Scientific benefits of moving one of LIGO Hanford detectors to India

B.S. Sathyaprakash, S. Fairhurst, B.F. Schutz, J. Veitch
School of Physics and Astronomy, Cardiff University, Queens Building, CF24 3AA, Cardiff, United Kingdom
S. Klimenko
Department of Physics, University of Florida, Gainesville, Florida, USA
Dave Reitze, Stan Whitcomb
LIGO, California Institute of Technology, Pasadena, USA

Abstract

LIGO Hanford is currently proposed to host two interferometers in the same vacuum system. Here we report on the scientific merits of moving one of the detectors to the southern Indian state of Karnataka - LIGO-India. This study considers the impact that LIGO-India has on the science objectives of advanced LIGO and Virgo. With the addition of a fourth site in India, the LIGO-Virgo network will have a longer baseline than any existing pair and thereby improve coherent detection and signal reconstruction, greatly improved sky localization of sources and enhanced duty cycle, especially of three-site networks. These improved features mean that the addition of LIGO-India will help achieve the scientific objectives of the LIGO-Virgo collaboration far more quickly and with greater precision than envisaged before.

1. Introduction

After successfully collecting data at design sensitivity for nearly two years, LIGO detectors are currently being upgraded to their advanced configurations with strain sensitivities 10 times better than their initial configurations. Virgo, with partial upgrade from its initial configuration, is currently taking data in coincidence with GEO600 but will soon begin further upgrades towards achieving sensitivities similar to advanced LIGO. The primary scientific objectives of the LIGO-Virgo collaboration are the following:

1. *Make a direct detection of gravitational waves:* Binary neutron stars are the most likely sources for a first direction of gravitational waves. The expected nominal rate of coalescences within the horizon of advanced LIGO is about 40 events per year. The rate is highly uncertain due to unknown parameters in modelling these systems; it could be smaller or larger by about an order-of-magnitude. Even if the real rates are at the lower end of the predicted rates, advanced detectors are very likely to make detection within a few years of observation.

2. *Constrain models of compact binary formation and evolution:* The current uncertainty in rate (some 3 orders-of-magnitude) will be greatly diminished by advanced detectors. In addition to making the first detection, advanced detectors will measure the rate to within a factor of a few in the local (i.e., <500 Mpc) Universe. This should then constrain models of the formation and evolution of compact binaries.

3. *Detect binary black holes and neutron star-black hole binaries:* Advanced detectors could make the first ever detection of binaries containing a black hole. The merger rate of such systems is highly uncertain. Nevertheless, such systems will be a new population of astronomical sources and they have a great potential for a better understanding of cosmology and astrophysics.

4. *Verify GRB-GW Association:* Advanced detectors will provide the opportunity to check if compact binaries, in which at least one of the companions is a neutron star, are progenitors of short hard gamma-ray bursts. Advanced detector networks will have a horizon of $z \sim 0.25$ to such inspirals and it is possible that a (small) fraction of the detected events are in coincidence with gamma-ray bursts. Short hard bursts are not seen at very low red-shifts and so it is possible that the LIGO-Virgo network will not observe any mergers in coincidence with GRBs. However, if their location on the sky could be measured accurately then it might be possible to identify afterglows in X-ray, optical or radio part of the EM spectrum.

5. *Measure Hubble parameter to within 5%:* Compact binary inspirals are self-calibrating standard sirens. Gravitational wave observations can measure both the absolute luminosity of the source (which is determined by the binary's *chirpmass* and the apparent luminosity (which is the strain measured by our detectors). Thus, we will be able to infer the luminosity distance to a source. To be useful as standard candles, it is necessary to identify the host and measure its redshift. Therefore, localizing the source on the sky is an extremely important prerequisite for advanced detectors in order to take advantage of the fact that we can measure the luminosity distance very accurately.

LIGO-India can positively impact each of these science objectives. In the rest of this document we will see how improved signal/source reconstruction with LIGO-India can be achieved.

