Draft of Site Chapter for LIGO Design Handbook

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28 November 1988

"XX" indicates numbers I didn't know. "*" at the beginning of a paragraph flags an argument which we've never fleshed out, or one I'm making with which I think it likely that there may be disagreement.

This draft contains some incomplete sections which likely should more properly be written by the engineering staff than the scientists. Do they belong here at all?

1 Number of Sites

SPECIFICATION The initial LIGO will comprise two widely separated sites within the United States.

RATIONALE

Of the three classes of source—impulsive, stochastic, and periodic—impulsive sources offer the best chance for early detection. Coincident detection at widely separated sites is the only way to demonstrate unequivocally that an impulsive signal is not due to local phenomena. Equivalent signals from separated antennas give the strongest discrimination both against external noise sources and internal glitches. Multiple interferometers at the same location provide inadequate discrimination.

Detection of stochastic sources requires signals from two antennas whose only plausible cross-correlation is due to gravitational waves. Again geographical separation is the key.

Detection of steady monochromatic gravitational waves is the only sort of measurement which could be plausibly made with a single site. The modulation of source frequency and amplitude due to the Earth's motion will be an unambiguous signature of a genuine gravitational wave, given sufficient signal-to-noise ratio.

The requirement for two sites could conceivably be satisfied with one detector in the United States and another in Europe or elsewhere. However, practical considerations demand two separated sites operated as a national as opposed to a multinational facility. The construction and operation of two sites as a single national observatory assures that

- At least two sites will exist.
- The receivers will be built on the same time-scale.
- They will have matched sensitivity and frequency range.
- They will be operated on the same schedule for coincident data collection.

The improved efficiency to be gained by building and operating the LIGO under a *common* as opposed to multi-national management is illustrated by considering the experience of astronomers making ultra-high resolution radio maps using the technique of VLBI. Most VLBI data are collected in a makeshift manner: dissimilar radio telescopes throughout the world are intermittently pressed into service for an observing run. The technique has proven successful, but its inadequacies, especially the severely limited observation time that has been achieved, led to the proposal of the national VLBA facility. The LIGO facility must be operated continuously, and the VLBI experience suggests this is achievable only if it is a national facility.

Detection of gravitational waves requires only two sites, but full extraction of astrophysical information from the signals requires at least three. Three sites allows determination of the location of the source on the sky, and the reconstruction of the complete waveform including the polarization. See Tinto and Gursel. (There is some limited ability to do this with two sites if there is locally determined polarization information from "orthogonal" 45 degree antennas. See site committee report.) For this reason, construction of additional antennas elsewhere in the world would be extremely advantageous scientifically. If no interferometers were built elsewhere, (or if built but not well coordinated in a network) it would be necessary to build a third American antenna to move beyond the detection stage to the era of doing mature science.

2 Size

SPECIFICATION

1. The LIGO vacuum system will be in the shape of an "L" with two arms of length 4.0 kilometers (absolute tolerance = plus or minus 0.2 km, two arms equal to a precision = 2.5 cm, two sites equal to a tolerance = 0.2 km).
2. The angle between the two arms will be 90 degrees (absolute tolerance = 15 degrees, two sites equal to a tolerance = 15 degrees).
3. The land under control of the LIGO project shall consist, at a minimum, of a strip XX feet wide along the line- of-march of the vacuum pipe, plus:
    (a) XX square feet at the vertex of the L
    (b) XX square feet at each end of the L
    (c) XX square feet at the mid-point of each arm of the L
    (d) XX square feet, at least XX feet from each of a., b., and c., for use as a headquarters area.
4. At least one of the sites shall be topographically suitable (see section XX below) for the addition of another L oriented 45 degrees (tolerance = 10 degrees) to the first L, with the land for such an addition either under control of the LIGO project or, in the judgement of the project, likely to be made available on reasonable terms.

RATIONALE

2.1 Arm Length

The size 4.0 kilometers can't be determined precisely by scientific arguments, but there are several arguments that show it is about right. An astrophysical signal of strength h moves test masses separated by L an amount $\Delta x = hL$. Interferometer length L affects sensitivity relative to two classes of noise. First, most noise enters as forces on the test masses. This type of displacement noise is independent of L, while the signal Δx increases with L; therefore the sensitivity of detectors dominated by test mass noise is proportional to L. Because the largest sources of test mass noise—seismic noise and thermal noise on the suspensions—fall steeply with frequency, these noise terms dominate at low frequency.

