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To cite this article: D G Blair et al 2008 J. Phys.: Conf. Ser. 122 012001

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The Science benefits and Preliminary Design of the Southern hemisphere Gravitational Wave Detector AIGO

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Abstract. 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. This allows the world array to be substantially improved. The orientation of AIGO allows much better resolution of both wave polarisations. This enables better distance estimates for inspiral events, allowing unambiguous optical identification of host galaxies for about 25% of neutron star binary inspiral events. This can allow Hubble Law estimation without optical identification of an outburst, and can also allow deep exposure imaging with electromagnetic telescopes to search for weak afterglows. This allows independent estimates of cosmological acceleration and dark energy as well as improved understanding of the physics of neutron star and black hole coalescences. This paper reviews and summarises the science benefits of AIGO and presents a preliminary conceptual design.
1. Introduction

Currently there are four kilometer scale gravitational wave detectors in the world (3 LIGO detectors in the US—L1 in Livingston, Louisiana, H1 and H2 co-located at Hanford, Washington) and the VIRGO detector in Pisa, Italy. There are also smaller detectors in Europe and Asia: GEO600 in Hannover, Germany, and TAMA in Tokyo, Japan. In the coming decade, 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 lower shot noise, leading to an amplitude sensitivity about 10 times better than existing detectors, enabling them to monitor a volume of the universe 1000 times larger than current detectors. Frequent neutron star inspiral events should be detectable as well as more distant binary black hole coalescences. 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 (see for example E E Flanagan and S A Hughes\cite{1}). Future improvements using third generation detectors will improve this capability even further.

The correlation of electromagnetic events with gravitational wave signals provides enormous science benefits. 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 itself, independent of 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\cite{2}. However, this requires the identification of the gravitational waves source locations to find the electromagnetic counter-part of the event.

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 to the product of the projected detector spacing and the signal to noise ratio. A world wide array of detectors can achieve an angular resolution of ~10arc minutes for signals in the audio frequency terrestrial detection band as discussed further below. However, the two dimensional projected detector spacing can only be large for all directions in the sky if the array contains a southern hemisphere detector. Here we summarise the scientific benefits of the AIGO detector and the then go on to summarise a preliminary conceptual design for this detector.

2. Scientific benefits of the AIGO observatory

It has long been recognised that an Australian detector disproportionately improves the science return of the existing international network of gravitational wave detectors. This disproportionate impact comes about for several reasons.

First, an Australian detector would improve our ability to determine, from gravitational waves alone, the location a gravitational wave event on the sky. Gravitational wave detectors largely determine position by triangulation using time of arrival information between different detectors—phase fronts of an incident gravitational wave interact with different detectors at different times. Coherent network analysis effectively resolves these differing times of arrival, enabling the detector array to be an all sky monitor with good angular resolution over all source directions. Detailed calculations by Wen et al\cite{3,4,5} indicate that inclusion of AIGO would on average improve the international network's ability to localize sources from about 12 square degrees to a fraction of a square degree as shown in Figure 1. Without AIGO, the error ellipses are typically about 1.5 deg × 8 deg. With AIGO, they are significantly smaller than 1 deg × 1 deg. The error ellipse would then be well matched to the field of view of most sensitive optical, X-ray and radio telescopes, so that it becomes possible to conduct very long exposure searches for electromagnetic signatures of gravitational wave events.
The second major impact of an Australian detector would be to improve our ability to measure both polarizations of a signal. At least two detectors with substantial different orientations are needed to fully reconstruct both wave polarizations from the data. The LIGO detectors in the USA are oriented in such a way that they do not provide information about both polarization components. This was a deliberate choice—by orienting both detectors such that they each measure the same wave polarization, the statistical confidence in any given detection is greatly increased. For the initial goal—unambiguous first detection of gravitational waves—this is a natural and appropriate choice of detector orientations. Unfortunately, this is not such a good choice of detector orientations once direct detection has occurred.

