Woan, G. (2005) *Gravitoastronomy with neutron stars.* In: Gravitational Wave and Particle Astrophysics Detectors, 23 June 2004, Glasgow, Scotland.

Gravitoastronomy with neutron stars

G. Woan, for the LIGO Scientific Collaboration
Institute for Gravitational Research, University of Glasgow, Glasgow G12 8QQ, UK

ABSTRACT

Recent advances in gravitational wave detectors mean that we can start to make astrophysically important statements about the physics of neutron stars based on observed upper limits to their gravitational luminosity. Here we consider statements we can already make about a selection of known radio pulsars, based on data from the LIGO and GEO 600 detectors, and look forward to what could be learned from the first detections.

Keywords: gravitational waves, pulsars, neutron stars, LIGO, GEO 600

1. INTRODUCTION

One of the clearest, most compelling, and famous pieces of evidence for the existence of gravitational waves comes from neutron stars. The "Hulse-Taylor" binary pulsar (PSR B1913+16) is a double neutron star system that has displayed a steady inspiral since its discovery[1] in 1974, with a loss of orbital kinetic energy that is accurately consistent with gravitational wave dissipation[2] (Fig. 1). Recent pulsar surveys have revealed around ten further relativistic binary systems,[3] including at least four other simple double neutron star systems (PSR B1534+12, B2127+11C, J1518+4904, J1811−1736) and and one double pulsar system (PSR J0737−3039). Future observations of these systems will provide stringent tests of the validity of General Relativity, but already there is little doubt that gravitational radiation plays an important part in the energy balance of these binaries.

Although these pulsars reveal the effects of gravitational wave dissipation, the evidence is indirect in the sense that the gravitational waves themselves are not being detected. No detectors presently operating have the low-frequency sensitivity necessary to detect gravitational waves emitted at twice the orbital periods of these systems. The shortest-period double neutron star system currently known is PSR J0737−3039, with an orbital period of 8 834.5 s[4, 5] and therefore an orbital gravitational wave frequency of about 0.23 mHz. This frequency is well below what can be reached by ground-based detectors and, at the strain sensitivity needed, barely detectable within one year by LISA. Only once these types of orbit have decayed to the point when the neutron stars are entering their final inspiral phase will they be seen by ground-based detectors as short, relatively high frequency chirps.

Although the direct detection of gravitational waves from the orbital quadrupole of these known systems will not be possible in the near future, there is some hope of seeing direct gravitational waves from the spinning neutron stars themselves. The present generation of ground-based gravitational wave detectors are reaching strain sensitivities for which the detection of direct gravitational radiation from spinning neutron stars is a real possibility.[7] In particular, the US LIGO[8] interferometers at Hanford (WA) and Livingston (LA) have now reached strain sensitivities as low as $6 \times 10^{-23}\,\mathrm{Hz}^{-1/2}$ at frequencies around 120 Hz and with broadband responses that are rapidly approaching the design sensitivities of these instruments. The UK/German GEO 600 detector,[9] located near Hannover, Germany, presently offers a sensitivity approaching that of LIGO Livingston at frequencies around 1 kHz and has a rapidly improving low-frequency response. The TAMA interferometer[10] near Tokyo, Japan, has been operating with an outstanding duty cycle for several years and has only recently been surpassed in sensitivity at 1 kHz, and the Italian/French VIRGO interferometer near Pisa, Italy, is nearing completion[11] and promises world-beating sensitivities at frequencies below about 50 Hz.

