AIGO: a southern hemisphere detector for the worldwide array of ground based interferometric gravitational wave detectors

P Barriga[1], D G Blair[1], D Coward[1], J Davidson[1], J-C Dumas[1], E Howell[1], L Ju[1], L Wen[1], C Zhao[1], D E McClelland[2], S M Scott[2], B Slagmolen[2], R Inta[2], J Munch[3], D J Ottaway[3], P Veitch[3], D Hosken[3], A Melatos[4], C Chung[4], L Sammut[4], D K Galloway[5], J Marx[6], S Whitcomb[6], D Shoemaker[7], S A Hughes[8], D H Reitze[9], B R Iyer[10], S V Dhurandhar[11], T Souradeep[11], C S Unnikrishnan[12], G Rajalakshmi[12], C N Man[13], A Heidmann[14], P-F Cohadon[14], T Briant[14], H Grote[15], K Danzmann[15,16], H Lück[15,16], B Willke[15,16], K A Strain[17] and B S Sathyaprakash[18]

[1]School of Physics, The University of Western Australia, Crawley, WA 6009, Australia

[2]Department of Physics, Faculty of Science, Australian National University, Canberra, ACT 0200, Australia

[3]Department of Physics, University of Adelaide, Adelaide, SA 5005, Australia

[4]School of Physics University of Melbourne, Parkville, Vic 3010, Australia

[5]School of Mathematical Sciences, Monash University, Vic 3800, Australia

[6]LIGO – California Institute of Technology, Pasadena, CA 91125, USA

[7]LIGO – Massachusetts Institute of Technology, Cambridge, MA 02139, USA

[8]University of Florida, Gainesville, Florida 32611, USA

[9]Department of Physics, Massachusetts Institute of Technology and MIT Kavli Institute, Cambridge, MA 02139, USA

[10]Raman Research Institute, C. V. Raman Avenue Sadashivanagar Bangalore, 560 080 India

[11]Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Ganeshkhind, Pune 411 007, India

[12]Gravitation Group, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai – 400 005, India

[13]Université Nice Sophia-Antipolis, CNRS, Observatoire Côte d'Azur, BP 4229, 06304 Nice Cedex 4, France

[14]Laboratoire Kastler Brossel, CNRS, Ecole Normale Supérieure and Université P. et M. Curie, Case 74, 4 place Jussieu, F75252 Paris Cedex 05, France

[15]Albert-Einstein-Institut, Max-Planck-Institut für Gravitationsphysik, D-30167 Hannover, Germany

[16]Leibniz Universität Hannover, D-30167 Hannover, Germany

[17]University of Glasgow, Glasgow G12 8QQ, UK

[18]Cardiff University, Cardiff CF24 3AA, UK

Abstract. This paper describes the proposed AIGO detector for the worldwide array of interferometric gravitational wave detectors. The first part of the paper summarises the benefits that AIGO provides to the worldwide array of detectors. The second part gives a technical description of the detector, which will follow closely the Advanced LIGO design. Possible technical variations in the design are discussed.

1. Introduction: Science Benefits of AIGO

An individual gravitational wave (GW) detector is almost omni-directional with a wide antenna pattern and poor angular resolution. In order to undertake GW astronomy and astrophysics, a network of detectors is indispensable. The existing network consisting of the two LIGO sites, Virgo and GEO has poor angular resolution along directions perpendicular to the line connecting the US and Europe, and correspondingly poor polarisation information. Limited information about the wave strength in the two polarisations will leave many questions about the sources unanswered, and underlines the case for extension of the network. The addition of a southern hemisphere detector maximises the network baseline, improving sensitivity and sky coverage and enabling astrophysical studies.

Advanced LIGO, Advanced Virgo and GEO-HF are upgrades of the initial ground-based interferometric GW detectors. They are currently under construction. To enhance this network new detectors are proposed: LCGT in Japan, AIGO in Australia and IndIGO a possible detector in India (figure 1). These advanced detectors are designed to have improved low frequency performance and lower shot noise, leading to amplitude sensitivity about 10 times better than existing detectors, enabling them to monitor a volume of the universe 1000 times larger than current detectors. They are expected to enable frequent detection of GW sources in the 10 Hz–10 kHz range. Localisation and identification of sources, plus full extraction of polarisation data from gravitational waveforms and joint GW–electromagnetic (EM) studies will allow general relativity to be probed in the strong field regime.

