Host Galaxy Discrimination using world network of gravitational wave detectors

Linqing Wen, Eric Howell, David Coward, David Blair
School of Physics, University of Western Australia, Crawley WA 6009, Australia

The proposed southern hemisphere gravitational wave detector AIGO increases the projected average baseline of the global array of ground based gravitational wave detectors by a factor ~ 4, while the proposed LCGT detector in Japan increases the baseline by a factor ~ 3. Here we show that the additional detectors allows the world array to be improved from an effective angular resolution $\sim$ one degree to about 10 arc minutes. This improvement reduces the average number of field galaxies from expected neutron star and black hole coalescence events by more than an order of magnitude. Using conservative assumptions, we show that unambiguous optical identification of host galaxies can be expected in about 30% of neutron star binary inspiral events. This can allow optical counterparts of events to be identified using deep exposures to search for afterglows, thereby allowing independent estimates of cosmological acceleration and dark energy as well as allowing improved understanding of the physics of neutron star coalescence.

1 Introduction

At the time of writing, several large-scale interferometric gravitational wave (GW) detectors are operating in their science mode. Operating detectors include three LIGO detectors in the US, one (L1) in Livingston, Louisiana, two others (H1 and H2, respectively) co-located at Hanford, Washington. There are also detectors in Europe and Asia: VIRGO in Pisa, Italy, GEO600 in Hannover, Germany, and TAMA in Tokyo, Japan. In the coming decade, several advanced detectors will be built, either as upgrades to existing facilities (Advanced LIGO and Advanced VIRGO), or as new detectors: LCGT in Japan and AIGO in Australia. The advanced detectors are designed to have improved low frequency performance and amplitude sensitivity about 10 times better than existing detectors, enabling them to monitor a volume of the universe 1000 times larger than current detectors. Future improvements using third generation detectors will improve this capability even further. Coalescing neutron star binary systems will be able to be observed to about 200Mpc, while black hole binaries will be able to be observed to distances 1Gpc [1, 2]. Estimates of the rate of neutron star coalescence events have been obtained in two ways: a) from empirical estimates based on the observed binary neutron star population [3] and b) from population synthesis. The population synthesis estimate for Advanced LIGO detections is ~ 20 per year [4] while the latest empirical estimate is $3 - 190$ events per Myr per Milky Way equivalent galaxy. If two similar detectors are added to the global array the signal to noise ratio is increased by about 1.4. Since the strain amplitude reduces inversely with distance but the number of sources increases as distance cubed, the event rate expected by adding detectors to the array could be doubled. It has long been recognized that the correlation of electromagnetic events with gravitational wave signals provides enormous benefits [5]. First it allows the velocity of gravitational waves to be estimated. Second, if the source is a binary inspiral, it allows the luminosity distance to be determined from the gravitational wave inspiral event, independent from the red shift determined from observation of the host galaxy. This allows a powerful independent probe of the Hubble law, cosmological acceleration and the equation of state of dark energy [6]. In the case of powerful electromagnetic events such as supernovae or gamma ray bursts (GRBs), follow-up searches for GW signals can be conducted in available archived data, so that science benefits can be realized retrospectively. However it is more likely that inspiral events will not be detected first by electromagnetic astronomy. If they correspond to short GRB's as commonly supposed, the large inferred GRB beaming factor [7] means that only a few percent events will be detected in gamma rays. Individual gravitational wave detectors have poor angular resolution with a beam width of ~ 120 degrees, so they are good all sky monitors but are completely inadequate for directional searches. This situation is greatly altered if an array of detectors is used. Then the coherent analysis of signals from the array allows the network to have diffraction limited resolution, where, as with VLBI radio astronomy, the angular resolution is set by the ratio of the signal wavelength, the projected detector spacing and the signal to noise ratio. A world wide array of detectors can achieve an angular resolution of ~ 10 arc minutes for signals in the audio frequency terrestrial detection band (see below for more details). If the above resolution is sufficient to identify the host galaxy of a GW inspiral event there are two possibilities. First, if the event is identified promptly, it will be possible for electromagnetic telescopes to undertake deep searches of the galaxy to search for the electromagnetic counterpart such as the predicted 'orphan afterglows' from GRB events. Second, even if the electromagnetic event is not detected, the localization may be sufficient to unambiguously determine the host galaxy and then obtain independent red shift measurements for the source. In both of these cases it allows the cosmological measurements to be recovered. Present detectors have insufficient range ($\sim$ 15 Mpc for standard $1.4M_{\odot}$ neutron star binary inspiral events) to expect a significant rate of detectable events. In addition, the range is too small for any measurements to have cosmological significance. However for the next generation of advanced detectors, if the range is combined with high angular resolution, the science benefits discussed above will be achievable. In this paper we use angular resolution estimates and galaxy count data to quantify the benefits of the world array. The world wide array of detectors becomes an all sky monitor with diffraction limited angular resolution. However, because of the non-uniform distribution of detectors the array does not have uniform angular resolution, but rather has a complex antenna pattern which follows the rotation of the earth. Because the individual detectors have different orientations relative to the line of site to potential sources, the array also has much better polarization sensitivity, especially when compared to the LIGO detectors alone, which are closely coaligned. This intentional configuration of LIGO increases the confidence for coincidence detection of the first signals, but means that they cannot distinguish the two polarization components of a source. For multiple non-aligned detectors (which is inevitable for detectors spread over a spherical surface) both polarizations are measured in a coalescence event, and then source orientation can be determined, enabling the luminosity distance of a coalescing binary source to be determined. Thus a global array achieves both improved directional resolution and greatly improved luminosity-distance resolution. The antenna pattern of the global array rotates relative to a galaxy distribution pattern consisting of filaments, clusters and voids in which there is a roughly 10-fold level of modulation of galaxy density. The ability of the global antenna to resolve individual host galaxies depends on the instantaneous coincidence of the antenna pattern with the galaxy distribution pattern. In one extreme, a source occurring in a region of low galaxy density may coincide with a high angular resolution direction of the antenna pattern, improving the probability of unique host galaxy identification. At the other extreme, a source in a region of high galaxy density may coincide with a direction of poor angular resolution.

