Alignment of the LIGO Detectors
Topics

- Gravitational Waves
- Precision Measurement
- Discoveries
- Focus on Alignment
2016 was the centenary of Einstein’s General Relativity

A geometric theory:
Gravitation arises from curvature of space-time
Curvature arises from matter, energy

Bizarre, but so far completely successful, predictions:
Perihelion shift, bending of light, frame dragging, gravitational redshift, gravitational lensing, black holes, ...

One key prediction remained elusive until September 14th, 2015:
Gravitational Waves
Gravity & Curved Space-time
Gravitational Waves

Credit: LIGO/Tim Pyle
Detecting the effects

GW’s produce time-varying *transverse strain* in space
→ Monitor separations of *free test particles*

In a galaxy far far away…

*(Earth)*
Michelson interferometer

Inertial test body

Laser

Beamsplitter

Inertial test body

Lx

Ly

Photodetector

Graphic: M. Evans, MIT
LIGO’s Interferometer

- Powerful lasers (200W)
- Large 40 kg mirrors with highly reflecting coatings
- Each core optic is actively controlled in longitudinal position and tip & tilt
- The interferometer core optics are suspended so that they are vibrationally isolated and free to respond to the passing GW

In order to reduce in band injection of noise the core optic actuation is limited in range, so initial alignment must be accurate
LIGO’s Optical Configuration

- Coupled Optical Cavities:
  - Power Recycling Cavity (PRC)
  - Signal Recycling Cavity (SRC)
  - Arm Cavities

- The actuation allows for fine alignment to correct for initial alignment errors & drift

- Once the interferometer is "locked" on an optical cavity resonance, wavefront sensors can measure tip/tilt errors relative to the optical cavity axis for feedback control

Will come back to optic alignment at a later slide ...
A “small” problem...

A wave’s strength is measured by the *strain* induced in the detector,

\[ h = \frac{\Delta L}{L} \]

We can calculate expected strain at Earth:

\[ |h| \approx 4 \frac{2GM^2}{c^2r} \approx 10^{-22} \left( \frac{R}{20\text{km}} \right)^2 \left( \frac{M}{M} \right) \left( \frac{f_{\text{orbit}}}{400\text{Hz}} \right)^2 \left( \frac{100\text{Mpc}}{r} \right) \]

If we make our interferometer arms 4,000 meters long,

\[ L = h \times L \approx 10^{-22} \times 4,000 \text{m} \approx 4 \times 10^{19} \text{m} \]

*A ten-thousandth the size of an atomic nucleus*
First direct detection of the inspiral and coalescence of a Black Hole Pair (14 Sep 2015) GW150914

29M☉ and 36M☉ black holes 1.3 billion light years away inspiral and merge, emitting 3M☉ of gravitational wave energy and briefly “outshining” the entire universe.

the LASER Interferometer Gravitational-wave Observatory

Network Aperture Synthesis and EM Source Follow-up

Each detector is ~omnidirectional

Arrival time triangulation

Sky map

X-ray, γ-ray follow-up

Optical follow-up

Palomar Transient Factory

IWAA, 10 October 2018
Source “Triangulation”

- **Interferometer Angular Orientation**
  - Sensitivity changes only in 2\textsuperscript{nd} order to arm deviation from orthogonality
  - Coincident sensitivity changes only in 2\textsuperscript{nd} order relative to angular misalignments
  - 0.5 deg error in either arm orthogonality or relative orientation between the observatories results in only a ~10 ppm sensitivity decrease
  - Not just “triangulation” – also use two waveform polarizations and astrophysical constraints
Observatory-to-Observatory baseline distance accuracy

- Data timing accuracy (1 usec, derived from GPS, checked by atomic clock) x Light Speed = ~300 m
- Actual waveform (signal) timing accuracy is ~0.1 ms (SNR = 10)
- GPS provides baseline accuracy (~5 m) << required
Beam Tube Alignment

- Requirement to maintain a 1m clear aperture through the 4 km long arms
- A straight line in space varies in ellipsoidal height by 1.25 m over a 4km baseline
- A maximum deviation from straightness in inertial space of 5 mm rms
- An orthogonality between arm pairs of better than 5 mrad
- This quality of alignment comfortably meets LIGO requirements
Field assembly of the beam tubes

- The alignment of the LIGO system was done using dual-frequency differential GPS.
- The BT’s are fabricated from 3 mm thick, spirally welded 304L stainless steel in 20 m sections.
- 4x controlled interface points were defined along each arm.
- These points were identified by monuments having measured geodetic coordinates.