1.1. Angular Resolution and Source Localisation

The addition of another detector, well out of the plane of the existing network, enables improved angular resolution for GW sources that would otherwise be poorly resolved.

For transient sources, such as short bursts and binary inspirals, the network directional sensitivity is determined by comparison of the signal phase at widely spaced detectors. Thus a fourth detector, placed well out of the plane formed by the existing three, will allow the number of sources that can be located to within a single galaxy to be increased by a factor of three.

AIGO improves the ability to determine, from GW detection alone, the location of the sources on the sky. The coherent analysis of signals from the array allows the network to have diffraction limited resolution, where, as with VLBI radio astronomy, the angular

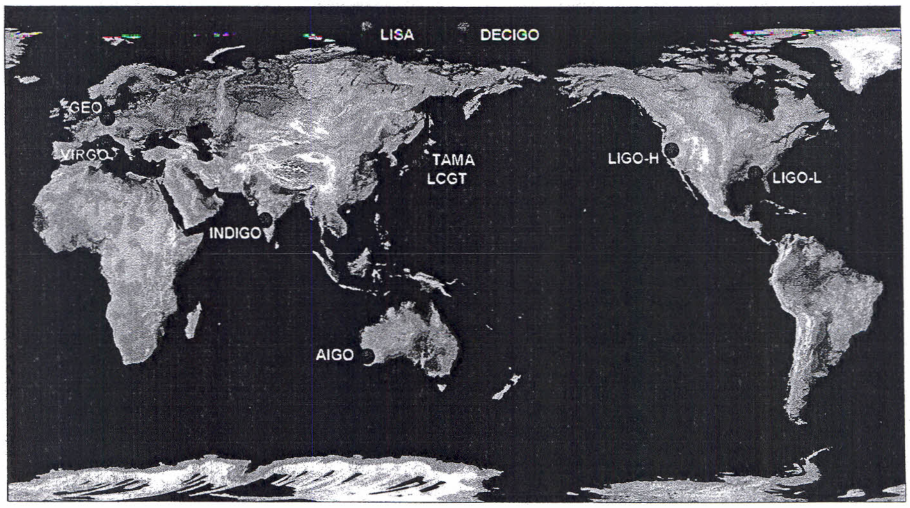

Figure 1. Location of existing and proposed interferometric gravitational wave detectors including the proposed space interferometers LISA and DECIGO.

resolution is set by the ratio of the signal wavelength to the product of the projected detector spacing and the signal to noise ratio. Detailed calculations by Wen *et al.* [1, 2] indicate that inclusion of AIGO would improve the international network's ability to localise sources. Figure 2 shows a significant improvement in the angular uncertainty on the sky when adding AIGO to the network of GW detectors. The increase in maximum baseline improves the angular resolution in almost all sky directions. It also reduces the number of galaxies within an average error ellipse by one order of magnitude as Figure 3 shows. As the figure shows the array is even further improved if LCGT is added. We note that since the angular resolution is inversely proportional to the frequency, the resolution will depend on the source type.

1.2. Gravitational Waves Polarisation

The primary goal of developing the science of GW astronomy requires the measurement of both GW polarisations, as this increases the potential to extract astrophysical information. To extract the two orthogonal polarisations (h_+ and $h_\times$) of the the incident wave, a network with detectors of different orientation in three dimensions is required.

The overlap of the individual antenna patterns spreads over the spherical surface of the Earth creating a non-uniform global antenna pattern. The angular resolution is inversely proportional to the projected detector separation and the signal to noise ratio [2]. This complex array antenna pattern rotates relative to a galaxy distribution pattern. The ability of the global antenna to resolve individual host galaxies will depend on the instantaneous coincidence of the antenna pattern with the galaxy distribution pattern.

Consider, for example, waves from binary coalescence. Advanced detectors expect to detect ~40 events per year. In this case, the amplitude ratio of the two GW property of GW signals that enables them to be powerful cosmological probes. Adding an Australian detector to the network augments its capability to measure polarisations simply due to its orientation on the nearly spherical surface of the Earth. Thus AIGO enables the network to obtain 2-3 times improved precision for distance estimation of sources [3].