Our results show that an array consisting of the current operating kilometer scale detectors has insufficient angular resolution to identify host galaxies. However if the array is enlarged through the addition of AIGO at Gingin, Australia, and LCGT in Japan, both with sensitivity comparable to Advanced LIGO, the ambiguity of host galaxy identification is reduced by more than an order of magnitude. We introduce a galaxy identification efficiency factor to quantify the ambiguity of host galaxy identification. It is estimated from the number of potential host galaxies within the angular resolution beam size, and within the luminosity distance error range for observed events.

Our results are based on estimates of the angular resolution of a detector array, based on a general method for the coherent combination of data from a network of detectors [8] and angular resolution estimates presented in [9]. In section 2 we summarise the method of angular resolution estimation and present the antenna patterns for various arrays, a) as all sky beam shape maps and b) as an angular resolution distribution function for different arrays. In section 3 we present an analysis of the galaxy density distribution and the host galaxy identification efficiency. In the conclusion we resolve the analysis to approximate numerical estimates which show that host galaxies can be uniquely identified for a significant fraction of all detected inspiral events.

2 Coherent Data Analysis for gravitational wave detector arrays

2.1 Methods

Methods for coherent analysis of data from an array of detectors have been under development for several years. Various methods have been unified into a single formalism based on the singular value decomposition (SVD)method [8]. The SVD method allows simple solutions to detection, waveform extraction, source localisation and signal based vetoing of interference. It is shown that the response matrix of the detector network can be decomposed into a product of two unitary matrices and a pseudo-diagonal matrix containing singular values. The unitary matrices can be used to form linear combinations of data from all detectors that have one to one correspondence to linear combinations of the gravitational wave signal polarisation components. Each newly formed data stream has a corresponding singular value representing the network's response to the new signal polarisations. Data streams with non-zero singular values represent the signal components while data with zero singular values represnt null streams with null response to gavitational waves and hence can be used for the localisation of GW sources and the vetoing of non-gravitational wave events. Using the null stream method Wen has provided explicit analytical expressions of the angular resolution of an arbitrary GW detector network in terms of observables such as time delay, geometry of the network, and SNRs at each frequency, or the received GW energy spectrum. The derivation is