The primary goal of developing the science of gravitational-wave astronomy requires the measurement of the polarizations, as this increases our ability to infer astronomically important information. Consider, for example, waves from binary coalescence, of which advanced detectors expect to detect more than 20 events per year. In this case, the amplitude ratio of the two gravitational wave polarizations encodes the inclination of the plane of the binary orbit with respect to the line of sight from the Earth. Once the orbital inclination is defined, the frequency evolution of the gravity wave signal contains a complete description of the system, and the observed amplitude therefore encodes the distance of the source. This remarkable property of gravitational wave signals enables them to be powerful cosmological probes. Adding an Australian detector to the network augments its capability to measure polarizations simply due to its orientation on the nearly spherical surface of the Earth. Thus with AIGO the network can obtain more precise distance information to sources\cite{2}.

The third benefit from the Australian detector relates to the noise performance of the network. For broadband stationary noise, the noise of a network of detectors is reduced as the square root of the number of detectors. While this factor is not large (only \(\sim 25\%\)), it has a much larger effect on the number of detectable sources, since the number of detectable sources depends on the volume of the accessible universe, which increases as the cube of the detector strain sensitivity. Thus the global array can be expected to detect almost double the number of signals with the addition of a single southern hemisphere detector of sensitivity comparable to the northern hemisphere detectors. For non-stationary noise, a larger network has the benefit of being much better at rejecting spurious signals. Such signals must mimic a gravitational wave passing through the network by arriving at each detector at a time and with appropriate amplitude to be consistent with a real gravitational wave signal. The probability of such a signal reduces as the power of the number of detectors, so the addition of a single detector reduces this probability. This reduction can be by a factor of 10-100 depending on the types of signal.

The above three improvements provided by adding AIGO to the world array enhances the knowledge we can gain about the gravitational wave sources. For some sources, such as core collapse supernovae, the waves are likely to be poorly understood prior to gravitational wave observations. For others such as waves from black hole binary mergers, the signals are likely to be only moderately well understood, while waves from coalescing binaries prior to merger are well understood. In the not-well-understood regime one must use the observed waves to solve an inverse problem and obtain an understanding of the dynamics of the source. Gursel and Tinto\cite{6} developed methods for performing the “inverse” problem, and examined how well it could be implemented using detectors located in North America, Germany, and Australia. Their work demonstrates that the addition of AIGO to the network improves the reconstruction of such waves. In the other extreme of a well understood system, the signal can be used to define the source distance and location on the sky.

Figure 1 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. AIGO improves the angular resolution and also eliminates 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 thereby obtaining good angular resolution in almost all sky directions. The array is even further improved if LCGT is added.
To quantify the problem of host galaxy determination, we need an estimate of the number of galaxies within the detector array angular resolution. Figure 2 shows the average number of galaxies per 1σ error ellipse for different gravitational wave detector arrays, as reported in Wen et al in 2007 [5]. We see that the average number of galaxies at 200Mpc varies from in excess of 200 for LIGO-VIRGO array (LHV) to about 4 if AIGO an LCGT are added to the array. Taking the galaxy distribution into account, Wen et al showed that about 25% of sources can be unambiguously identified with a galaxy. This allows the Hubble Law to be tested without actual identification of an optical outburst.

Figure 2 The average number of galaxies expected within a 1-σ error ellipse for different gravitational wave detector arrays, based on the angular resolution of each array for each sky direction. The figure shows that the number of galaxies per error ellipse is reduced from almost 200 for the LIGO-VIRGO array, to less than 10 for LIGO-VIRGO-AIGO. For a single additional detector, AIGO gives the greatest benefit, but the best array contains AIGO and LCGT. The symbols in the figures are: C—LCGT, A—AIGO, V—VIRGO, LH—LIGO.

3. Preliminary Conceptual design for AIGO
A preliminary conceptual design for AIGO utilizes the maximum arm length possible on our site of about 5km. The extra arm length has the advantage of diluting local noise sources such as thermal noise and control system noise, allowing slightly less demanding specification for coating acoustic loss and control systems. With Advanced LIGO (AdvLIGO) test mass and control specifications, the maximum inspiral range is increased from about 200Mpc to 250Mpc, corresponding to a doubling of the accessible volume of the universe.

