



# LIGO and I2U2:

# Making LIGO Physical Environment Data Available for Discovery-based Learning



#### Eric Myers

with Fred Raab and Dale Ingram

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Hanford, Washington

on behalf of the LIGO Scientific Collaboration

"Physics in a New Light" New York APS/AAPT Spring Symposium West Point, New York 13-14 April 2007











### **Optics & Education**

(for "*Physics in a New Light*", Joint NY APS/<u>AAPT</u> Spring Symposium 2007)

#### LIGO interferometers are ultra-high precision optical devices

(the largest on the planet, and largest optical instruments with their own overpass!)

➔ Operation of such ultra-high precision optics requires constant monitoring of the physical environment (seismic, magnetic, weather, ...)

These data can be used by students and their teachers for discovery-based learning (real data, and possibly real research!)

#### **Astrophysics**

(for "Recent Advances in Astrophysics", NY APS Fall Symposium 2007)

- LIGO seeks first to *detect* gravitational waves (non-optical waves), then
- To use gravitational waves (GW's) for astronomical observations



### **Gravitational Waves**





#### Rendering of space-time stirred by



Changes in space-time produced by moving a mass are not felt instantaneously everywhere in space, but propagates as a wave.

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#### Electromagnetic Waves

- Travel at the speed of light
- "transverse"
- Two polarizations: horizontal and vertical
- Vector dipole in both E and B



- Solutions to Maxwell's Eqns.
- EM waves can be generated by a <u>changing</u> dipole charge distribution.

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# **Example: Binary Inspiral**

A pair of 1.4M/ neutron stars in a circular orbit of radius 20 km, with orbital frequency 400 Hz produces GW's (a strain of amplitude  $h = \Delta L/L$ ) at frequency 800 Hz.



=2

1× /15 Mpc

Wave frequency is <u>twice</u> the rotation frequency of binary.

(1.4M/binary inspiral provides a useful translation from dimensionless strain *h* to "reach" of the instruments, in Mpc )











Producing significant gravitational radiation requires a large change in the quadrupole moment of a large mass distribution.

The most likely astronomical sources are:

- 1) Coalescence of binary systems, such as the inspiral of pairs of neutron stars or black holes (NS-NS, NS-BH, BH-BH) CHIRP!
- <u>C</u>ontinuous <u>W</u>ave sources, such as spinning (asymmetric!) neutron stars ("gravitational pulsars"), or body oscillations of large objects (neutron star "r-modes").
- 3) Unmodeled Bursts from supernovae or other cataclysmic events (spherical symmetric = no GW -- requires changing quadrupole!)
- 4) Stochastic background from the early universe (Big Bang! Cosmic Strings,...) a "cosmic gravitational wave background" (CGWB)
- 5) Something unexpected...!





### **Michelson Interferometer**



Measuring  $\Delta L$  in arms allows the measurement of the <u>strain</u>

$$h = \Delta L/L$$
,

which is proportional to the gravitational wave amplitude h(t). (Larger L is better, and multiple reflections increase effective length.)



Laser Interferometer Gravitational wave Observatory

LIGO Livingston Observatory (LLO)

Livingston Parish, Louisiana

L1 (4km)





LIGO Hanford Observatory (LHO) Hanford, Washington H1 (4km) and H2 (2km)

Funded by the National Science Foundation; operated by Caltech and MIT; the research focus for ~ 500 LIGO Scientific Collaboration members worldwide.

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### The LIGO Observatories

LIGO Hanford Observatory (LHO) H1 : 4 km arms H2 : 2 km arms

> LIGO Livingston Observatory (LLO) L1 : 4 km arms

Adapted from "The Blue Marble: Land Surface, Ocean Color and Sea Ice" at visibleearth.nasa.gov NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff









- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (thermal noise) inside components limit at mid frequencies
- Quantum nature of light (shot noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels







### **Technical Challenges**

- ✓•Typical Strains <  $10^{-21}$  at Earth ~ 1 hair's width at 4 light years
- ✓•Understand displacement fluctuations of 4-km arms at the millifermi level (1/1000<sup>th</sup> of a proton diameter)
- ✓•Control the arm lengths to 10<sup>-13</sup> meters RMS
- ✓•Detect optical phase changes of ~  $10^{-10}$  radians
- ✓•Hold mirror alignments to 10<sup>-8</sup> radians
- Engineer structures to mitigate recoil from atomic vibrations in suspended mirrors
- ✓•Do all of the above 7x24x365