2. Detector Networks

According to current plans, it is expected that by 2015 we will have an advanced detector network consisting of three LIGO detectors at two sites (two at Hanford and one at Livingston) and Virgo (see Figure 1). We shall call this network HHLV. It is essentially a 3-site network and requires all four detectors to be operating in order to triangulate an event on the sky[1]. The baseline consists of arms that are (in light travel time) 10 ms for HL, 25 ms for HV and 26 ms for HL.

By moving one of the Hanford detectors to India, creates a 4-site network HILV that consists of four separate 3-site networks with a far larger baseline, owing to arms with the Indian detector being 36 ms for HI, 39 ms for LI and 22 ms for VI. We shall designate this new detector HILV.

Previously, we had also considered the benefit of moving one of the Hanford detectors to Australia. The baseline with the Australian detectors with each of HLV is very large: 40 ms for AH, 42 ms for AL and 37 ms for AV. We shall call the network formed by Australia and HLV as AHLV. Australia being in the southern hemi-sphere and antipodal to LIGO Livingston, creates the longest possible baseline with LIGO detectors.

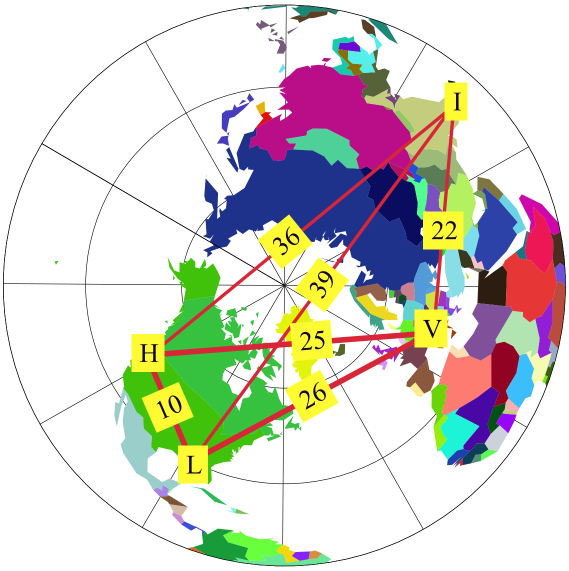

Figure 1 Projected globe shows the available networks and their baselines. HHLV network has one 3-site network; HILV has four 3-site networks with a baseline that is 1.5 times longer than the longest HHLV baseline.

In what follows we shall consider two 4-detector networks HHLV and HILV and four 3-detector networks, HIL, HIV, HLV, ILV, and study their ability to measure parameters of a source. We will also compare some of our results for the 4-detector networks with AHLV.

3. Sources considered in the study

Binary neutron stars are the most promising sources for a first direct detection by the advanced detector network. We shall, therefore, consider a population of binary neutron stars

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[1] Currently we include Hanford data in the analysis only if both detectors are operating.

all placed at a luminosity distance of D_L=200 Mpc, which is the distance reach of advanced LIGO averaged over binary orientation with respect to the line-of-sight and sky position. We take 1000 binaries, each consisting of a pair of neutron stars of mass $m_1=m_2=1.4M_\odot$ (total mass $M=2.8M_\odot$ and symmetric mass ratio $\nu = m_1 m_2/M^2=1/4$), in a quasi-circular inspiralling orbit. We place them at random locations on the sky uniformly distributed over the sky, with random polarization angles and inclination angles of the binary orbit with the line-of-sight.

For each source and different networks we then compute the signal-to-noise ratio ρ as well as measurement accuracies of the chirpmass $M_c=\nu^{3/5}M$ (which happens to be the best-measured binary parameter), the symmetric mass-ratio, the luminosity distance, the sky resolution, the inclination angle, the polarization angle, the time-of-coalescence and the phase of the waveform at that epoch. Thus, our Fisher matrix is a 9×9 matrix and care should be taken in computing its various elements and in inverting it to obtain the covariance matrix. Our comparison of different networks is largely based on the results from the computation of the covariance matrix.