a direct result of applying the Fisher information matrix calculated from on the response of each detector to an incoming signal to set limits on how well GW sources can be localized through decoding information from delays in the wave arrival-time between detectors. Wen's results are presented for best and worst case scenarios for short duration GWs where the detector antenna beam pattern can be treated as constant, where the waveform is either known or unknown. In this analysis we assume that candidate inspiral events are modeled by optimizing the signal to noise ratio so as to fit to a known waveform so that the best case scenario can be used (this would not be appropriate for core-collapse supernova signals with unknown waveform). The angular resolution of a network can be written in a form reminiscent of the diffraction limit in wave optics. The source direction error area is inversely proportional to the square of the network SNR and the characteristic frequency and the projected area (normal to the wave direction) formed by any two pairs of detectors parallel transported to create a vertex. The expression also contains weighting factors related to the detector sensitivity [9]. Using the above formalism, all sky maps can be created showing the angular resolution for all directions in the sky for a particular detector network. The maps are obtained by first calculating the covariance matrix for each source direction by

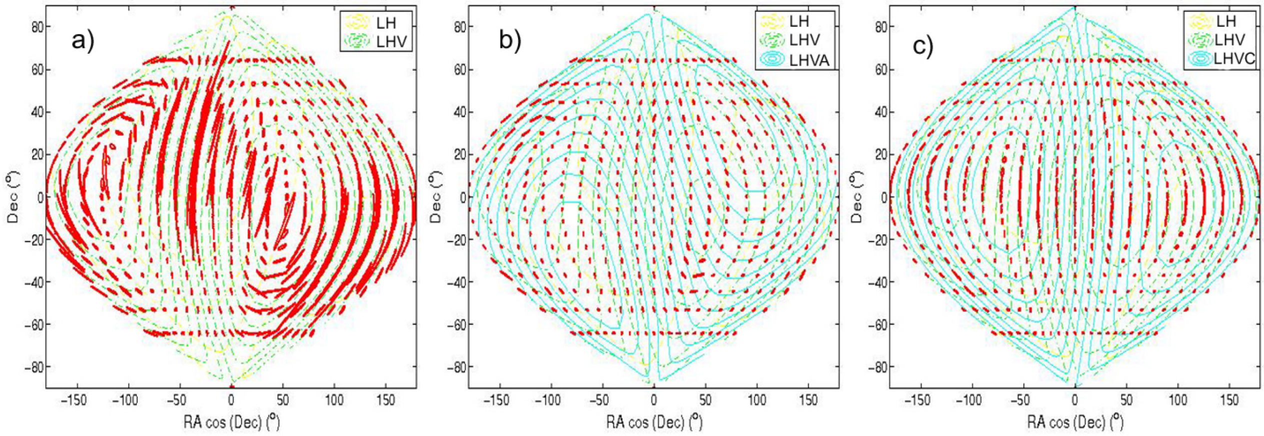

Figure 1: The first panel a) shows the antenna pattern for the array LHV. The improvement that can be achieved by the addition of a southern hemisphere detector is demonstrated in panel b) using AIGO and panel c) for LCGT.

inverting the Fisher information matrix. The contour of the $1-\sigma$ error ellipse can then be obtained. The axis of the error ellipse can be identified from the eigenvalues of the covariance matrix and the area is determined from the determinant. See [9] for further details.

2.2 Antenna Patterns

We consider detector arrays consisting of the kilometer scale detectors discussed in the introduction : L (Livingstone),H (Hanford) V (Virgo), A (AIGO at Gingin, Western Australia) and C (LCGT, located near the Kamiokande neutrino detector in Japan) . In addition in section 2c) we will consider the existing smaller detectors G (GEO at Hannover, Germany, and T (TAMA in Tokyo). Figure 1a) shows the antenna pattern for the array LHV. On much of the sky the angular resolution is characterized by a very elongated ellipse, due to the fact that the detectors are nearly coaligned and have short projected arm spacing in certain directions. Figures 1b) and 1c) show the dramatic improvement for the cases LHVC and LHVA. By inspection of these two maps it is clear that the advantages contributed by LCGT and AIGO are somewhat complimentary. This is demonstrated in the next section where we show the angular resolution distribution functions including the case LHVCA.

