# Improved source localization with LIGO India

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**Abstract.**
A global network of advanced gravitational wave interferometric detectors is under construction. These detectors will offer an order of magnitude improvement in sensitivity over the initial detectors and will usher in the era of gravitational wave astronomy. Gravitational wave sources can be localized on the sky, primarily through time of arrival measurements at the detectors, allowing for followup observations by telescopes. In this paper, we evaluate the improvement in sky localization obtained by relocating one of the Advanced LIGO detectors to India.

There is currently a proposal to situate one of the Advanced LIGO [1] detectors in India [2]. This would entail installing one detector at each at Livingston, LA and Hanford, WA(rather than two at Hanford) and the third detector in India. The global network will be augmented by the Advanced Virgo detector in Cascina, Italy [3] and the KAGRA detector in Kamioka, Japan [4]. One of the main motivations for the move to India is the improvement in localization of sources afforded by a network with an additional site remote from the other sites. Localization of gravitational wave sources to (relatively) small regions of the sky will enable wide field electromagnetic telescopes, such as LOFAR [5], Palomar Transient Factory [6], Pan Starrs [7] and SkyMapper [8] to perform followup observations of gravitational wave events. The joint electromagnetic and gravitational wave observation of sources willprovide new insight into the central engines powering electromagnetic transients [9, 10] and allow for independent measurements of distance and redshift sources [11].

In this paper, we investigate in detail the improvement in localization afforded by the installation of a LIGO India detector. At this stage, a site for a detector in India has not been fixed so we consider two locations. The first, as introduced by Schutz [12], has the detector placed at the location of the Giant Metre-wave Radio Telescope (GMRT) [13] at 74 deg 02' 59" E 19 deg 05' 47" N. The second is a site close to Bangalore, at 76 deg 26' E 14 deg 14' N, in an area that is seismically quiet [14]. In both cases, the arms are chosen (arbitrarily) to be oriented North and West, although the orientation of the detector will not greatly affect the localization [15, 16] . Examining two locations gives some insight into the effect of moving the detector. Of course a more detailed study (such as the one described in [15]) would be required before fixing the location and orientation of a detector in India.

The primary method by which a gravitational wave source will be localized on the sky is by triangulation using measured time delays between the sites [17]. Thus the localization accuracy will be dominated by the timing accuracy in the detectors as well as the separation between sites. In [17], the timing accuracy in a given detector was shown to be

$$\sigma_t = \frac{1}{2\pi\rho\sigma_f} . \tag{1}$$

Timing accuracy is inversely proportional to both the SNR $\rho$ and effective bandwidth $\sigma_f$ of the source, defined as

$$\begin{aligned} \rho^2 &= 4 \int_0^\infty \frac{|h(f)|^2}{S(f)} df , \\ \sigma_f^2 &= \left( \frac{4}{\rho^2} \int_0^\infty f^2 \frac{|h(f)|^2}{S(f)} df \right) - \left( \frac{4}{\rho^2} \int_0^\infty f \frac{|h(f)|^2}{S(f)} df \right)^2 , \end{aligned} \tag{2}$$

where $h(f)$ is the Fourier transform of the signal and $S(f)$ denotes the one sided noise power spectral density of the detector. The approximations used to obtain equation (1) break down at low SNR, where second order effects become important [18]. Also, we have neglected the effect of correlation between timing and other parameters. These correlations will affect the observed end time in all sites in a similar way and will thus not have a significant effect on the recorded time delays between sites.

We consider localization of a source using only observed time delays between the sites. From a set of observed time delays, the sky location of the source can be inferred. The errors on the arrival times determine the uncertainties in the location. For two sites, a single time delay suffices to localize the source to a ring in the sky. In principle, it may be possible to break the degeneracy on the ring based on additional information, such as spin or other features in the signal [19]. Even then the localization area will be large, and we will not consider localization regions for a two detector network here. For three sites, the observed time delays lead to two possible locations of the source which are mirror images in the plane of the detectors. In many cases, the observed amplitudes of the signal in the three detectors will enable the correct choice of a single location, although this is not always possible [20, 16]. Here, we assume that the degeneracy can be broken and for each source consider only the 90% confidence localization region around the true sky location.