The Fisher matrix analysis is a local analysis, which is valid only in the limit of large signal-to-noise ratio. Moreover, it does not capture parameter degeneracies and other complexities that might be present in the likelihood surface.

We have, therefore, used a Bayesian parameter estimation method to compute posterior distribution of the same nine parameters but over a smaller portion of the parameter space. This allows us to make a qualitative study of the different networks.

Since the angular resolution of the detector networks is very critical for advanced LIGO science we have also used the time-of-arrival information to compute the angular resolution. This latter method is fully analytical and hence compliments our Fisher matrix and Bayesian parameter estimation results. Let us begin by looking at the results of our study for sky localization.

4. Relative merits of HHLV and HILV for measurement

We will now consider the relative merits of the various detector networks in measuring the parameters of a source.

A. Angular resolution of the networks

The diffraction limited angular resolution of a detector of baseline L, using radiation of wavelength λ, is $\Delta\theta = 1.22\ (\lambda/L)$ radians. This is can be thought of as a 1-sigma error in one of the angles to triangulate a source that produces a signal-to-noise ratio of 1 in our detector. Starting from this, one can make a rough estimate of the 90%-confidence angular sky area to be $(\Delta\theta)^2 \sim 10$ sq deg., taking the minimum SNR of a detected event to be 10, the wavelength of radiation to be 300 km and the baseline to be 14,000 km. More detailed calculations show this to be roughly correct. A minimum of 3 detectors is required to resolve a source on the sky and as expected the resolution gets better both because of longer baselines and greater number of sites.

Figure **2** plots the 90%-confidence regions in estimating the position of a source as a function of the source location on the sky for the 4-detector networks HHLV, HILV and AHLV. In Figure **3** we also plot the cumulative histogram of the 90%-confidence sky areas (in square degrees) computed using Fisher matrix analysis for four 4-detector networks and four 3-detector networks.

It is pretty obvious that due to its short baseline, HHLV has a very poor localization of sources, sometimes the 90% confidence region being hundreds of square degrees. This is especially so for sources lying close to the plane of the three sites. Even the best survey telescopes might not be able to follow-up on identifying the host galaxy within the 90% confidence region in a significant portion over the sky.