2.3 Angular Resolution Distribution Functions

We now consider the effective angular resolution $\Delta\theta$ derived from the angular resolution area DW for the different detector arrays. The cumulative distribution of the 1-sigma effective angular resolution $\Delta\theta = \sqrt{\Delta\Omega/\pi}$ of various GW detector networks is plotted in figure 2. The y-axis indicates the fraction of sky directions for which the angular resolution exceeds a given value. We used a total of 6400 data points distributed uniformly in the solid angle of sky directions. Different symbols indicate different networks. We start with the 3-detector network LHV and add sequentially G, T, A, and C. Solid blue lines represent the best-case scenario such as binary inspirals where the waveform is known, while dotted lines represent the worst case scenario for unknown waveforms. For given signal to noise ratio the results are relatively weakly dependent on the choice of waveform, The waveform used here is that of $10M_\odot$ black hole – black hole binary merger from Baker et al. [10]. The wave strength is chosen such that max SNR =10 for LIGO detectors. The same GW waveform is used for all sky directions. The noise spectral density used is based on the design sensitivity of the first generation detectors while for AIGO and LCGT detectors, we assume LIGO sensitivity. Note that the angular resolution depends only on the relative sensitivity of the detectors so we can also apply these results to Advanced detectors assuming they have the same relative sensitivity.

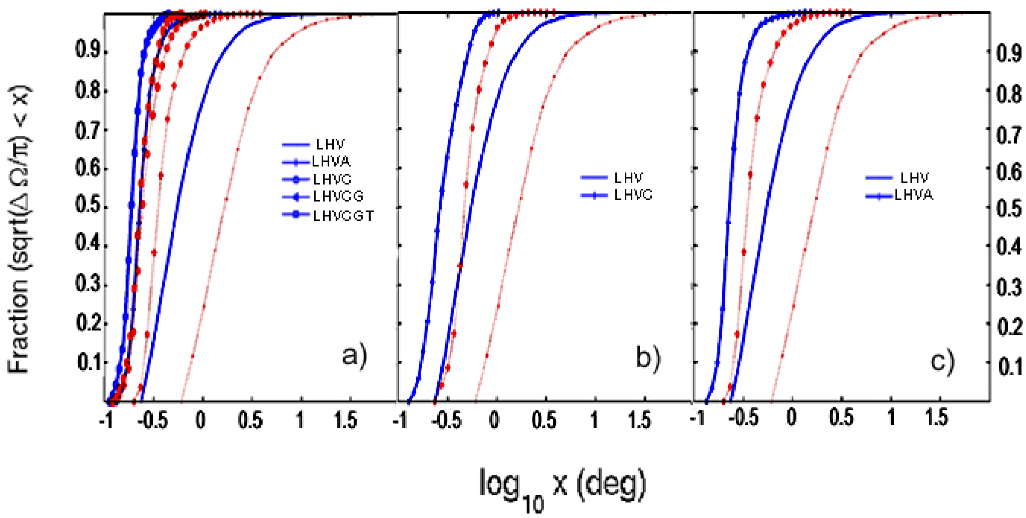

Figure 2: Angular resolution of the existing world array a) LHV with the successive addition of A,C G and T, which shows the successive improvement provided by the addition of C and A, but negligible improvement due to the addition of the last two lower sensitivity detectors. Panels b) and c) show the effect of adding C or A separately to the array. The blue curves represent the best case where the waveform is known (such as a binary inspiral), while the red curves refer to the worst case of unknown waveforms.

Figure 2 demonstrates the advantage of increasing the number of detectors in the array and also of obtaining maximum out of plane volume in the array by placing one detector in the southern hemisphere. The best array response is obtained by the addition of both LCGT and AIGO. AIGO significantly improves the ambiguity problem which arises if all the detectors are close to a common plane. The out of plane response also increases the maximum baseline significantly thereby obtaining good angular resolution in almost all sky directions.