Our design uses slightly smaller beam spots than AdvLIGO, (55mm) to maintain 1ppm arm cavity diffraction loss. This slightly increases the test mass thermal noise but reduces the overlap factor for parametric instability. The vacuum arms are chosen to be the same diameter as LIGO’s. The vacuum design has been shown to allow LIGO vacuum specifications to be exceeded. A passive solar thermal bakeout system has been demonstrated experimentally. The vacuum system will include future provision for ion pumps.

Vibration isolation will use multistage passive isolators developed at UWA, subject to successful evaluation. Two are currently being evaluated on an 80m optical cavity. The isolators have an extra preisolation stage compared with the VIRGO design. Otherwise they are conceptually similar to those of VIRGO but are much more compact, occupying about 10% of the volume (and are correspondingly cheaper).

We propose to use sapphire for the test masses, because this material has a low acoustic mode density compared with fused silica, which would reduce the problem of parametric instability. Sapphire also has the advantage of fast thermal response, which means that the system comes into thermal quasi-steady state much more rapidly than fused silica, further aiding parametric instability control.

The absorption requirement of the two inner test masses is 50ppm/cm. This is typical of good quality material currently available. The end test masses can use sapphire of lower optical quality. Auxiliary optics will be made from fused silica: mirrors for a quasi-stable power recycling cavity, the 10m input mode cleaner and 1m output mode cleaner.

The test mass suspension system follows the design developed by Lee at UWA, utilising four thin niobium ribbons with micro-cantilever suspension from equatorial holes in the test masses. The test masses are controlled electrostatically using annular bifilar comb capacitors incorporating an RF local control readout which serves as an auxiliary local sensor. They are supported by a control mass which plays the role of a VIRGO marionetta. Main test mass control is by actuators on the control mass.

The laser, injection locked to the successful Adelaide 10W laser now in use, will initially have a power of 100W. This may need to be augmented to 200W, subject to performance of the vacuum squeezing. Vacuum squeezing is currently not part of the AIGO baseline design but could be implemented if the technology is available.

Two prototype auxiliary optics suspensions have already been developed. These use two stages of horizontal pre-isolation (one inverse pendulum, one Roberts linkage), one Euler spring and one pair of blade springs for vertical isolation. These will be used to support the mode cleaner mirrors as well as the power recycling and signal recycling mirrors.

Hartmann sensor technology for monitoring wavefront distortion has been developed at Adelaide and recently demonstrated in Gingin. The AIGO design includes Hartmann sensors with CO2 laser thermal control to monitor and compensate wavefront distortion in all test masses as well as the beam splitter and compensation plates. The control specification is to better than 1nm. Closed loop thermal compensation control has been successfully implemented at the Gingin facility.

The proposed interferometer configuration will be detuned Resonant Sideband Extraction. The control strategy is likely to be based on an ANU concept in which control signals are injected into both beamsplitter ports. We propose to use an 80m stable power recycling cavity containing a thermal compensator lens.

The input mode cleaner design for AIGO will use a triangular 10m cavity with apex mirror output for reduced astigmatism. An output mode cleaner will be employed to reject light in higher order
modes and control modulation sidebands from reaching the photodetectors. This is likely to be based on the AdvLIGO concept of a 4 mirror ring cavity silicate bonded onto a glass breadboard.

4. Discussion and Conclusion
We have shown that a global array of gravitational wave detectors that contains AIGO is substantially improved. Better polarisation resolution allows improved distance estimates for inspiral events. Roughly 25% of detected inspiral events can be identified with a particular galaxy. This enables independent measurements of the Hubble constant with or without detection of an optical outburst. The addition of AIGO doubles the number of detectable sources and reduces non-stationary noise by more than an order of magnitude. A 5km interferometer has significant advantages, particularly in reducing thermal noise, and in principle can detect double the number of sources compared with a single advLIGO interferometer.

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