There are numerous proposed configurations for the advanced detectors [1, 21], and it is likely that several configurations will be used as the sensitivity of the detectors develops. For this work, we are primarily interested in the sensitivity of the detectors and the frequency bandwidth of the signal. For simplicity, we will restrict attention to Binary Neutron Star (BNS) systems and characterise the sensitivity by the *BNS horizon* — the distance at which an optimally oriented and located BNS system would be observed with a signal to noise ratio of 8. The *BNS range* —the volume and orientation averaged distance at which a BNS gives SNR 8 — is a factor of 2.26 smaller than the *horizon.* In [22], we listed the sensitivity and frequency bandwidth of a number of different configurations of the advanced detectors with various sensitivities and bandwidths. In this paper, we use a fiducial detector with a BNS range of 160 Mpc (360 Mpc horizon) and a frequency bandwidth of 100 Hz. It is important to note that the results obtained are just illustrative of what might be achievable by an advanced detector network. The actual localization of sources will depend upon the sensitivities of the detectors and may also be influenced by non-stationary features in the noise. Furthermore, it is very likely that the source localization of the detector networks will evolve over time as the detectors approach their final, design sensitivities.

In [22] we introduced several characterizations of detector networks with regard to localization. Here we present the results for networks containing a detector in India. Where appropriate, we also show the comparable network with two detectors in Hanford, instead of one

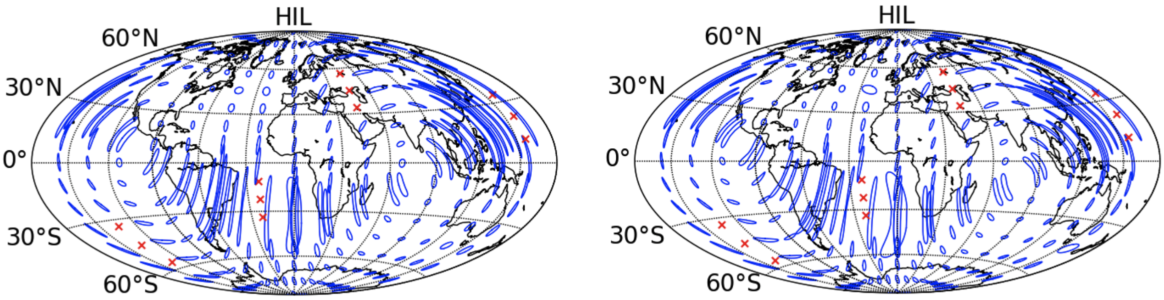


**Figure 1.** Localization with a three site LIGO network. The plots show the 90% localization ellipses for a face on BNS merger at 160 Mpc. A $\times$ is plotted at points where the network would not confidently detect the system. The left plot shows the localization ellipses with a detector in India at the location of GMRT. The right plot shows localization for a site close to Bangalore. The qualitative features of the plots are similar but the localization ellipses do vary substantially in some parts of the sky. This is most evident close to the plane defined by the three detectors. Moving the detector changes this plane and consequently the regions of the sky for which sources cannot be well localized.

Hanford and one India, to give a sense of the improvement. First, we examine the localization for a source at a fixed distance. We simulate the signal for a BNS merger, oriented face on, at a distance of 160 Mpc (equal to the BNS range of a single detector) and compute the 90% localization area. We require the expected network SNR of the source to be greater than 12 and require a single detector SNR above 5 in at least two detectors. This excludes regions of the sky where a source at 160 Mpc would not be confidently detected. These thresholds are motivated by results of recent searches of LIGO and Virgo data [23].

In Figure 1 we show the localization of face on BNS sources at 160 Mpc that is possible using three LIGO detectors located at Hanford, Livingston and India. We show the results for the two different LIGO India locations described above. The detector orientation will not have any effect on these results as we are considering only face on systems which give a circularly polarized gravitational wave signal, although the orientation will have an effect on localization of generic binary systems. In both cases, there are large areas of the sky for which the localization is good, but there is a clear band where localization is rather poor and the ellipses become elongated. This corresponds to sources lying in (or close to) the plane formed by the three detectors. For sources close to the plane, the localization out of the plane is poor as a large change in position corresponds to only a small change in time delays between sites. We have not shown the corresponding plots for a Hanford–Hanford–Livingston network as the two site network would only serve to localize sources to a ring on the sky.