3 Host Galaxy Identification

We now go on to use the above results to quantify the problem of host galaxy determination. This requires an estimate of the number of galaxies within the detector array angular resolution. To estimate the galaxy space density we use the results of Madgwick et al. [11] who have used data from the 2dF Galaxy Redshift Survey (2dFGRS) to determine the luminosity functions for both late type galaxies, which are undergoing active star formation and quiescent early type galaxies. As binary coalescence events are expected to occur in both galaxy types [12] we use the corresponding luminosity functions to estimate the space density for spiral and elliptical type galaxies. We further assume that low mass galaxies represent a negligible contribution to the population of potential sources. To account for uncertainty in luminosity distance measurements, d_L, in approximate correspondence with Cutler and Flanagan [16], we assume that measurement accuracies will be $\approx 20\%$. We therefore define the number of galaxies within the angular resolution beam size as the number within a shell of $\pm 0.2 d_L$.

Figure 3 shows the average number of galaxies per $1-\sigma$ error ellipse, estimated from the 2dFGRS data. We see that the average number of galaxies within 200 Mpc, the expected detection range for neutron star - neutron star inspirals, varies from in excess of 866 for LHV to about 22 for LHVAC. At 100 Mpc corresponding ratio is 108 to 3.

To quantify the ambiguity in host galaxy identification for different networks, we will use a galaxy identification efficiency factor. We define the efficiency as unity if the number of galaxies per field of view per luminosity distance range is less than two. At large distances, the efficiency will fall due to the increasing number of galaxies within the luminosity distance range and the reduction in event SNR which degrades the angular resolution.

In addition to the uncertainty in luminosity distance measurements, we also account for

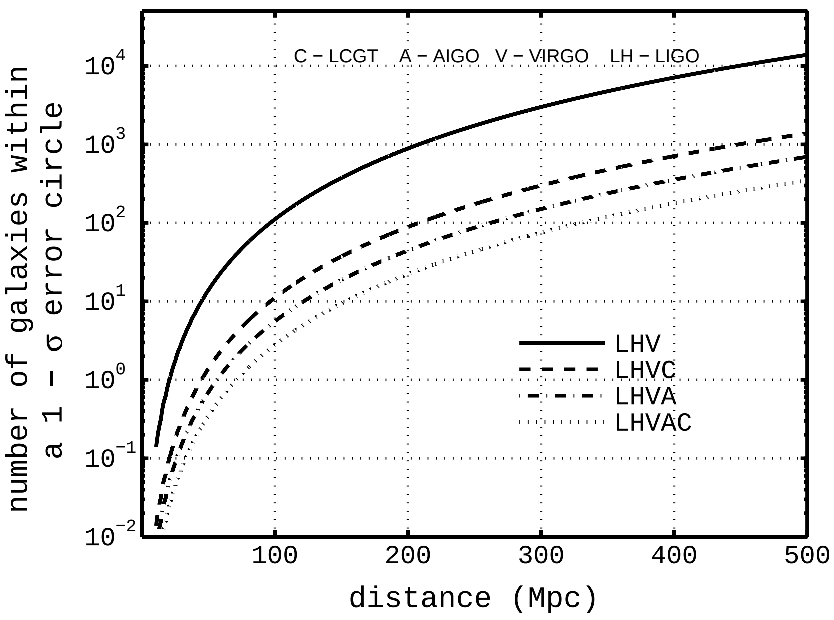

Figure 3: The average number of elliptical and spiral galaxies per $1-\sigma$ error ellipse, estimated from the 2dF galaxy redshift survey. We show curves corresponding to different gravitational wave detector network arrays. The angular resolution of each array corresponds to the 90% sky directions of Figure 2.

galaxy density contrast by using the the σ_8 parameter. This parameter represents the amplitude of the rms density fluctuations of matter σ_{8m} and galaxies σ_{8g}, in a sphere of radius 8 h^{-1} Mpc. We can relate these two quantities using the bias parameter [13]:

$$b^2 = \sigma_{8g}^2/\sigma_{8m}^2 = (\Delta\rho/\rho)_{gal}^2/(\Delta\rho/\rho)_m^2 \tag{1}$$

The last part of this expression relates the overdensity of the galaxy tracer to the mass overdensity. Estimates from the 2dFRS of $\sigma_{8m} = 0.73$ and $b = 1.10$ [15] yield $\sigma_{8g} \sim 0.8$. This value corresponds to upper and lower limits on the space density of galaxies n, of $\pm 0.8n$. This, almost an order of magnitude variation in galaxy space density, corresponds to the density contrast between galaxy clusters and voids and is in agreement with other studies [14, 15]. Since galaxy clusters make a small contribution to the total number of galaxies, we employ the mean and lower limits to account for galaxy density contrast in our calculations.