### S5 science run started 14 Nov 2005...







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### **Educational use of LIGO PEM data**

- LIGO interferometers are ultra-high precision optical instruments!
- Operation requires careful monitoring of the physical environment of the instruments.
- PEM data (and data products derived from them, such as DMT BLRMS) can be used by students for inquiry-based learning projects:
  - LHO/Gladstone HS Program (1999-2004)
  - LIGO/I2U2 partnership (2005-

LIGO lingo:

PEM = "Physics Environment Monitoring" DMT = "Data Monitoring Tools"

BLRMS = "Bandwidth Limited RMS"







A partnership between LIGO Hanford Observatory and Gladstone High School (near Portland, OR), supported by NSF, and administered (1999-2001) under the Student, Scientist, Teacher (SST) program run by Pacific Northwest National Lab (PNNL). (Continued informally until 2004.)

- One teacher and three students spent 8 weeks at LHO in summers 1999 and 2000.
- Science classes during school year involved a variety of projects aimed at understanding PEM seismic data transferred to GHS via Internet.
- The students who had hands-on experience from a summer internship were a key resource.
- Students met with a LIGO scientist via telecon every 3 weeks, and they visited the LHO site once during year.
- Students built "demo" instruments which gave them hands-on experience with equipment without risk of breaking something.



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 Students wrote software to translate data into a form they could more easily read

 Students viewed, modeled and analyzed data with Excel, MATLAB, perl, and C/C++

 Students found a correlation between microseism (sub-Hertz seismic motion) at LHO and wave heights reported by NOAA buoys off the Oregon and Washington coast:



Wave height can be used as a "proxy" to predict overall microsism activity at Hanford

 A microseism monitoring tool written by a GHS student was used for several years in the LHO control room until DMT Framework was developed and a new Monitor was written.

#### A Sampling of Student Presentations (2002):

- "Accelerometer Measurements through a LabView Interface"
- *"Running a LIGO Earth Tide Calculator at Gladstone"*
- "Processing LIGO Microseism Data in MS Excel"
- "Processing Microseism Differences"
- "Modeling the GHS Microseism Software using MATLAB"
- "Twenty Years of Wave Heights and Wind Speeds from Pacific Ocean Buoys"
- "Examining the Magnetic Field of the Earth in Southeastern Washington"
- *"Keeping the Wheels on the Bus--the Life of a Project Administrator"*





### µseism and wave height

1.00E-05 T

(wave heights rescaled by 10<sup>-7</sup>)





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ocean-buoy wave-height data (right)





- *QuarkNet* is a successful education project run by *Fermilab* E&O office
  - Network of in-school Cosmic ray detectors
  - Teaching materials for "*e-Labs*" ("one stop shopping")
  - Collection of teachers making use of these
  - QuarkNet centers
- QuarkNet organizers sought to extend the idea, so invited large physics experiments to join the effort: ATLAS, CMS, STAR, LIGO, with Adler Planetarium, U. Chicago
- Aimed at leveraging Grid Computing for educational use
- Title of project is "Interactions in Understanding the Universe" (I2U2)
- Initial pilot funding from NSF for 2005-2006, extended for 2006-2007.



### Einstein@Home



- Searching through the data streams for evidence of gravitational waves from a periodic source at an arbitrary sky position requires an extremely large amount of computing power - more than available Beowulf clusters!
- Einstein@Home uses the *Berkeley Open Infrastructure for Network Computing* (BOINC) to perform the search on a "small" chunk of data on a volunteer's PC, all while displaying a nifty <u>screensaver</u>.

Anybody can join: <u>http://einstein.phys.uwm.edu/</u>

Web site includes discussion "forums" for interaction between users, and with project developers.







# LIGO I2U2 Software Development

### --Goals --

- Provide <u>easy</u> access to LIGO environmental data (seismometers, magnetometers, tilt-meters, and weather stations)
- Provide analysis tools with functionality and feel similar to those available to scientists in the LIGO control rooms (such as DMT, DTT, DataViewer, ilog)
- Provide interface for use of "Grid" computing
- Provide supporting tools for interaction and collaboration between students, teachers, e-Lab developers, and possibly LIGO scientists (SST)





## Tool, LIGO Analysis (TLA)

A web based <u>Analysis Tool</u> which has a user interface (adjustable!) similar to LIGO control room tools (DMT, DTT, & ROOT) and with the potential to provide much of the same functionality (with influences from LabView)

