LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO –
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LIGO Capabilities in Measuring Changes in the Environment at Low Frequencies

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1. LIGO CAPABILITIES IN MEASURING CHANGES IN THE ENVIRONMENT AT LOW FREQUENCIES

1.1. Basic concepts:

LIGO primary mission is to measure and record small pertubations in space-time due to gravitational waves originating in astrophysical sources. The Einstein tensor theory of gravity predicts that gravitational waves will propagate with the velocity of light and cause free space to stretch and contract along mutually orthogonal directions both transverse to the wave propagation. The strain field LIGO senses is a stretch along one arm and a compression along the other. The measurement is made by comparing the time it takes light to traverse the two arms. The propagation time will be longer in one arm and shorter in the other in the gravitational wave field. To gain sensitivity the light beams are passed back and forth along the arms many times before a comparison of the light travel times is made interferometrically. The light beams travel between mirrors (the test masses) at the near and far ends of the arms. The mirrors are decoupled from motions of the ground by passive vibration isolation systems consisting of an assembly of springs and masses. The isolation system provides an attenuation of ground motion of 10^6 or more at frequencies above 10 Hz. To provide further isolation and a long coherence time (low damping) coupling to the sources of thermal noise, the mirrors are individually hung as pendula. The pendula begin an isolation that grows with the square of the frequency above about 1 Hz, the pendulum frequency. The unprecedented sensitivity to a differential strain along the two LIGO arms occurs at frequencies above 100 Hz (15 Hz in advanced LIGO). It is in this region that LIGO is sensitive to an rms strain in round numbers of 10^{-21} (10^{-22}).

LIGO is specifically designed to be insensitive to external perturbations in the environment in its sensitive operating band 80 to 5000 Hz for initial LIGO and 12 to 5000 Hz for advanced LIGO. Outside of this band the LIGO sensitivity is not remarkable and other instruments may be more capable depending on the variable being measured. At low frequencies, 30 Hz and less for initial LIGO, ground noise is not well isolated and the system is subject to laser frequency and amplitude noise as well as noise in the electronics.

1.2. Servo systems:

The interferometer is maintained at its operating point against the low frequency noise (the out of gravitational wave band noise) by a set of feedback systems that attempt to hold the rms motion of the test masses to less than 10^{-12} meters and to rms angular motions of less than 10^{-8} radians. The feedback systems effectively whiten the remaining noise by removing the very large excursions from the environment at low frequencies. They also remove, in the differential strain sensing mode, the laser frequency noise by closing a loop on the laser frequency from the common mode of the interferometer. Common mode is the stretch or compression of the two arms together which is directly sensitive to frequency changes of the laser. The differential mode (the one that contains the gravitational wave information) is insensitive to the frequency fluctuations of the laser to a few parts in a 1000 due to slight imbalance in the properties of the two arm cavities. The servo error signals of the common and differential mode do contain infomation about the environment but it is strongly corrupted by the laser and electronics noise outside of the gravitational wave band. As will be argued below, the environment is more cleanly measured in ancillary apparatus and not in the interferometer output.

1.3. Coincidence measurements:

A key part of the LIGO strategy to search for astrophysical burst events is to use the coincidence of gravitational wave events at the Livingston and Washington State sites. The orientation of the detectors along a great circle connecting the two sites gives maximal sensitivity to gravitational waves with the same polarization. The separation of the sites by several thousand kilometers has multiple purposes. The separation is large enough so that environmental perturbations with frequencies in the sensitive gravitational wave band are likely not to be correlated at the two sites and therefore less likely to cause a false gravitational wave detection. The separation also is useful, once a detection has been made, to allow for localization of the gravitational wave source by measuring differences in the arrival times of the bursts at the two sites. The two LIGO sites alone can only provide source loci restricted to curves on the sky. The international network of gravitational wave detectors will be needed to determine the position of the sources (multiple curves with intersections by using different pairs of detectors).

1.4. Environmental monitoring system:

LIGO has been designed to have an accidental (non gravitational wave) coincidence less than once every ten years. To achieve this very small accidental rate a system of environmental monitors has been installed at both sites along with the interferometers. The intent is to make careful measurements of the environmental parameters and by knowledge of the influence of any one of the parameters to the interferometer output (transfer functions) to either veto or regress (depending on the type of gravitational source being sought) the remaining environmental signals in the interferometer output. The environmental monitors are intended to have greater sensitivity to the environmental perturbation than the gravitational wave interferometer. Currently the environmental monitoring system consists of the monitors in **Table 1**.