The accompanying graph shows the projected noise spectrum of the LIGO Mark I receiver at the design length of 4 kilometers, and at several shorter lengths. The degradation in sensitivity due to test mass noise over the key 100 Hz to 1 kHz band is evident at shorter lengths. Clearly, even longer arms would improve the situation. A natural maximum comes when the round trip time in the arms reaches half the period of the gravitational wave signal. For 1 kHz, this is a length of 150 km, while for 100 Hz it corresponds to 1500 km.

A second class of noise, shot noise in the optical system, limits sensitivity at high frequency. The shot noise sensitivity is independent of L in a non-recycled system, but is proportional to $\sqrt{L}$ in a system with standard recycling, and proportional to L with periodic recycling (in a simple model where the recycling gain is limited by reflectivity of the mirrors).

So why choose 4 km instead of 100 km? Mostly for practical reasons. One has to do with the availability of sites. In the United States there is probably no place other than the Great Salt Lake Desert which could meet the topographic criteria (see section XX below) at the high end of this range. The Columbia site can barely accommodate 4 km.

Cost is itself the strongest reason for restricting the length to 4 km. The total cost of a 100 km antenna would be prohibitive. A cost model which distinguishes between costs which grow in proportion to antenna length and those which have to be paid independent of the length gives a natural economic length to the LIGO. A vacuum system which is so short that the cost is dominated by the length-independent costs is too short. A vacuum system which is so long that the length-independent costs are negligible, so that it costs an extra factor of two to buy an additional factor of two in low frequency sensitivity, is probably too long. Although the details of the argument depend on the specific LIGO design and cost estimate, we have consistently found that 4 km falls in between the two extremes.

From the flavor of the preceding argument, it is clear that the precision with which we specify the absolute length of 4.0 kilometers is not given by scientific arguments alone. Rather we want to choose the largest installation which is feasible (however feasible is determined). Also, we must guard against being pushed down the slippery slope of trading a bit of length at a time to solve budget problems as they arise.

The numerical value of the length tolerance, 0.2 km or 5 percent of 4 km, allows a range of lengths which can plausibly be rounded to 4 km.

The tolerance in arm length match at a single site is supposed to represent what is readily achievable with present-day standard laser distance measurements used by surveyors. (If this number is incorrect, please change it.)

In some simple receiver designs, the arm length match is an important parameter in determining the contribution of frequency noise to the noise budget. In such cases, construction precision of a few cm would be sufficient, as final trimming can be allowed for in the adjustments built into suspensions. Robert Spero has promised a detailed memorandum pointing out that several techniques demonstrated on the 40-m interferometer can reduce or eliminate any first-order dependence on arm length match. Even so, it is probably a good idea to match the arms as closely as is easy.

The tolerance on the match of the arm length at the two sites has been set no tighter than the overall design tolerance. (Perhaps there is an engineering reason to match them more closely.)

2.2 Opening Angle

We use two arms because we reject frequency noise by "subtracting" the outputs of the two arms, either electronically or preferably by interference ("recombination"). Two arms at 90 degrees give maximum sensitivity to gravitational waves, because their characteristic tensor polarization causes opposite effects in orthogonal directions. The signal is proportional to the sine of the angle between the arms (so parallel arms give zero sensitivity to gravitational waves). The tolerance of 15 degrees on the perpendicularity of the arms is determined by our (somewhat arbitrary) decision not to sacrifice more than 3.4 percent of sensitivity to this effect. (If we used up all of the site committee's 10 percent performance margin in angle alone, which wouldn't be advisable, we could tolerate plus or minus 25 degrees. At 5 percent, we have plus or minus 18 degrees.)

If there is some engineering reason we can think of, we can set a tolerance on the match in this angle between the two sites.

2.3 Area of Land Required

*The width of the strip along the antenna line is primarily determined by consideration of the need for room during construction. If we want a permanent road along the antenna, this should also be factored in.