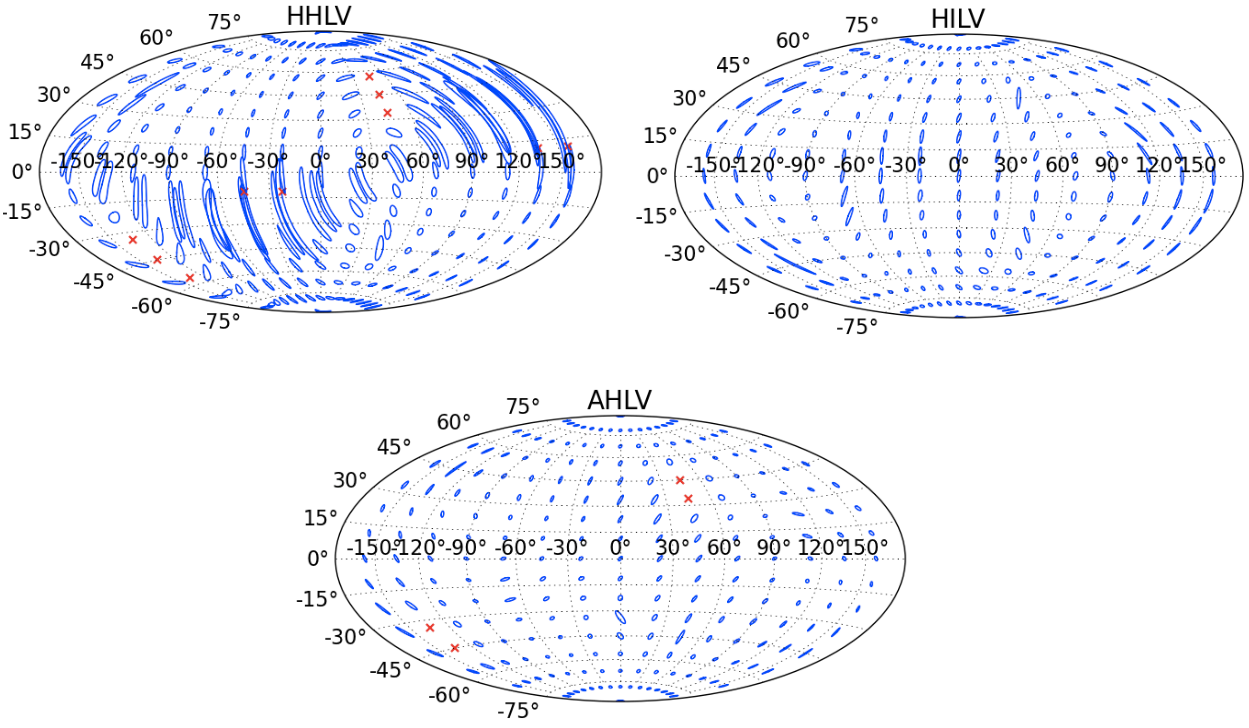

Figure 2 Angular resolution of various networks depicted in terms of error ellipses on the sky within which the source is has a 90% likelihood to be found for HHLV, IHLV and AHLV.

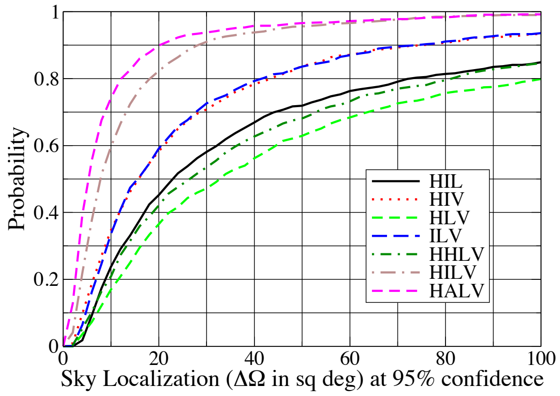

Figure 3 Cumulative probability density of 90% confidence region within which a source is localized. There is 50% chance that a source randomly selected from our catalogue is localized to within 5 sq deg in AHLV, 8 sq deg in IHLV and 30 sq deg in HHLV, at 90% confidence level.

A fourth site that is not in the plane formed by the three LIGO and Virgo sites, and far away from all of them, greatly improves source localization ability. We see that HILV could resolve the sources by an order of magnitude or more in certain regions of the sky as does AHLV. For 50% of the sources, the 90% confidence region is 5 square degrees for AHLV and 8 square degrees for HILV, as opposed to about 30 square degrees for HHLV.

In addition to providing a better localization of sources, HILV (and also AHLV, but not shown here) resolves degeneracies in parameter estimation. An example of this is shown in Figure **4** where we plot the likelihood surfaces for the joint distribution of RA and dec. The likelihood is bimodal for the three-site network of HHLV when the source happens to lie in a certain region of the sky, as in this example. The sky position is strictly bimodal in the case of a 3-site network, if only timing information is used to triangulate the source. This is because, for a source with certain time-delays in a 3-sitenetwork, there is a source that is antipodal to it with respect to the detector plane that causes exactly the same time delays and hence indistinguishable. However, additional information (the difference in antenna pattern and polarization) in the waveform, that depends on the source position on the sky, breaks this degeneracy even in a 3-site network over a large fraction of the sky, but the degeneracy remains over a significant region. This degeneracy is completely resolved when a fourth site is included. Luminosity distance and orbital inclination with respect to the line-of-sight are two other parameters for which degeneracies are resolved in a 4-site network, which impacts key science objectives of the advanced detector networks.