1.3. Gravitational Waves and Electromagnetic Waves

The correlation of EM sources with GW signals provides enormous science benefits. It is possible to search for EM transients correlated with candidate GW events that alone would have insufficient signal to noise ratio to be able to claim detection. Thus, instead of restricting candidate detection to high signal to noise ratio events, corresponding to say one false positive detection in 50 years, one can work with a reduced signal to noise where the false positive rate is say one per day. If the angular resolution is adequate, then EM detectors can search the error ellipse for a coincident afterglow. An EM source spatially and temporally correlated with a GW candidate is extremely unlikely. Therefore low signal to noise ratio GW events can translate into highly significant detections of GW. In this way EM correlation enables increases in the sensitivity and the horizon distance for the GW detector array, corresponding to a substantially improved event rate.

If a detected GW burst or inspiral chirp of GW is accompanied by an EM signal such as a gamma-ray burst, then a comparison of the arrival times of the two bursts will give an immediate, high-precision measurement of the speed of GW relative to that of light. Such a test depends crucially on having sufficient angular resolution for the GW signal to identify reliably that the EM pulse came from the same source. For binary black hole inspirals, the luminosity distance can be determined from the GW inspiral event, independent of the red shift determined from observation of the host galaxy. This allows a powerful independent probe of the Hubble law [4], cosmological acceleration and the equation of state of dark energy [3].

Optical telescopes distributed around the world can potentially respond to GW triggers and search the relevant sky directions. A 1 m fast response robotic telescope has been installed at the proposed AIGO site. It is primed to respond to external triggers robotically and has already observed gamma-ray burst afterglows as faint as apparent magnitude $\sim$23 [5].

1.4. Noise performance

Broadband stationary noise in a network of detectors is reduced as the square root of the number of detectors. While this factor is not large ($\sim$ 25%), it has a much larger effect on the number of detectable sources. This number depends on the volume of the accessible universe, which increases as the cube of the detector strain sensitivity. Therefore with the addition of a southern hemisphere detector of sensitivity comparable to the advanced detectors is expected to double the number of detectable sources.

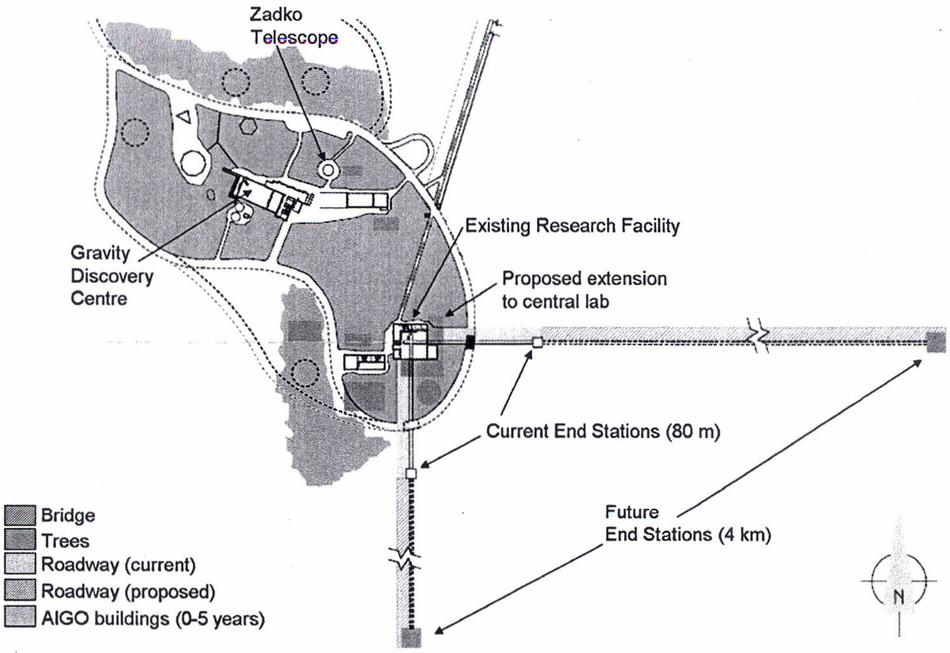

Figure 4. Proposed AIGO site at Wallingup plain 80 km north of Perth in Western Australia.

back into the interferometers arms. This power recycling technique increases the circulating power in the arm cavities without affecting the frequency response of the interferometer [10].