The limiting low-frequency responses of these devices are largely defined by environmental factors, with seismic noise being a dominant effect below a few tens of hertz. Although much work has been done on very low frequency seismic isolation, notably by the VIRGO team, it remains the case that the the majority of known radio

---

Further author information: (Send correspondence to G. Woan)
Graham Woan: E-mail: graham@astro.gla.ac.uk

Gravitational Wave and Particle Astrophysics Detectors, edited by
James Hough, Gary H. Sanders, Proceedings of SPIE Vol. 5500
(SPIE, Bellingham, WA, 2004) · 0277-786X/04/$15 · doi: 10.1117/12.550057

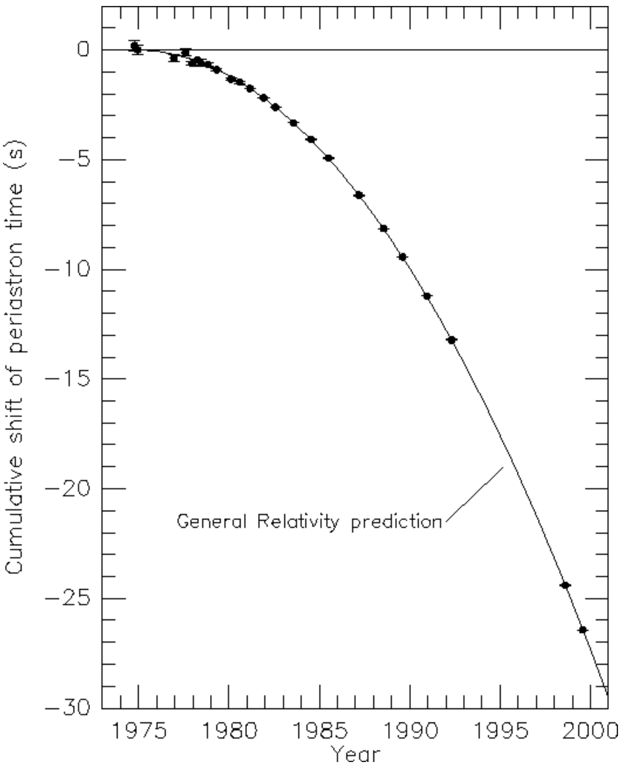

Figure 1. The observed orbital evolution of PSR B1913+16 (dots) compared to the prediction of General Relativity, assuming the system is damped by emission of gravitational radiation (from Weisberg and Taylor[6]).

pulsars have spin periods that fall outside the main sensitivity band of these interferometers. This is clear from Fig. 2, showing a histogram of pulsar gravitational wave frequencies (taken as twice their rotation frequencies) for 1 488 pulsars from the ATNF pulsar catalogue (www.atnf.csiro.au/research/pulsar/psrcat/), overlaid on the LIGO design sensitivity curve for a 1 yr observation, adjusted for mean antenna pattern and source orientation parameters. The figure reveals how nature has conspired against us. Most pulsars have spin frequencies that are around an order of magnitude too low to be seen by LIGO. Only those with rotational frequencies greater than about 25 Hz stand a significant chance of being seen through the seismic wall comprising the left of the sensitivity curve. Of these accessible pulsars most are probably recycled neutron stars, spun-up by accretion of matter from a binary partner. Indeed of the 110 pulsars contributing to the histogram with spin frequencies greater than 25 Hz, 70 are seen in binary systems.

One of the pulsars within the band deserves a special mention. The Crab pulsar (PSR B0531+21) is a young pulsar ($P/(2\dot{P}) \simeq 1\,250\,\mathrm{yr}$) with an expected gravitational wave signature that at present is just below 59.6 Hz. The Crab pulsar has a high spindown rate of about $-3.74 \times 10^{-10}\,\mathrm{Hz\,s^{-1}}$ and is an important target for gravitational wave detectors because the upper limit to the gravitational power it emits, based on the inferred rate of loss of rotational kinetic energy, is well above the noise floors of several detectors operating at design sensitivity for 1 yr. Although there are several other important ways in which the Crab pulsar is visibly losing energy, including X, UV and optical emission and the power needed to support the expansion of the supernova remnant,[12, 13] its energy budget is not sufficiently well understood to rule out gravitational wave emissions at a level that could be detected by present-day interferometers. However, the Crab pulsar shows a considerable amount of timing noise[14] and on timescales of months to years it is important that the rotation history of the pulsar is carefully tracked throughout.[15]