LIGO Interactions in Understanding the Universe					
Dataflow	Beginner Logged in as Eric Myers				
Data Flow Data Selection Co	ntrols Plot Graph				MaatDaint
Follow these steps to complete your analysis:           Data Flow        >         Data Selection        >         Controls	Plot Graph			Guest account. hyssaps /	vvestPoint
Use the control below to select the dataflow for your analysis [Right now there is only one 'transformation' you can select.]	Ligo Intera	uctions in Understanding th	e Universe		
Dataflow: Select the dataflow for your analysis.  Plot one channel	Data Selection		Intermediat Logged in as Eric	yes acout	
Ir01 Peni FrTSerie TPot	Data Flow Dat	ata Selection Controls	Plot Gr.	Interactions in Understanding	g the Universe
[Someday there will be more choices t	Time Interval: 12 hours Select start and stop times for your analysis	is.	Contro	ol Panel	Advanced Logged in as Eric Myer
Appry - changes are applied immediately   besag tever. 1 _ 1	Starting Time/Date: 30 Mar 2007 11:14:46 GMT Input In01: H0:DMT-BRMS_PEM_LVEA_SEISX_0.	Ending Time/Date: 30 Mar	2007 23:14:46 GMT	Data Flow Data Selection Controls	Plot Graph
	Site: Hanford (LHO) v Subsystem: Data Monitoring Tool (DMT) Station: Corner Station (LVEA) v Society Filtered 0, 1 to 0, 2 Hz (SEIS)	·	Dataflo Input C Hanfor	w: 'plotIchan' hannel: d, LVEA, H0:DMT-BRMS_PEM_LVEA_SEISX_0.1_0.3Hz.mean	Data Flow     Data Selection     Controls
	Sampling:     minute trend vi (mean)       Apply     Changes are applied immediately	y   Debug Level: 1 ⊻ π	Time in	terval: 12 hours 30 Mar 2007 11:14:46 GMT (GPS 859288486) to 30 Mar 2007 23:14:4	Plot Graph
	<< Previous Step	Reset Session	Executi	[There are no controlable parameters for the selected but if there were, they would appear here.]	data now,
			Est	imated run time: 5.4 seconds Pres imated frame files: 12	s the 'Go' button to start the analysis.
Tutorial available as a PDF	file		Output [He Exc	Files: re you would select names for intermediate output files (LIGO_LW format el files) associated with any output terminals in the block diagram (if there	:) or export files (eg. R or MS e are any).]





### **Analysis Tool Plot**



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Basic functionality now works to plot a single channel ("the circuit is complete"), but there is much more to be added.

Only minute-trend data, but soon to add second trends, raw data (256 Hz), and 10-min and 1-hr trends

Potential to incorporate DMT Monitor Framework, first to use existing "monitors" (e.g. Bandwidth filtering of magnetometer data, as is now done for seismic data), but also possibly to turn an interesting student-designed data transformation into a control room Monitor.







Make Entry Latest Log Today Previous Next List Past	LIGO ele	LIGO electronic logbook (the "ilog").				
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17:22:16 Wed Mar 16 2005 (Local)       Topic: Commissioning       Author: Brian OReilly       Replaces the or A new channel L0:PEM-         Subentry       During a short interruption of science mode today (for S. O'Keefe et. al. visit) I connected a new PEM channel. The channel is L0:PEM-RADIO_ROOF and taken from a rooftop antenna. The idea is to monitor the 24.483 MHz radio sig which have been seen in L0:PEM-RADIO_LVEA.	Project leader HS Teacher Joined: Jan 25, 2006 Posts: 44 ID: 8 Washington LIGO Hanford	The 0.1-0.3 Hz band obviously carries a lot of earthquake information, but we saw in the group 1 plots that this band also is affected by other longer-term influences. I induged in the luxury of running a 90-second analysis job to form the attached plot which shows the entire month of December 2006 at 0.1-0.3 Hz. At these frequencies there is more to the story seismic story than the occasional passing of earthquakes! Dale Ingram LIGO Hanford Observatory 10: 270   User ctrl: 📓   Rating: 0   Rate: 🗄 / 🖹 [Post to thread] [Reply to THIS post]				
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### Web site features