Table 1: Environmental monitors in the LIGO facilities

INSTRUMENT	DISTRIBUTION
3 axis seismometers	one per building
2 axis tilt meters	one per building
high sensitivity coil magnetometers	one per site
low sensitivity peaking strip magnetometers	one per building
microphones	one per tank or optical table
3 axis accelerometers	one per tank or optical table
radio frequency interference receiver	one per building
cosmic ray shower detector	one per site

Note: should it become important in subsequent discussions, the specific sensitivity and frequency range of each monitor will be given. All except the high sensitivity coil magnetometer and the cosmic ray shower detector are readily available commercial instruments.

If there is interest in using the LIGO facilities to measure the environment, it is recommended that investigators consider using the data from the environmental monitor system in addition to or rather than the interferometer. A good way to highlight this is to realize that LIGO uses the seismometers at the ends of the arms to determine the microseismic motions (0.1 to 0.4 Hz) and then feeds this information forward to the test mass controls to compensate for the microseismic motion. The coherent difference of the seismometer signals along an arm is much more quietly measured by the seismometers than by the interferometer itself so that the correction does not introduce noise in the gravitational wave band (80 to 5000Hz). In other words, in the 0.1 to 10 Hz band the environmental monitoring system is designed to be a significantly better sensor than the interferometer.

1.5. Ambient environmental noise at the LIGO sites:

Table 2 gives some initial information about the ground noise at the two LIGO sites. The Washington (LHO) site is reasonably quiet except for surface noise generated by winds. The seismic environment is measured by the DOE in its survelience of the Hanford facility as well as by the LIGO environmental monitoring system. The Louisiana site (LLO) is seismically noisy. It is closer to urban centers and is, furthermore, surrounded by forest that is almost continually being logged. A major crude oil pipeline runs under the facility. The seismic environment in Livingston has forced the laboratory into a high priority program to develop an active seismic isolation system so that the Louisiana interferometer can be run both day and night. Interestingly, the interferometer in Louisiana has equivalent performance with those in Washington at night even though the ground noise is ten times larger. The LIGO environmental monitoring system in Louisiana may be the only continuously operating seismic station within several 100 km.

Table 2:Noise at the LIGO sites

Parameter	Washington State LHO	Louisiana LLO
rms seismic noise in the 0.1 Hz band	0.3 microns (any time)	3 microns (at night)
rms seismic noise in the 1 Hz band	0.001 microns	0.01 microns (at night)
minimum size earthquake detectable at night at a distance of 1000 km	Richter 3	Richter 4

The table does not reflect the large variability of the seismic noise at the Louisiana site which can grow in both the 0.1Hz and 1 Hz bands by another factor 10 to 30 depending on the storms and anthropogenic activity in the vicinity of the site. The Washington site is close enough to bedrock to sample the Earth well, the Louisiana site is sitting far from bedrock on the clay and sand deposited from the Mississippi river for many millenia.

Additional information concerning the status of the LIGO instrument can be found on various web pages. The LIGO Laboratory maintains a web page at http://www.ligo.caltech.edu/. A presentation on the current state of the LIGO given at the American Association for the Advancement of Science meeting in February 2003 can be found at

http://www.ligo.caltech.edu/docs/G/G030024-00.pdf

1.6. Some crude estimates that are useful in further discussion:

Table 3 contains some first order estimates of environmental and anthropogenic effects that bring some scale to thinking about searching for unusual events. The estimates are no better than to a factor of 3 to 10 and do not claim any real authority.

Table 3: Estimates for a variety of excitations

Excitation	energy	amplitude
Richter 4 earthquake	10^{17} ergs energy release	5 micron displacement amplitude at 1000km
Richter 3 earthquake	3 x 10^{15} ergs energy release	0.5 micron displacement amplitude at 1000km
1 ton rocket hitting earth at terminal velocity in air	10^{14} ergs at the surface equivalent to Richter 2 earthquake	0.05 micron displacement amplitude at 1000km
1 ton chemical explosion	10^{14} ergs at the surface equivalent to Richter 2 earthquake	0.05 micron displacement amplitude at 1000km
100kg tree falling under gravity	10^{11} ergs	10 micron amplitude at 1 km in 1 Hz band

Figure 1 shows a plot of magnitude of earthquake generated vs the expolsive yield in tons of TNT for a range of explosions measured by the Russians in Europe and Asia. **Table 4** comes from the American Institute of Physics Handbook and lists the global yearly rate of naturally ocurring earthquakes as a function of earthquake magnitude.

