small fraction of a wavelength – “lock”
   Nearly all of the disturbance is from low-frequency ground vibrations

Use a clever scheme to sense and control all four length degrees of freedom
   Modulate phase of laser light at very high frequency
   Demodulate signals from photodiodes
   Disentangle contributions from different lengths, apply digital filters
   Feed back to coil-and-magnet actuators on various mirrors

Arrange for destructive interference at “antisymmetric port”
Length Sensing and Control
Feedback Basics

High frequency: servo has no effect; measure just the input disturbance

Low frequency: measure the combination of input disturbance and servo; can infer input disturbance
Summary of Noise Sources

![Graph showing initial interferometer sensitivity with various noise sources labeled, including Initial LIGO, suspension thermal, seismic, gravity gradient, noise, radiation pressure, test mass internal, residual gas, 10^-6 Torr H_2, stray light, facility, residual gas, 10^-9 Torr H_2, and strain sensitivity for the LIGO 4km interferometers with plotted data points and lines for different scenarios.]
LIGO Science Runs

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Duty factors:

- **H1**: 59 %, 74 %, 69 %, 80 %, 73 %
- **H2**: 73 %, 58 %, 63 %, 81 %, 77 %
- **L1**: 43 %, 37 %, 22 %, 74 %, 62 %

(so far)
Data Collection

Shifts manned by resident “operators” and visiting “scientific monitors”