*The size of the lots near the vertex, ends, and middles of arms is to provide room for buildings.

*We will need some buildings for purposes not involved in the minute-to-minute running of the interferometers. The separate headquarters area is for these buildings.

*The question of a minimum distance between the headquarters area and the instrument buildings is still under review. Also not determined is the extent to which we want to pad the size of the lots around the instrument buildings to create a noise buffer, as opposed to assuming that we will take care of external noise by proper siting in the first place.

2.4 Expansion

*The idea behind considering future addition of a second antenna at 45 degrees to the first is to determine complete gravitational waveforms, which requires polarization information. The site committee report pointed out the intimate connection between waveform solution and source position determination. The site committee compared simultaneous solutions from two sites, both of which had two "orthogonal" antennas, with solutions obtained from three sites, one of which had an extra antenna. Although the two site method works to certain degree, it is far inferior in precision and robustness. For this reason, the committee felt it was an undue burden on the project to require the capability to build orthogonal antennas at both sites. It seemed reasonable to expect that either a third antenna will be built in Europe or elsewhere anyway, or that the successful discovery of gravitational waves by the two site LIGO would generate enough enthusiasm so that construction of a third site would be accomplished.

Subsequent work by Tinto and Gursel has shown how to get a complete solution from three sites each with a single L. Upon review of this calculation, the project may want to delete the requirement for orthogonal capability altogether.

3 Location

SPECIFICATION

- The two LIGO sites should be separated by at least 300 km, preferably by a distance between 2500 and 4500 miles.
- The locations of the two LIGO sites should be such that, in combination with an antenna in Europe, they give the best time delay discrimination in two orthogonal directions, as expressed by an Area Figure of Merit (defined in Site Committee Report) of greater than 0.12.

RATIONALE

3.1 Site separation

At a minimum, the two LIGO sites should be far enough apart so that there is negligible probability of correlated external noise. The site committee report specifies 300 km as a safe lower limit on the distance, but characterized this number as "flakey".

The preferred separation range is based on a desire to maximize the information to be obtained from time delays. The top end of the range is the distance at which Earth curvature effects have made the two sites' average sensitivity decline by 5 percent. Below the bottom end of the range, there is reduction in time delay information with no substantial increase in sensitivity. The number is sensitive to assumptions about the polarization of the source and the signal-to-noise ratio. Details of the argument are given in the site committee report.

3.2 Triangle Area

If three sites are nearly in a line, there is almost no information added beyond what the two most distant sites provide. A measure of the amount of information added is given by the area of the triangle defined by the three sites. The site committee expressed this in normalized form as the Area Figure of Merit. Tables of values for selected sites are given in their report.

3.3 Latitude

Weak Preference: Sites closer to the equator are marginally better (at the 10 percent level across the U.S.) at detecting sources in the Virgo Cluster.

4 Orientation of Antennas

SPECIFICATION

- There is no requirement on the absolute orientation of the antennas.
- The orientation of the two antennas with respect to one another should be, to a precision of plus or minus 13 degrees, the average of two alignments:
    - the coincident projection alignment, in which the antennas are oriented so that, when projected onto the plane which bisects the line connecting the sites, the arms of the antennas are superposed.

- the Virgo-optimized alignment, which gives the best match in signal strengths from sources in the Virgo cluster (i.e., near the celestial equator.)

The coincident-projection alignment is given by

$$\alpha = 2 \arctan \frac{\tan \gamma_- \sin \overline{\beta}}{\cos \beta_-}$$

where (β_1, γ_1) and (β_2, γ_2) are the latitudes and longitudes for two L-detectors, $\overline{\beta} = (\beta_1 + \beta_2)/2$, $\beta_- = (\beta_1 - \beta_2)/2$, $\gamma_- = (\gamma_1 - \gamma_2)/2$, and α is the difference in orientation, with positive α indicating that detector 2's bisector should be rotated counterclockwise on a conventional map relative to detector 1's by α. For example, if
$(\beta_1, \gamma_1) = (44.67^\circ, -67.9^\circ)$ (Columbia),
$(\beta_2, \gamma_2) = (34.95^\circ, -117.78^\circ)$ (Edwards),
then $\alpha = 33.27^\circ$. So if Columbia's bisector is oriented 20° East of North, then the coincident-projection alignment for Edwards is 13.27° West of North, modulo 90°.