Table 4: Global rate of earthquakes/year vs Richter value

Richter	rate/year
5	1000
4.5	2700
4.0	7500
3.5	21000
3.0	59000
2.5	170000

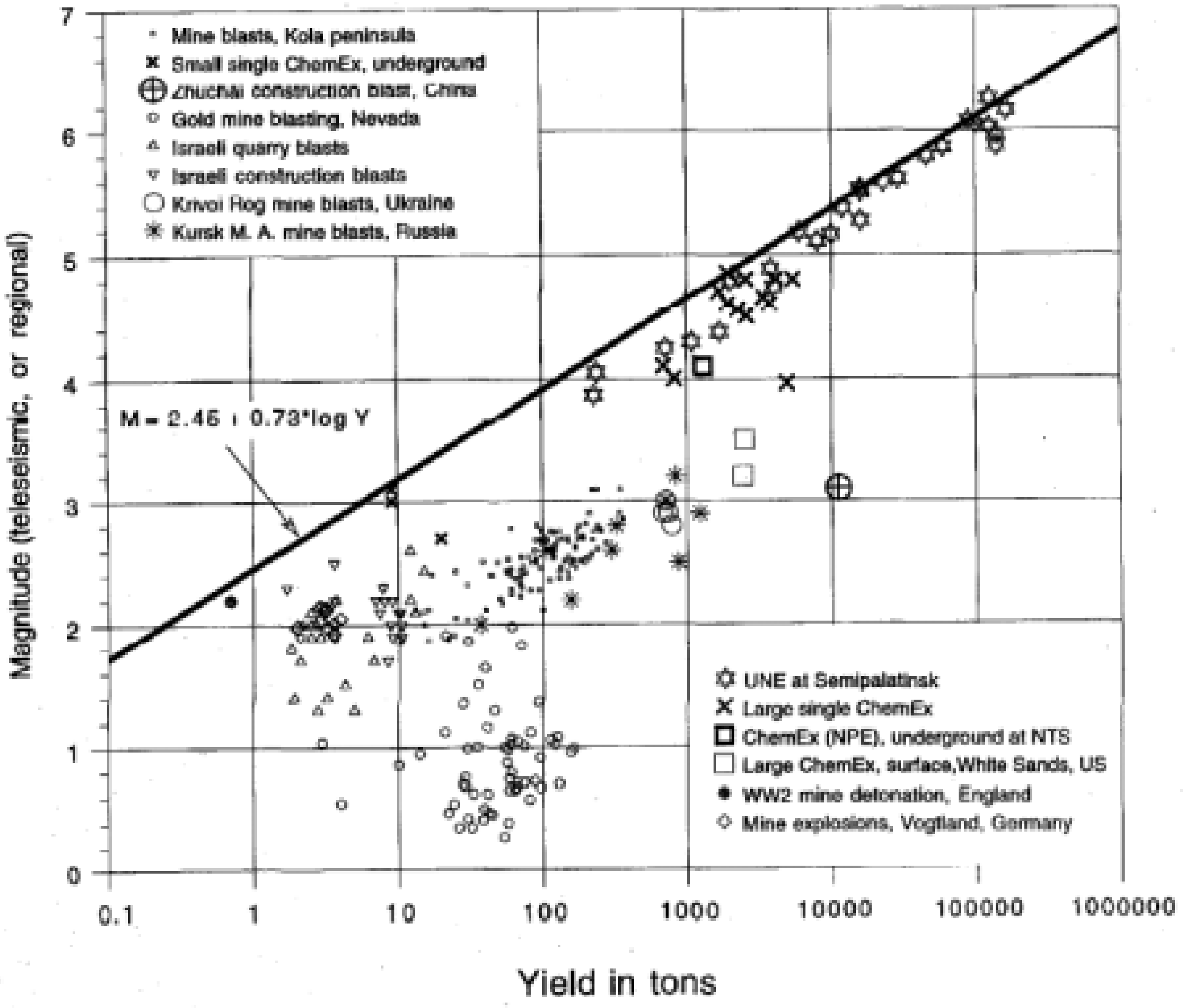

Figure 1. Plot of magnitude of explosive event versus yield in tons of TNT. Plot taken from V.I. Kahlturin et al., Bull. Seism. Soc. Am., Vol 88, No. 6 (1998) 1151 – 1524.