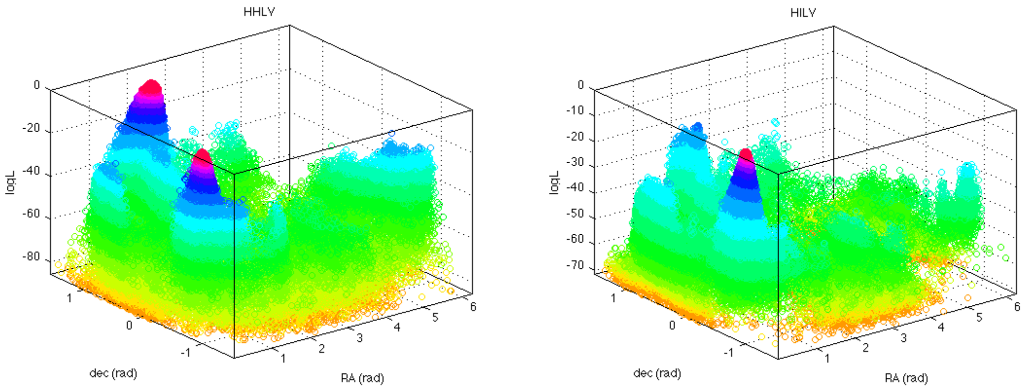

Figure 4 Degeneracy in sky localization in HHLV (left) is broken when a fourth site is available in the network (right) as shown by the likelihood of the source location estimated by a Bayesian MCMC simulation.

B. Why is sky localization such a big deal?

Detection Majority of the science goals rely on good angular resolution of the source. For instance, accurately locating the source position on the sky helps in identification of the host galaxy, which impact confirming first detections of not only gravitational radiation but also binary black holes, but also mixed binaries consisting of neutron stars and black holes: Association of a specific galaxy with first events greatly enhances detection confidence. Moreover, binary black holes will be a new type of source; it is important to know where they form, what their environment is, etc.

Cosmology Host galaxy identification is critical for cosmology. It is well known that compact binaries are standard candles and can measure the luminosity distance but they are not able to measure the redshift. Host galaxy gives the source's redshift and hence one will be able to measure the Hubble parameter and, with future detectors, other cosmological parameters.

Astrophysics In astrophysics, host identification helps verify that binary neutron star mergers are progenitors of short hard gamma ray bursts. With good source position, one should be able to carry out follow-up observations to hunt for afterglows associated with GW emission in x-ray, optical and radio. Galaxy type and environment and their relation to binary mergers will be very important for testing models of compact binary formation and evolution.

Once the host is identified, can use that as prior information to improve measurement accuracies of other parameters. For instance, estimation of distance gets better, as also the source orientation and polarization angle. Finally, tighter constraints on the parameters will help test GR to a greater degree of depth.

C. Network visibility

Figure **5** plots the cumulative distribution of the signal-to-noise ratio (SNR) for different networks, namely the probability that the SNR is larger than the value on the horizontal axis.

We have assumed that the analysis is carried out by coherently combining the data from different detectors and have shown coherent SNR for different detector networks.

The key result is that on average the 4-detector networks of HHLV and HILV both have the same signal visibility, the SNR being 14.0 or more for 50% of the sources. 80% of the sources will have an SNR of larger than 10.0. Just as 4-detector networks, all 3-detector networks also have the same visibility, the SNR being 12.4 or more for 50% of the sources; this is a fraction 0.9 of that for 4-detector network and hence 3-detector networks will have a volume coverage that is 70% that of 4-detector networks.

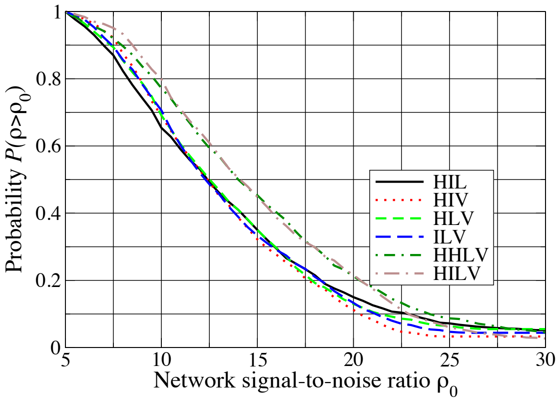

Figure 5 Cumulative distribution of the signal-to-noise ratio for the various networks. The 4-detector networks both have the same as SNR and so do 3-detectors networks.