*The Virgo-optimized alignment has to be calculated with a computer program. Schutz and Tinto have done this for Edwards- Columbia, among other pairs.

RATIONALE

4.1 Absolute Orientation

Without foreknowledge of the location and polarization of the sources, there is no preferred absolute orientation for an antenna. Schutz and Tinto (1987) showed that for a pair of antennas separated by 4200 km the averaged sensitivity only varies at the 2 percent level as the orientations of the antennas are rotated (together).

4.2 Relative Orientation

As summarized in the site committee report, a guiding principle in designing the LIGO is to maximize the probability of detecting gravitational waves. In so far as it doesn't conflict with this objective (by more than a negligible amount), a second principle in design choices is to maximize the information to be obtained from the gravitational signals which are detected.

Choice of interferometer alignment is a case where these two objectives conflict, so we have to stick to the priority of making the detection. Aligning the detectors maximizes the chances that, if the signal is big at one site, it will be big at the other. This increases the chances that we will have statistically significant coincident detections.

Note that we have paid a price for this choice, assuming that we are successful in detecting gravitational waves. Coincident alignment throws away most of the information about the orthogonal polarization component. Furthermore, coincident alignment also causes many signals to have low amplitude at both antennas. So we have reduced the sky coverage of the pair, although only if the waves are not linearly polarized would we have as many statistical coincidences without alignment as with it.

Schutz (quoted in site committee report) has argued that most gravitational waves are likely to be elliptically polarized, and therefore that coincident alignment won't increase the number of signals which are strong at both sites. Then, he argues, it makes more sense to get extra information by deliberately misaligning the antennas. This is a perfectly respectable argument, but it is too much of a risk to take, in the judgement of the site committee.

The difference between coincident projection alignment and Virgo-optimal alignment is small (around 10 degrees for Edwards- Columbia). Specifying the average of the two as the best choice is a judgement call, reflecting uncertainty about the distribution on the sky of the first gravitational wave sources to be detected. Specifically, supernovae may be strong enough to be the first sources to be seen. They are abundant enough that the strongest signals will clump in the nearest cluster of galaxies, the Virgo Cluster. On the other hand, if supernovae are weak, it may be that decaying neutron star binaries are the first sources we see. They are less abundant, and will only be seen at reasonable event rates (several per year) if we can see them substantially beyond the Virgo Cluster. At this distance, the distribution of galaxies begins to look rather isotropic. No one can say with any confidence which scenario is more likely. Anyway, we don't pay much of a price for straddling, so we split the difference on this issue.

Outline of remainder of section:

Characteristics of an ideal site
Available for free or cheap, sale or long-term lease
Flat enough to allow line-of-sight with min cut and fill
Below ground construction?
Soils and drainage suitable for construction, minimize blasting

Environmental concerns easily met
Seismically and acoustically quiet
little human activity, wind and trees, ocean?
Low probability of future development
Convenient to transportation, construction labor source,
  technically trained staff, maintenance
Convenient to home institutions, outside visitors
Security
Mild climate

How to weigh different criteria
No natural point system
Judgement required to weigh risks of being stopped cold
  (as in environmental impact, security regulations),
  versus costs in dollars (e.g. need for blasting rock)
  costs in sensitivity (seismic noise), or costs
  in inconvenience (distance to sites from home
  institutions.)

Description of Specific sites

Location
Map
summary of topography, rms, cut and fill along antenna line
  size of available parcel, orientations allowed

ability to add (in future) length, arms
soils and drainage, rock and clay from drilling, seismic refraction
  construction options available (above ground, below ground)
  climate: temperature variations, precip., wind
access by road, rail, air, (distance to heavy routes for
noise as well)
  ownership
environmental impact statement--requirements and status
  seismic noise (acoustic noise?)
construction labor cost factor (what is correct term?)
  pre-existing infrastructure, security, etc.
population density in area, nearby industry, traffic on nearby
   routes, prospects for future growth
availability of electric power, water, other services
support from local government, universities
earthquake and flood risks
RF environment
externally mandated restrictions (below gnd only, bldg heights,...?)