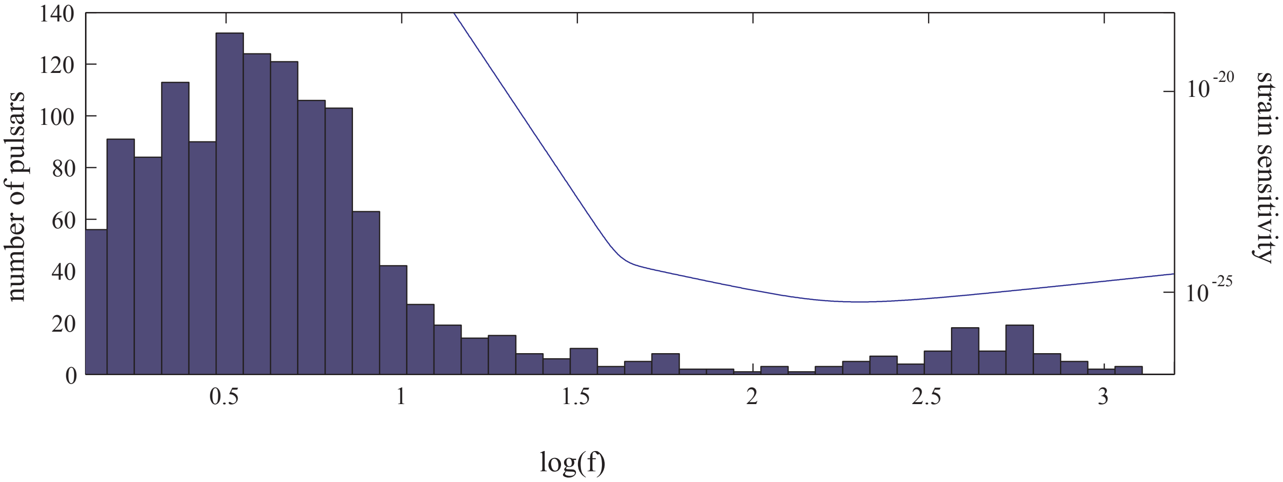

Figure 2. Histogram of known radio pulsars binned by their expected gravitational wave frequency ($f = 2f_{\mathrm{rot}}$). The smooth curve shows the design strain sensitivity of LIGO for a 1 yr observation, adjusted for the mean antenna pattern over the sky and mean pulsar orientation parameters.

2. EMISSION MECHANISMS

Several studies have highlighted how spinning neutrons stars might emit gravitational radiation. Mechanisms include the free precession of the neutron star, modelled as a symmetric top,[16–19] structural instabilities (specifically, r-modes),[20] accretion-induced deformation (with special reference to low mass X-ray binary systems)[21–23] and structurally triaxial stars.[24] Although none of these models present compelling reasons why the present generation of detectors should detect strong signals from neutron stars, the considerable amount of uncertainty that exists in our understanding of neutron star structure and dynamics mean that it would be negligent to ignore the possibility. Even apparently simple upper limits to the emission strength, based on the energy conservation arguments highlighted above, contain structural assumptions concerning the rigidity and core/crust coupling of the neutron star.

Although these assumptions are reasonable, we know already that the simple model of a pulsar as a flywheel braked by magnetic dipole radiation is wrong. The braking index, n, of a pulsar is defined by

$$\dot{f}_{\mathrm{rot}} \propto -f_{\mathrm{rot}}^{n}, \tag{1}$$

and for an electromagnetically braked rigid rotator $n = 3$. Measurements of braking index are difficult, as they rely on observations of the second derivative of the pulsar period, but those that have been measured show systematic deviations from this value. The braking index of the Crab pulsar is 2.51,[14] and that of the Vela pulsar is 1.4.[25] In contrast, the braking index due to pure gravitational radiation is $n = 5$, which seems totally at odds with observation. The most probable cause of the low observed values of n is torque from the pulsar wind and variations in the magnetic field and moment of inertia of the neutron star, resulting in an effective electromagnetic braking index < 3. As we expect the gravitational component of the overall dissipations to be low, it becomes apparent how some gravitational braking (with an index of five) can be consistent with observation if the effective electromagnetic index is sufficiently low. Palomba[26] has estimated that as much as 40 percent of the spindown of the Crab pulsar could be due to gravitational damping and still give an overall braking index of 2.51, although the required equatorial ellipticity for the pulsar, at 3×10^{-4}, is still larger than can be justified by most structural models for neutron stars.