Beam tubes were aligned using dual-frequency differential GPS, 5 mm/4 km straightness*

Beam Tube Alignment

Final Alignment (images from)

- GPS Antenna Mounted on the Beam Tube Support Ring
- GPS Antenna Cart (equipped with linear bearings & a plumb alignment with a fixed height antenna rod) checking Position of Beam Tube "Surveyor's Nail"
Final Alignment

- Supports were aligned for the final time after installation had proceeded for three to four sections, i.e., 80 m from the installation activity.
- This was just before the beam tube became covered by cement enclosures.
Chamber Alignment

• Chambers house complex primary as well as input/output optic suspension systems / fixed mirrors

• X and Y – Azimuth “Offset” monuments were established from the existing monuments used to position the beam tubes.

• These axial and transverse positional coordinates are referenced to the global coordinates set, by conventional optical survey techniques
Initial Alignment Mode

- Adjust input beam direction to go down the beamtubes and be centered on the optics
- Pre-align ("dead reckon") main optics without optic actuation based on optical survey (100 μ rad)
- Static initial alignment of main optics using actuation (acquisition tolerance 0.5 μ rad)

Acquisition Alignment Mode (allows IFO locking)

- Holding mode: main optics are held within the acquisition alignment tolerance continuously during the lock acquisition procedure

Detection Mode

- Sense and control alignment of the IFO (3 nrad rms)
- Sense and control centering of the beams of the main optics

Diagnostic / Calibration Mode

- Provide diagnostic capability of performance
- Provide calibration procedures

The optics are freely suspended, must position to a small fraction of a wavelength of main laser light (1064 nm) in order to enable active, linear, servo-control.

Footnote explaining the dual use of the term "initial alignment": LIGO commissioners co-opted the term "initial alignment". They mean it in a different sense than is used for the "Initial Alignment System (IAS)". In G1400193, IAS is referred to as "coarse alignment".
Primary Optic placement and alignment tolerances

- Axial positioning within $\pm 3$ mm
- Transverse position within $\pm 1$ mm vertically and $\pm 2$ mm (depending on optic)
- Angular pointing to within 10% of the actuator dynamic range, which corresponds to $\pm \sim 100\mu$rad generally
1. Additional monuments placed with view of optics
2. Tables positioned and aligned using “Total” Station Theodolite & Optical Level
3. Zemax OpticStudio used for Ray Trace
4. Co-ordinates transferred in 3D CAD (SolidWorks)
5. Then once layout complete checked with rays
6. Approximate Alignment using Templates
7. On table monuments also used for Approximate Alignment
8. Precise alignment: in situ using retro-reflectors with attached target and a laser autocollimator mounted on the Total Station
9. Integrated Alignment check: Using PSL beam in low power mode projecting through particular group of optics
Key Equipment Used by LIGO

Optical level (Sokkia B2o AutoLevel)

Optical Transit Square (Brunson model 75-H)

Total Station (Sokkia Set2BII and SetX1)

Visible Laser Autocollimator (Newport LDS vector) with custom periscope.

Infrared Laser Autocollimator (4W fiber coupled laser and Davidson D-271-106)

Coordinate Measuring Machine (Romer)

Lateral Transfer Retroreflectors (PLX)

Full details at https://dcc.ligo.org/LIGO-T1000230/public
Optical Levers in aLIGO

- Serve as optical alignment references to 1 micro radian over a time span of one hour.
- To keep the interferometer aligned until lock is acquired and the interferometer’s angular feedback system can take over.
- Also very useful in case where lock is lost, can go back and look at last position of optical levers as starting point.