#### Hello, Eric Myers! Select your e-Lab: Project glossary, using same LIGO software that runs Wikipedia OuarkNet CMS LIGO STAR ATLAS Cosmic Rays Eric Myers mytalk my preferences my watchlist my contributions logout Q PARTICIPANTS article annotations edit history protect delete move unwatch Status Your account - modify preference Logout from your account LIGO e-Lab ideas DISCUSSION ROOM ASSIGNMENTS School - set your school affiliation The Aquarium Room - General Topics There are many interesting questions you can ask and try to answer using the data now available from LIGO. The best Cosmic Ray's Diner - QuarkNet e-Lab COMMUNITY The ROOT Cellar - CMS test beam e-Lab Meeting and Discussion Rooms investigation is one you think of yourself to answer your own questions, but if you don't have any immediate ideas as to what UNDERSTANDING THE UNIVERSE Education & Outreach The Gladstone Room - LIGO e-Lab Participant Profiles to investigate then you might find something below which sparks your interest. User Helpdesk: Questions and Pro The Cascade Room - Adler i-Lab Don't feel that you have to answer the exact guestion listed here: Instead, think of it as a starting point for developing the RESOURCES question which most interests you! navigation Glossary NEWS Discussion/Logbook [edit] CMS e-Lab site Earthquakes LIGO e-Lab documentation Glossary March 6, 2007 LIGO Data now flowing Recent Changes 1. What happens to the tiltmeters when there is an earthquake? Tool, LIGO Analysis (TLA): LIGO data are now flowing again List of Articles 2. Is there any effect on weather due to earthquakes? Production [stable] Click here for more information List of Categories Testing [semi-stable] 3. Do the components of an earthquake at different frequencies all arrive at LIGO at the same time? Random Page Development [unstable] March 1, 2007 21:38 UTC 4. Do all earthquakes all have the same duration? About12U2 LIGO Hanford Observatory (LHO) No new LIGO data LIGO Hanford iLogs 5. Do earthquakes look exactly alike at different stations (LVEA, EX, EY)? Right now we are not getting any new data Help for the LIGO Analysis Tool. New data should 6. Is there any effect on the frequency or magnitude of earthquakes due to weather? external links be available after a server is upgraded at **I2U2 LINKS** 7. Did anything interesting happen on your birthday? If so, can you reconstruct the story of what happened (as a LHO. × QuarkNet I2U2 Home detective reconstructs a crime from the crime scene)? Click here for more information LIGO Hanford QuarkNet 8. How long after a big earthquake does something show up at LIGO? Observatory February 6, 2007 19:31 UTC I2U2 Wiki at U. Chicago 9. What is the smallest earthquake LIGO can detect? LHO Network Outage search The primary network connection at the 10. What is the smallest earthquake which can knock the LIGO interferometers out of lock? BOINC developer's notes LIGO Hanford Observatory will be down for BOINC wiki 11. Is there any effect on the frequency or magnitude of earthquakes due to weather? maintenance starting at midnight (PST) Feb Go Search 12. How does the distance to an earthquake affect the magnitude of the signal detected at Hanford? 8th and lasting from 4 to 6 hours. The Analysis Tool will likely not be available 13. How does the depth of an earthquake affect the magnitude of the signal detected at Hanford? toolhox during that period. 14. Can you use the data from LIGO to figure out the direction to an earthquake? Click here for more information What links here 15. Can you use the data from LIGO to figure out the distance to an earthquake? Related changes January 18, 2007 23:20 UTC POWERED BY [edit] Upload file Seismic Activity (in general) Special pages 1. Does the weather affect the seismic activity at LIGO in ways other than just earthquakes? Printable version **RSS News subscription** 2. Was anything interesting happening on your birthday? Permanent link [edit] What Else? for project/server status Anybody who has an idea for a LIGO investigation can add it to this list! You might discuss it first with your classmates and teacher. You might even find that your idea can be turned into more than a single question.

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### **Teacher Activities**



Summer 2006 intern teacher John Kerr

- Used second-trend data (from control room) to study p-wave/s-wave timing
- Tested Analysis Tool when it was ready
- Wrote TLA tutorial



#### Teacher workshop, August 2006

At Hanford, included control room visits, training in use of Analysis Tool and discussion of classroom activities

#### Initial student classroom trials in 2006-07





- Improvments to the Analysis Tool
- Create "e-Lab" teaching materials for I2U2 site



- LHO Teacher internships for Summer 2007
- LHO Teacher Workshop planned for Summer 2007





- LIGO interferometers are ultra-high precision optical devices
- Operation of LIGO instruments requires monitoring of the physical environment
- PEM and related data can be used by students and their teachers for discovery based education.

Try it out:

http://tekoa.ligo-wa.caltech.edu/tla

(user: nyssaps / password: WestPoint)

"A great discovery solves a great problem, but there is a grain of discovery in the solution of any problem." - G. Polya, 1944

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