2.1. Triaxial neutron stars

Of the mechanisms mentioned above, gravitational wave emission due to equatorial asymmetries in the neutron star is perhaps the most plausible. Freely precessing (‘wobbling’) neutron stars are expected to damp themselves on timescales of a year, so that unless some pumping mechanism is present we would not expect observed pulsars to wobble significantly,[18, 19] a conclusion supported by the rather stable pulse profile we see from most pulsars. Similarly, theoretical predictions of strain amplitudes from r-mode instabilities in recently formed (extragalactic) neutron stars indicate they will be undetectable for the foreseeable future, although accretion-induced instabilities in galactic low-mass X-ray binaries (such as Sco-X1) could be detectable with Advanced LIGO.

On the other hand, crustal asymmetries in the surface on neutron stars can be expected up to a level corresponding to the crustal breaking strain,[23] $\sigma_{\max}$, allowing equatorial ellipticities of order

$$\epsilon_{\max} \sim 5 \times 10^{-8} (\sigma_{\max}/10^{-3}), \tag{2}$$

where

$$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}, \tag{3}$$

and I_{jj} refers to the principal moment of inertia around the j axis of a neutron star whose equator lies in the xy-plane. Ellipticities of 10^{-7} to 10^{-8} seem plausible via this mechanism, and the neutron star would be expected to induce a strain of amplitude

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} f^2}{r} \epsilon \tag{4}$$

and frequency $f = 2f_{\mathrm{rot}}$ in an optimally oriented detector a distance r from the source.

A more generally-oriented detector will be strained by an amount

$$h(t) = F_+(t,\psi) h_0 \frac{1+\cos^2\iota}{2} \cos\Phi(t) + F_\times(t,\psi) h_0 \cos\iota \sin\Phi(t), \tag{5}$$

where $F_{+,\times}$ are the antenna pattern responses in the direction of the source to the 'plus' and 'cross' polarisation components of the wave. ι is the angle between the pulsar spin axis and the line-of-sight to the observer, ψ is the polarisation angle of the radiation (the angle between the lines of intersection of the wave plane and the equatorial planes of the neutron star and the Earth) and Φ is the phase evolution of the sinusoidal signal. If the neutron star is a radio pulsar, Φ is expected to evolve in the same manner as the observed pulse phase, though at twice the rate, and is taken as known to within a phase offset ϕ_0. This phase evolution includes contributions from both the intrinsic slowdown and timing noise of the pulsar and the Doppler shifts induced by the motion of the interferometer, fixed to the surface of a spinning and orbiting Earth, as well as similar Doppler shifts due to orbital motions of the pulsar if it is in a binary system.

The analogy with radio pulsar detection and analysis is very close, and radio timing observations of known pulsars are more than good enough to provide an accurate template to which we can match any putative gravitational wave signal from a targeted pulsar. The more difficult problem of searching for spinning neutron stars that are not radio pulsars can be tackled by dividing the parameter space, which now includes sky position, period and period derivative as unknowns, into non-redundant hypervolumes each covered by its unique source template.

3. SEARCH METHODS

A broad range of techniques have been developed within the LIGO Scientific Collaboration (LSC) to search for continuous wave sources in interferometer strain data. These include blind searches looking for excess monochromatic power but taking into account only the Doppler shift of the observer and the antenna pattern of the receiver, efficient all-sky searches and deep directed searches using maximum likelihood methods, hierarchical searches that combine coherent and incoherent stages to improve efficiency further and targeted searches that look specifically for signals from known radio pulsars. The maximum likelihood (or '$\mathcal{F}$-statistic') method and the targeted searches are now quite mature, and have been used on data from the LIGO and GEO interferometers since their late engineering runs.