D. Measurement of the luminosity distance

Measuring the distance to a source is tricky in astronomy but gravitational radiation from an inspiralling binary is a standard candle and our detectors measure both the source's absolute luminosity, which depends on the rate at which the system's frequency increases, and apparent luminosity, which is the strain caused by the radiation in our detectors. Thus, one can infer the luminosity distance to a source. Figure **6** plots the measurement accuracies of the distance for various detector networks. We see that there is considerable improvement in detectors with long baselines. This is true irrespective of whether the network consists of 3 sites or 4. As expected, HILV can measure distances to binary neutron star sources to a fraction accuracy of 30% for an arbitrary source.

What is remarkable is that the three-site network of HIV can also have a similar accuracy, followed by ILV. The most significant factor for the improvement is that a longer baseline not only helps in improving the angular resolution, it also facilitates, as we shall see below, in a better measurement of the binary's orbital orientation with respect to the line-of-sight. Since the luminosity distance and orbital inclination are strongly correlated, breaking that degeneracy helps in a more accurate measurement of both parameters.

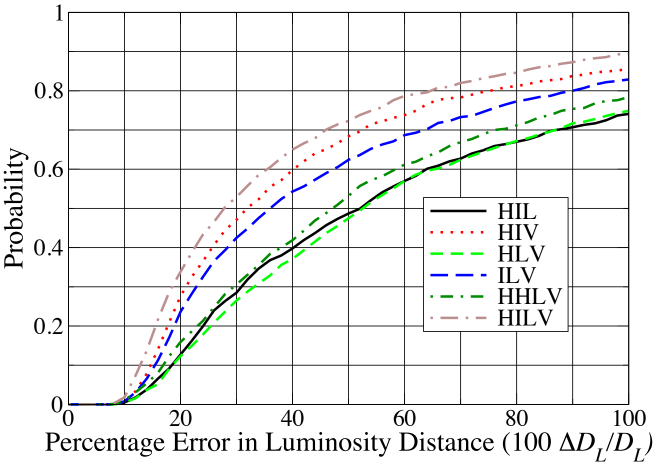

Figure 6 Cumulative distribution of the measurement of the luminosity distance to a binary neutron star source.

E. Binary Orientation and Polarization Angle

Figure **7** plots the cumulative distribution of the error in the inclination angle (left panel) and the polarization angle (right panel). These two angles together define the orientation of the binary with respect to the detector coordinate system: ι is the angle between the radial vector connecting the detector to the binary and binary's orbital angular momentum; ψ gives the orientation of the semi-major axis of the binary's circular orbit, projected onto a plane perpendicular to the line-of-sight. An accurate measurement of these two angles is necessary to fully reconstruct the source.

The 4-site network improves the determination of the orientation by a factor of 2. Since orbital inclination is considerably degenerate with the luminosity distance, the superior performance of HILV also helps in determining the luminosity distance slightly better. Moreover, measuring the inclination of the orbit to a higher precision can be helpful for testing gamma ray burst models: binaries with gamma-ray counterparts should be observed to be face-on systems.