Cartoon of Optical Lever system

Side view of end station at LHO with Optical Levers shown

Close-up of instrumentation used in Optical Lever system

https://dcc.ligo.org/LIGO-T1000517/public
Arm Length Stabilization (ALS)

- Alignment is facilitated by locking the Fabry-Perot arm cavities independent of the rest of the interferometer with auxiliary low finesse 532 nm (doubled frequency) lasers.

- First the light of each auxiliary laser is made to resonate within each respective arm.

- Next the feedback is handed off to the cavity length actuators, so that the cavity length follows the laser frequency.

- The auxiliary lasers are then phase locked to the main science laser, so that the cavities can be tuned on and off resonance with the main laser beam.

- The cavities are only tuned onto resonance with the main beam once the rest of the interferometer is locked.

- Finally the feedback is switched from the auxiliary laser to the main laser.
Alignment Sensing & Control (ASC)

- Requirement is to suppress the angular motion of the mirrors without reintroducing noise in the gravitational-wave signal.
- The angular motion has two fundamental contributors:
  - Seismic noise transmitted to the mirrors via their suspension systems and
  - Shot noise of the sensors transmitted to the mirrors via the control system itself.
- Sensing in LIGO
  - Quadrant Photo-Diodes (QPD)
    - Relative position → pitch & yaw
  - Wavefront Sensors (WFS)
    - RF QPD yields In-Phase and Quadrature Phase pitch & yaw
    - References the optical axis of the cavity
- 26 degrees-of-freedom
  - Input beam (pos + angle)
  - 11 optics form the PRC, SRC, FP arm cavities (yaw, pitch)

IWAA, 10 October 2018
What next?

Alignment technology played a key role in opening a revolutionary new window on the Universe.

This is a new field - we’ve just scratched the surface. We have plans for increasing sensitivity to sample 100x greater volume of space.

Beyond that, we are developing concepts for bigger instruments, up to 40km in size, that can map the entire universe in gravitational waves.

Leading to New alignment challenges

T. A. Callister, M. W. Coughlin, and J. B. Kanes

LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

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Abstract

A valuable tool for advanced gravitational-wave detectors is the stochastic gravitational-wave background. The stochastic background imparts a weak correlated signal into networks of gravitational-wave detectors. Traditional searches for the gravitational-wave background rely on measuring cross-correlations of widely-separated detectors. Stochastic searches, however, can be adversely affected by uncorrelated effects which may also be present, including correlated frequency-dependent noise. As stochastic searches become sensitive to ever-weaker signals, it is necessary to develop methods to separate a true astrophysical signal from other spurious sources. Here, we describe a novel method to achieve this goal — gravitational wave geodesy allows for the localization of radio telescopes, so too can our observatories. We introduce a new method that can be used to infer the positions and orientations of gravitational-wave sources, and verify a true observation of the gravitational-wave background yield constraints on the source geometry, we demonstrate that we can successfully validate true gravitational wave signals while rejecting spurious signals due to correlated instrumental noise.

1. Introduction

The recent Advanced LIGO-Virgo observation of a binary neutron star merger multiple events (Abbott et al. 2016a, 2017a,b, 2018) reveals the potential of future detectors to make unambiguous measurements of the gravitational-wave background by detecting the signals from pairs of detectors. As the suppression of all gravitational-wave signals too weak to individually detect, the stochastic gravitational-wave background is expected to be dominated by compact binary mergers at cosmological distances (Neijssel & Mandel 2008; Roseno 2011; Zhu et al. 2011; Wu et al. 2012; Zhu et al. 2013; Callister et al. 2016). Although the stochastic background is orders of magnitude weaker than instrumental detector noise, it will nevertheless impact a weak correlated signal to pairs of gravitational-wave detectors. The stochastic background may therefore be detected in the form of cross-correlations between widely-separated gravitational-wave detectors (Christensen et al. 1992; Allen & Romano 1999; Romano & Cornish 2017).

T. A. Callister, M. W. Coughlin, and J. B. Kanes

Gravitational-Wave Geodesy: A New Tool for Validating Detection of the Stochastic Gravitational-Wave Background, Accepted for publication Coming soon