The first generation of interferometric GW detectors (LIGO and Virgo) used marginally stable power recycling cavities in an essentially flat/flat configuration. These cavities did not confine the spatial modes of the RF sidebands which led to significant spatial mode-mismatch between them and the carrier. Also marginally stable signal recycling cavities will reduce the amplitude of the GW-sidebands by resonantly enhancing the scattering of light into higher order spatial modes. As a consequence stable recycling cavities are an integral part of the optical design of the next generation of interferometric GW detectors [11, 12, 13]. Figure 5 shows the proposed optical layout for AIGO, including an input mode-cleaner (IMC), a power recycling cavity (PRC), two arm cavities, a signal recycling cavity (SRC) and an output mode-cleaner (OMC). The IMC has been thoroughly studied [14, 15] and the current design includes a suspended IMC, however an optical fibre mode-cleaner is being studied by research institutes in France and could be included in the AIGO design [16].

Due to the higher circulating power in advanced detectors, test masses that form the Fabry-Perot arms are made of high purity fused silica to reduce thermal effects. To control these effects a fused silica compensation plate will be installed behind each ITM inside the PRC; sensing will be done using off-axis Hartmann sensors. This configuration had been successfully tested at the Gingin test facility [17]. Test masses will be heavier ($\sim$40 kg) in order to reduce the effects of radiation pressure. Multi-layer dielectric

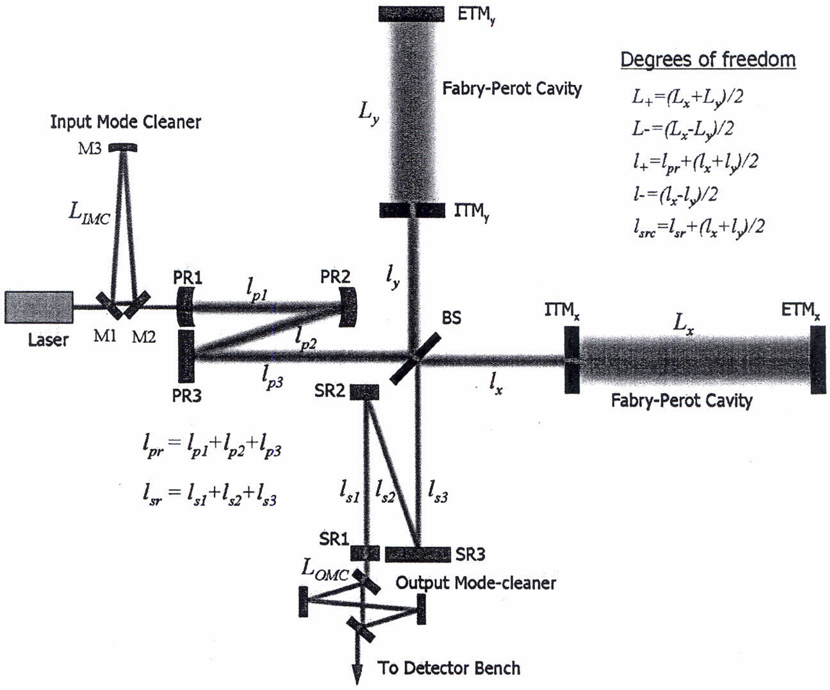

Figure 5. Dual-recycled advanced interferometric GW detector proposed for AIGO. The figure shows stable recycling cavities and length degrees of freedom, including input mode-cleaner (IMC) and output mode-cleaner (OMC). The power recycling mirror (PRM), beamsplitter (BS), both input test masses (ITMx and ITMy), and both end test masses (ETMx and ETMy). It shows stable power recycling cavity (PRC) formed by the power recycling mirrors (PR1, PR2 and PR3) and both input test masses passing through the BS. Also a stable signal recycling cavity (SRC) formed by the signal recycling mirrors (SR1, SR2 and SR3) and both ITMs. It also shows the different degrees of freedom that need to be controlled.

provide an excellent reference for aligning the injection of squeezed light [25].