Figure 4 shows the efficiency factors we derive for four cases a) the existing array LHV, b) array LHVA, c) array LHVC and d) array LHVAC. The shaded area is set by two limits: a mean galaxy density and a detector network that has optimal angular resolution over 90% of the sky; secondly, a lower estimate of number density and 50% sky directions. The dark line shows the average identification efficiency for each detector array.

For the case of neutron star inspiral events, these results show that the optimal network LHVAC will identify ≈ 6 or less galaxies at the maximum expected detection range of 200 Mpc. In addition, we see that LHVAC can identify 2 or less galaxies within a $1-\sigma$ error ellipse out to a distance of 140 Mpc. This means that unambiguous optical identification of host galaxies can be expected in about 30% of neutron star binary inspiral events. In comparison, the LHV array will allow the identification of 2 or less galaxies out to a distance of 34 Mpc, whilst the addition of a single southern hemisphere detector will extend this range out to a distance of 92 Mpc for LHVC and 116 Mpc for LHVA.

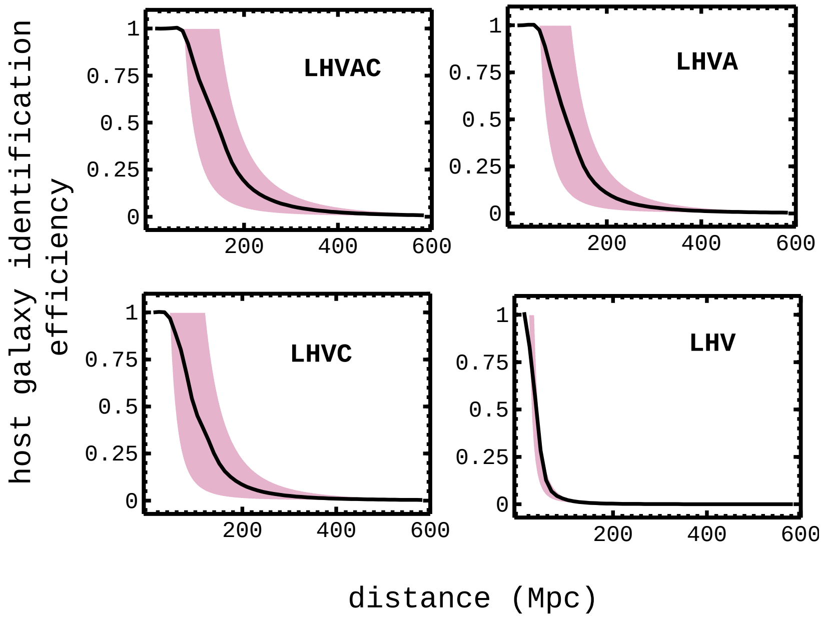

Figure 4: The host galaxy detection efficiencies for the four detector array configurations of Figure 3. All curves include 20% uncertainties in the determination of the luminosity distances as estimated by Cutler and Flanagan [16]. The shaded area is set by two limits: a mean galaxy density and a detector network that has optimal angular resolution over 90% of the sky; secondly, a lower estimate of number density and 50% sky directions. The dark line shows the average identification efficiency for each detector array.

4 Discussion and Conclusion

We have shown that a global array of GW detectors that contains AIGO and LCGT is substantially improved. The efficiency in host galaxy determination is near unity for about 30% of all coalescing binary sources within 200 Mpc. We can expect that an average of about 6 sources per year could be uniquely identified with particular galaxies, assuming current event rate estimates. In the case of ambiguity, the number of potential galaxies is not large. A relatively small number of deep exposures would be able to search effectively for associated electromagnetic emission.

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