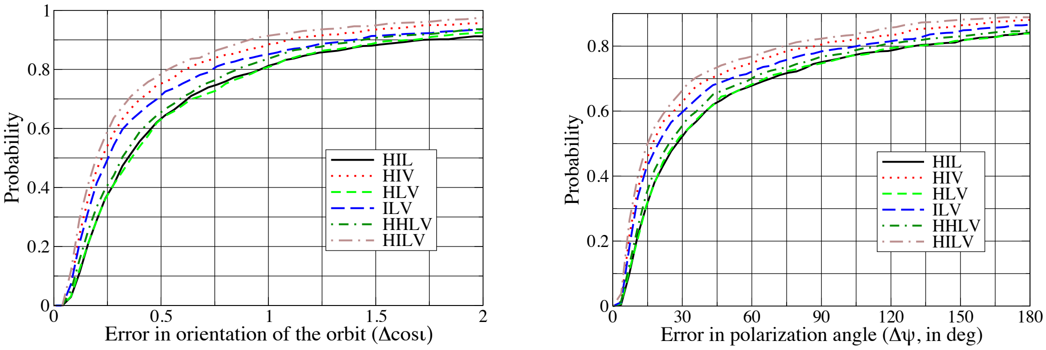

Figure 7 Cumulative distribution of the measurement accuracy in orientation (left) and polarization angle (right).

F. Measurement accuracy of mass parameters

Figure **8** plots the cumulative distribution of the percentage error in the chirpmass (left panel) and the symmetric mass ratio (right panel). More specifically, the plots give the probability that the error is smaller than the value on the horizontal axis.

At 50% probability, the errors for 4-detector networks are about 15% smaller than they are for 3-detector networks. This is almost entirely due to the larger SNRs of the 4-detector networks. The HILV network has slightly better parameter accuracies than the HHLV network, since a 4-site network breaks degeneracies between the binary masses and the luminosity distance that is present in a 3-site network.

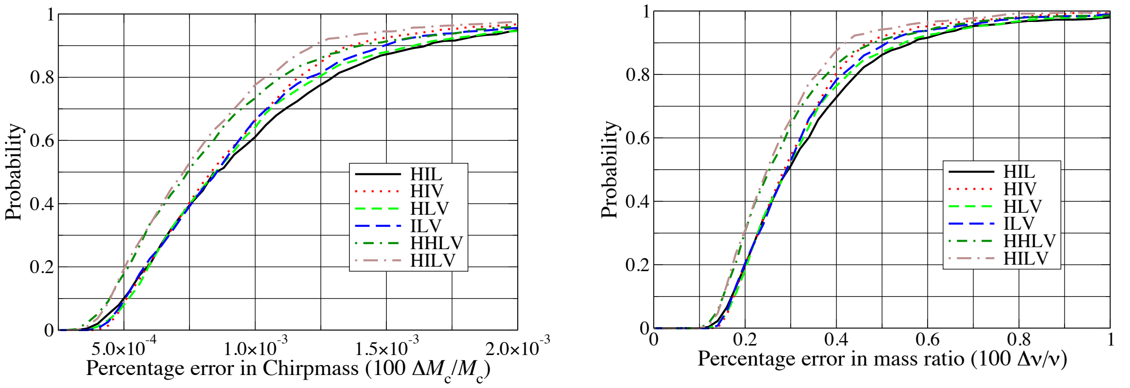

Figure 8 The cumulative probability density for measurement accuracy of chirpmass (left) and symmetric mass ratio (right).

Accurate measurement of the binary masses helps in testing general relativity in different ways. For instance, from the results obtained, one can deduce that the total mass can be typically measured to better than 2 parts in 1000. In comparison, the mass lost by the system to gravitational radiation could be as high as 3% of its total mass, far larger than the accuracy with which we can measure the total mass of the binary before merger. Thus, it might be possible to observe the effects of mass loss during an inspiral. Preserving such measurement accuracies is an important science goal in any planned alteration of the network. We conclude that there is essentially no improvement or any deterioration in the ability to measure intrinsic parameters when one of the Hanford detectors is moved to India.

G. Duty cycle

If we assume that each detector has a duty cycle of 80%, and that the duty cycles of the two Hanford detectors are not independent, then the duty cycles of networks consisting of 1, 2, 3 and 4 sites is given in Figure **9**. A minimum of 3-site is required to triangulate a source on the sky. The HHLV network consists at most of a 3-site network and its duty cycle for this configuration is 0.51.

HILV, on the other hand, is a 4-site network and so consists of one 4-site configuration with a duty cycle of 41% and four 3-site configurations with a duty cycle of 41%. Thus, the duty cycle for HILV with three or more sites is 82% as opposed to 51% of HHLV.