2.3. Vibration Isolation

Advanced LIGO has chosen to implement a 'stiff' pre-isolation technique based on hydraulic systems distributed on each corner of the vacuum chamber, complemented by a two-stage 6-DOF active isolator in vacuum [26]. These provide vertical and horizontal pre-isolation for the whole chamber combining geophones and seismometers with high resonant frequencies in a high-bandwidth control loop. A four-stage pendulum test-mass suspension provides significant additional isolation in the GW band.

A different approach in terms of pre-isolation has been taken by other groups adopting a 'soft' design [27, 28, 29]. Primarily based on very low resonant frequencies, these are achieved with different damping solutions based on anti-spring designs and electromagnetic coupling, complemented with low bandwidth feedback control loops. A vibration isolation system based on multiple cascaded stages, see Figure 6 (a), has been developed by UWA. The design includes two stages of horizontal pre-isolation, (Hannover) [35]. It is based on a high stability low power master laser with low frequency fluctuations, which is amplified in a master-oscillator power-amplifier (MOPA) configuration to 35 W. The slave oscillator is an injection-locked oscillator that relies on a birefringence compensation scheme [36].

Up to the medium power stage, the laser corresponds to the MOPA laser currently being used in the Enhanced LIGO science run [37]. After high power amplification a bow-tie configuration pre-mode-cleaner is installed in order to reduce higher order optical modes and provide filtering for power noise at radio frequencies. A reference cavity provides frequency stabilisation with feedback to the NRPO laser. By controlling the temperature of this reference cavity one can stabilise the laser to the slow drift of the long arm cavities due to Earth tides. An AOM frequency shifter placed in the beam path towards the reference cavity is used as an actuator to stabilise the laser to the AIGO suspended input mode-cleaner, which is a much quieter frequency reference.

2.5. Vacuum System

Following the successful experience of LIGO the long baselines will be fabricated from pre-treated, air-baked 304L-grade stainless steel (SS304L). The partial pressure of hydrogen is required to be $\sim 10^{-9}$ mbar to obtain residual gas-phase noise of $\sim 10^{-25}$ Hz$^{-1/2}$ [38]. The vacuum-tube diameter ($\sim$1.2 m) is set by the light-scattering requirements, and also by the possible need for additional optical cavities within the tube, such as a suspension point interferometer [39].

The SS304L, while in the form of a roll, will be baked at 450°C for 36 hours in a low-humidity air atmosphere to reduce the hydrogen outgassing rate [40]. The baffles, designed to minimise the scattering of light within the tube, will also undergo baking and will be installed along with the tube fabrication. Once the tube is installed low temperature vacuum baking (150°C) to remove species such as H_2O, CO, and CO_2 [41, 42, 43] will be performed using a solar bakeout technique already tested experimentally [44]. Stiffening rings will be used at regular intervals to prevent the collapse of the tube under atmospheric pressure and every 200 m bellows will be located to compensate for thermal expansion. The tube will be supported on concrete footings along the length to ensure linearity within 5 mm.

A prototype vacuum control system is working satisfactorily at the 80 m test facility and is planned to be extended to the 4 km. To achieve the vacuum specifications it is necessary to use three or four pumps along each arm. End-station tanks will be pumped separately, so they contribute no additional load. The effects of baffles on the ultimate vacuum were modelled by Sunsmithian [45], showing that baffles only degrade the ultimate vacuum by a few percent.