Next, we consider the global network comprising three LIGO detectors, the Virgo detector and the KAGRA detector. In Figure 2 we show the localization afforded by a network comprising four or five detectors (three LIGO plus one or both of Virgo and KAGRA). For each network, we show localizations with either two US LIGO sites (with two Hanford detectors) or three LIGO sites including a LIGO India detector located near Bangalore. The three site networks (HHKL and HHLV) provide comparable localizations to the three site LIGO network HIL in that there are regions of the sky where sources are well localized, other regions where the localization is poor and even a few areas where the source would not be confidently detected. The results for HHKL show poorer localization than the other three site networks as these sites are rather close to being co-linear (as discussed in [22]) so there is only really one good direction of localization. The four site networks show good localization over the majority of the sky with slightly worse

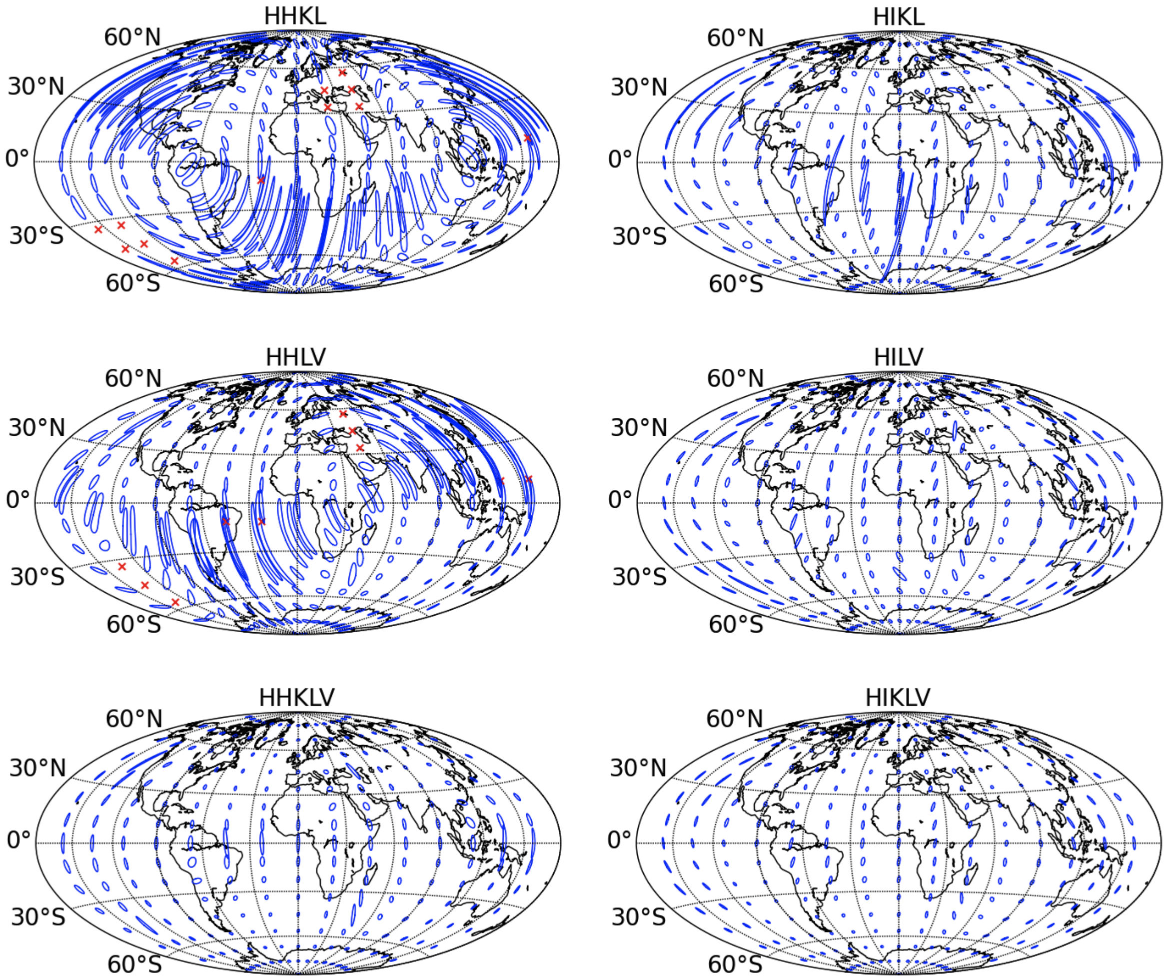


**Figure 2.** The localization accuracy for face on BNS at 160 Mpc in various networks of advanced detecors. The ellipses contain the 90% localization regions for sources from various points in the sky. A $\times$ is plotted at points where the network would not confidently detect the system. The plots show the localization for six different networks: Hanford–Hanford–KAGRA–Livingston (HHKL); Hanford–India–KAGRA–Livingston (HIKL); Hanford–Hanford–Livingston–Virgo (HHLV); Hanford–India–Livingston–Virgo (HILV); Hanford–Hanford–KAGRA–Livingston–Virgo (HHKLV); Hanford–India–KAGRA–Livingston–Virgo (HIKLV).

performance for the HIKL network as the four sites are nearly co-planar and sources lying close to this plane are not well localized. The five site network shows good localization over the entire sky.