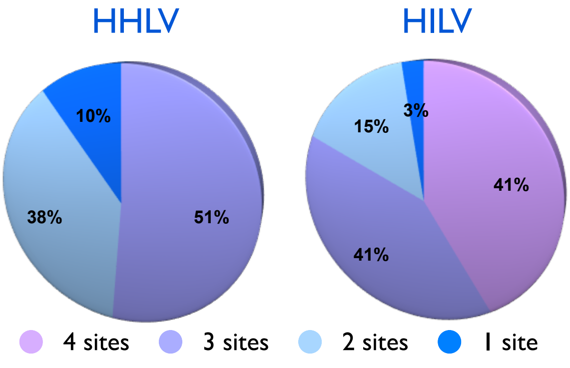

Figure 9 Duty cycle of HHLV and HILV networks. HILV has 82% duty cycle for 3-site networks as opposed to 51% of HHLV.

Improvement in the operation of the two Hanford detectors may allow future analyses to include data from one of the detectors when the other is not in lock. It is then possible to treat the duty cycles of the two detectors to be completely independent. In this case, the joint duty cycle of 3-site networks in HHLV rises to 61%, still 25% less than the HILV's joint 3- and 4-site duty cycle.

From a purely detection point of view, we should be able to identify events in coincidence in two or more detectors at different sites. The common environmental noise makes it very difficult to be confident about an event that occurs only in the two Hanford detectors. The duty cycle for detection then is nearly 90% in HHLV and 97% in HILV.

5. Summary

In conclusion, moving one of the Hanford detectors to southern India has significant advantages in achieving the key science objectives of advanced detectors by providing a factor of 3.5 improvement in sky localization of sources, as also a better estimation of the luminosity distance and orbital inclination. Once the 4-site network begins to operate, the nominal joint duty cycle of 3- and 4-site networks will be 82%, compared to the 51% of the 3-site network in HHLV.

6. Appendix

Recently, Bernard Schutz carried out a detailed study of detector networks based on certain figures-of-merit (FOMs). The following Table summarizes his results. The various quantities defined in the Table have the following meaning: *The mean horizon distance* is the maximum detection distance, scaled to the mean horizon distance (maximum range) of a single detector observing at the same threshold. *Detection volume* is the volume inside the antenna pattern, on the same scale. *Volume filling factor* is the ratio between the detection volume in column 3 and the volume of a sphere with radius equal to the maximum range in column 2. The remaining columns are the FOMs: *Triple detection rate* measures the overall detection rate and is given for two different values of the duty cycle: 80% to represent a likely figure at the start of operations, and 95% to represent a reasonable long-term operation goal. The values of triple detection rate are smaller than the detection volume by factors representing the loss of 3-site observing time to duty cycle downtime. *Sky coverage* measures how isotropic the network antenna pattern is. *Directional precision* reflects angular accuracy: the typical solid angle uncertainty is inversely proportional to directional precision, so that larger values denote more accurate networks. The first row of the table is for a single detector, to facilitate comparisons.

Network	Mean Horizon distance	Detection volume	Volume Filling factor	Triple Detection Rate (at 80%)	Triple Detection Rate (at 95%)	Sky Coverage	Directional precision
L	1.00	1.23	29%	–	–	33.6%	–
HLV	1.43	5.76	47%	2.95	4.94	71.8%	0.68
HHLV	1.74	8.98	41%	4.86	7.81	47.3%	0.66
AHLV	1.69	8.93	44%	6.06	8.28	53.5%	3.01
HHJLV	1.82	12.1	48%	8.37	11.25	73.5%	2.57
HILV	1.57	8.77	54%	5.95	8.13	79.0%	2.02
AHJLV	1.76	12.1	53%	8.71	11.25	85.0%	4.24
HIJLV	1.63	12.0	66%	8.64	11.1	100%	3.02
AHIJLV	1.85	15.8	60%	11.50	14.69	94.5%	4.88