[5] D. M. Coward, M. Todd, T. P. Vaalsta, et al, *Publ. Astron. Soc. Aust.*, 2009. submitted.
[6] E. E. Flanagan and S. A. Hughes, *Phys. Rev. D* **57**, 4535–4565, 1998.
[7] Y. Gürsel and M. Tinto, *Phys. Rev. D* **40**, 3884–3938, 1989.
[8] D. Coward, D. Blair, R. Burman, et al, *Rev. Sci. Instrum.* **74**, 4846–4854, 2003.
[9] D. Coward, J. Turner, D. Blair, et al, *Rev. Sci. Instrum.* **76**, 044501, 2005.
[10] R. W. P. Drever, *Lecture Notes in Physics, Berlin Springer Verlag* **124**, 321–338, 1983.
[11] Y. Pan, *arXiv:gr-qc/0608128v1*, 2006.
[12] M. A. Arain and G. Mueller, *Opt. Express* **16**, 10018–10032, 2008.
[13] P. Barriga, M. A. Arain, G. Mueller, et al, *Opt. Express*, **17** 2149–2165, 2009.
[14] P. J. Barriga, C. Zhao, and D. G. Blair, *Phys. Lett. A* **340**, 1–6, 2005.
[15] P. Barriga, C. Zhao, L. Ju, et al, *J. Phys. Conf. Ser.* **32**, 457–463, 2006.
[16] P. LaPenna, Technical Report G070361-00-Z, LIGO, 2006.
[17] Y. Fan, C. Zhao, J. Degallaix, et al, *Rev. Sci. Instrum.* **79**, 104501, 2008.
[18] G. M. Harry, et al, *Class. Quantum Grav.* **24**, 405–415, 2007.
[19] R. Abbott, R. Adhikari, S. Ballmer, et al, Technical Report T070247-00-I, LIGO, 2008.
[20] O. Miyakawa, R. Ward, R. Adhikari, et al, *J. Phys. Conf. Ser.* **32**, 265–269, 2006.
[21] A. Buonanno, T. Chen, and N. Mavalvala, *Phys. Rev. D* **67**, 2003.
[22] P. Fritschel and G. Sanders, Technical Report T000062-00-D, LIGO, 2000.
[23] S. Hild, H. Grote, J. Degallaix, et al, *Class. Quantum Grav.* **26**, 055012, 2009.
[24] F. Beauville, D. Buskulic, L. Derome, *Class. Quantum Grav.* **23**, 3235–3250, 2006.
[25] H. Vahlbruch, S. Chelkowski, B. Hage, *Class. Quantum Grav.* **23**, S251–S257, 2006.
[26] A. Stochino, B. Abbot, Y. Aso, et al, *Nucl. Instrum. Meth. A* **598**, 737–753, 2009.
[27] G. Losurdo, M. Bernardini, S. Braccini, et al, *Rev. Sci. Inst.* **70**, 2507–2515, 1999.
[28] M. V. Plissi, C. I. Torrie, M. E. Husman, et al, *Rev. Sci. Instrum.* **71**, 2539–2545, 2000.
[29] S. Marka, A. Takamori, M. Ando, *Class. Quantum Grav.* **19**, 1605–1614, 2002.
[30] R. Rinker, PhD Thesis, Department of Physics, University of Colorado at Boulder, 1983.
[31] J. Winterflood, PhD Thesis, School of Physics, The University of Western Australia, 2001.
[32] B. H. Lee, L. Ju and D. G. Blair, *Phys. Lett. A*, **350**, 319–323, 2006.
[33] J. C. Dumas, P. Barriga, C. Zhao, *Rev. Sci. Instrum.*, 2009. accepted for publication.
[34] P. Barriga, J. C. Dumas, A. A. Woolley, et al *Rev. Sci. Instrum.*, 2009. accepted for publication.
[35] B Willke, K Danzmann, M Frede, et al *Class. Quantum Grav.* **25**, 114040, 2008.
[36] M. Frede, R. Wilhelm, D. Kracht, et al, *Opt. Express* **13**, 7516–7519, 2005.
[37] M Frede, B Schulz, R Wilhelm, et al *Opt. Express* **15**, 459–465, 2007.
[38] D. Coyne, Technical Report T040001-00-D, LIGO, 2004.
[39] Y. Aso, M. Ando, K. Kawabe, et al, *Phys. Lett. A* **327**, 1–8, 2004.
[40] W. A. Carpenter, P. B. Shaw, L. Jones, et al, *J. Vac. Sci. Technol. A* **18**, 1794–1799, 2000.
[41] K. Odaka and S. Ueda, *J. Vac. Sci. Technol. A* **13**, 520–523, 1995.
[42] M. Bernardini, S. Braccini, R. D. Salvo, et al, *J. Vac. Sci. Technol. A* **16**, 188–193, 1998.
[43] J. R. J. Bennett, S. Hughes, R. J. Elsey, et al, *Vacuum* **73**, 149–153, 2004.
[44] D. Berinson, D. Blair, P. Turner, et al, *Vacuum* **44**, 151–154, 1993.
[45] S. Sunil and D. G. Blair, *J. Vac. Sci. Technol. A* **25**, 763–768, 2007.