Next, we would like to investigate the distribution of 90% localization areas for a realistic catalogue of detectable sources. We choose the sources to be uniformly distributed in volume and source orientation and impose the same thresholding criteria introduced above to restrict to detectable signals. The rate of BNS mergers in the nearby universe is uncertain to about two orders of magnitude [24]. For illustrative purposes, we choose a rate that would give 40 sources per year with an SNR greater than 8 in a single detector. This corresponds to the "realistic" astrophysical rate of [24]. Since we use the same rate for all the networks, the results are directly comparable, but the precise numbers should not be interpreted too strictly as the true rate could

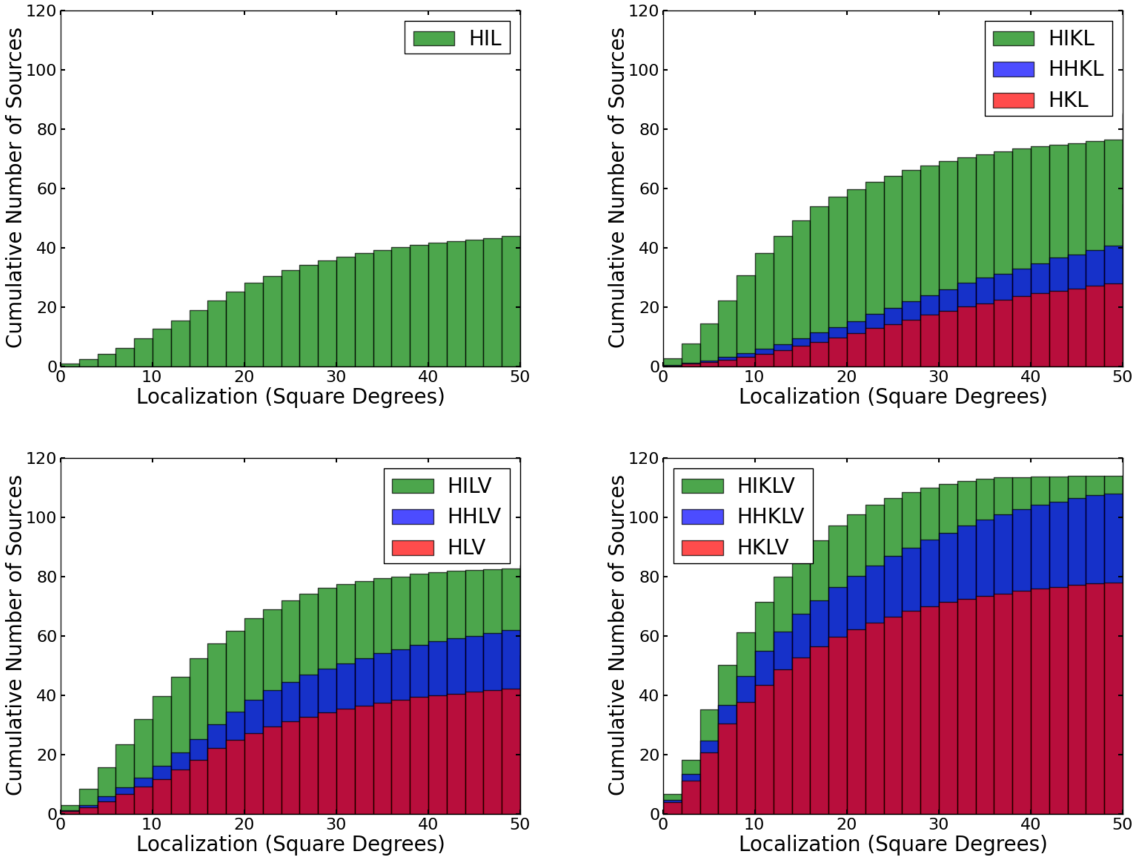


**Figure 3.** The number of sources localized within a given area in the sky for various networks of detectors. LIGO only networks (upper left) — HIL shown, HHL and HL omitted as no sources are well localized. LIGO-KAGRA networks (upper right) — HIKL, HHKL, HKL shown (from top to bottom). LIGO-Virgo networks (upper right) — HILV, HHLV and HLV shown. LIGO-KAGRA-Virgo networks (lower left) — HIKLV, HHLKV and HKLV shown. In all cases, the presence of a detector in India (rather than two at Hanford) improves the source localization dramatically, although it does not significantly affect the total number of observable signals (not shown on the plots). A single Hanford detector (and no detector in India) leads to a 25-40% reduction in well localized sources, and indeed in the overall number of observed sources. All results assume a rate of 40 events per year at SNR 8 or higher in a single detector.

reasonably be an order of magnitude larger or smaller than the rate used here.

The number of sources that will be detected by the various networks increases significantly with the addition of a detector, but varies little between the networks. With our assumed rate, the three detector networks would observe 55-60 sources annually; four detector networks 82-87; five detector networks 110-115. However, the fraction of sources that are well localized will vary significantly with detector locations. Figure 3 shows how well sources are localized with the various three, four and five detector networks. In all cases, there is a clear improvement in localization between a network with a LIGO detector in India over the corresponding network with two detectors at Hanford. This is particularly evident for a LIGO only network, where the (two-)Hanford–Livingston network is incapable of localizing sources to better than a ring on the sky while almost half of the sources observed by Hanford–Livingston–India are localized to within $20\,\mathrm{deg}^2$. For the four detector networks, an detector in India provides two or three times as many sources localized within $20\,\mathrm{deg}^2$ compared to having two LIGO detectors at Hanford. The five site network opens the possibility of the majority of sources to be localized within $10\,\mathrm{deg}^2$. These localizations are of interest as the current and future generations of wide field, transient telescopes have field of views from 3 to $20\,\mathrm{deg}^2$ [5, 6, 7, 8]. Thus, it will be feasible to perform follow-up observations of the majority of gravitational wave sources.

In the long term, we expect to be in a position where five advanced gravitational wave detectors are operating at their design sensitivity. Even at this stage, there will be a considerable advantage to having each detector at a unique site. It seems unreasonable to assume that the detectors will operate with 100% duty cycle — both due to the need to perform maintenance on the detectors, and the inevitable disturbances from local environmental factors. Indeed, it is typical to assume that each detector will have around an 80% duty cycle [25], with the downtime in the two Hanford detectors being highly correlated. The five site network provides considerable redundancy and, assuming 80% duty cycle in each detector, would give nearly 75% duty cycle for a four or more detector network and 95% duty cycle for a three or more detector network. This compares to a 40% four site duty cycle and 80% three or more site duty cycle for the global network with two LIGO Hanford detectors.

Finally, we must consider the fact that the re-location of a detector to India will delay its installation by several years [2]. Consequently, there will be a time when the network is operating with only two Advanced LIGO detectors. In Figure 3, we also show localization of sources using networks with one LIGO detector at Hanford and one at Livingston, but no LIGO India detector. These show a reduction in the number of well localized sources by between 25 and 40%, and indeed a reduction in the overall number of observed sources by a similar amount. For example, with the realistic astrophysical rate and the above duty cycle assumptions, each year the HLV network provides 13 sources localized to better than $20\,\mathrm{deg}^2$ and 40 total sources compared to 18 well localized and 60 total sources for the HHLV network. Thus, the relocation of a detector to India would cause a reduction in the number of sources detected (and localized) in the short term, but lead to significant long term benefits.

In summary, we have discussed in detail how the re-location of one of the LIGO detectors to India provides a significant improvement to the ability of the global gravitational wave network to localize sources, as well as providing a greater redundancy to the network. This improvement will come at the cost of a delay in the completion of the third Advanced LIGO detector, but the long term benefits make this worthwhile. The ability of four and five site gravitational wave detector networks to accurately localize sources will be critical to enabling gravitational wave observations to play their full part in the upcoming era of multi-messenger astronomy.

## Acknowledgements

This work has benefitted from discussions with numerious colleagues including Duncan Brown, Ray Frey, Bala Iyer, Dave Reitze, Bangalore Sathyaprakash, Patrick Sutton and Stan Whitcomb. This research was made possible thanks to support from the Royal Society.

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