3.1. Targeted searches

Here we will concentrate on describing the method used to target radio pulsars. The approach used is to beat the expected signal down to d.c. by multiplying the data stream by $\exp[-i\Phi(t)]$ (known as 'heterodyning', although strictly it should be homodyning) and tightly filtering the result. This is a well-known way to carry out pulsar searches, and although it does not exploit the speed advantage of Fourier methods it does make it easier to tackle data that is badly contaminated with close spectral lines and which is significantly non-stationary or discontinuous in time. These are all circumstances which apply to recent interferometer data (although the data quality is improving rapidly), and heterodyning methods have proved a simple and robust way to extract the necessary source information from the data stream.

After heterodyning and filtering, the noisy time series should contain a signal from the pulsar with variation over time due solely to the motion of the source through the quadrupole antenna pattern of the interferometer. Gravitational wave detectors do not track the sky, so the best that can be achieved is a form of transit array (to use a radio analogy) using several interferometers with a broad and complicated overall antenna pattern.

Once heterodyned, the data are rebinned in time at a rate that is a trade-off between bandwidth, which we should like to be as narrow as possible to exclude interference, and stationarity, which is defined by the performance of the instrument. We have found that one sample per minute is a suitable choice for the LIGO and GEO interferometers. The signal within these data now has the form

$$\begin{aligned} y_k \equiv y(t_k;\boldsymbol{a}) =& \frac{1}{4}F_+(t_k;\psi)h_0(1+\cos^2\iota)\mathrm{e}^{i\phi_0} \\ &- \frac{i}{2}F_\times(t_k;\psi)h_0\cos\iota\,\mathrm{e}^{i\phi_0}, \end{aligned} \tag{6}$$

where $\boldsymbol{a}$ is a vector in our parameter space with components $(h_0, \iota, \psi, \phi_0)$ and t_k is the time-stamp of the kth bin. We proceed by evaluating the joint probability distribution (pdf) of the heterodyned data, $\{B_k\}$, given this signal model:

$$p(\{B_k\}|\boldsymbol{a},\{\sigma_k\}) = \prod_k \frac{1}{2\pi\sigma_k^2}\exp\left(\frac{-|B_k-y_k|^2}{2\sigma_k^2}\right). \tag{7}$$

Although the data are calibrated so that a strain signal would appear with the correct numerical value in the data the noise floor σ_k can be expected to vary over time and must be determined along with the source parameters, $\boldsymbol{a}$. In circumstances where a wide band around the pulsar frequency is clean, this can be done by making point estimates of the noise variance in the heterodyned (but unbinned) time series at regular intervals. If strong filtering is necessary to reject interference then these point estimates become noisy, as there are fewer samples with which to work, and we instead marginalise over the σ_k in Eqn. 7, taken as constant for some stationarity period (determined by instrumental performance but typically 30 min) to give a modified likelihood that depends only on the signal model and the data.

We proceed by determining the posterior probability of $\boldsymbol{a}$ by assigning uniform prior probabilities to h_0 ($h_0 > 0$), ϕ_0, ψ and $\cos\iota$ and applying Bayes theorem

$$p(\boldsymbol{a}|\{B_k\}) \propto p(\boldsymbol{a})p(\{B_k\}|\boldsymbol{a}). \tag{8}$$

Finally, it is useful to express this posterior probability as marginalised probabilities for the four individual components of $\boldsymbol{a}$. In particular, the marginal probability for h_0

$$p(h_0|\{B_k\}) \propto \iiint p(\boldsymbol{a}|\{B_k\})\,\mathrm{d}\iota\,\mathrm{d}\psi\,\mathrm{d}\phi_0, \tag{9}$$

normalized so that $\int_0^\infty p(h_0|\{B_k\})\,\mathrm{d}h_0 = 1$, can be used to define a convenient upper limit on the strength of the signal. We can say that, given our data *and priors*, there is a probability of 0.95 that the true value of h_0 lies below $h_0^{95\%}$ where

$$0.95 = \int_0^{h_0^{95\%}} p(h_0|\{B_k\})\,\mathrm{d}h_0, \tag{10}$$

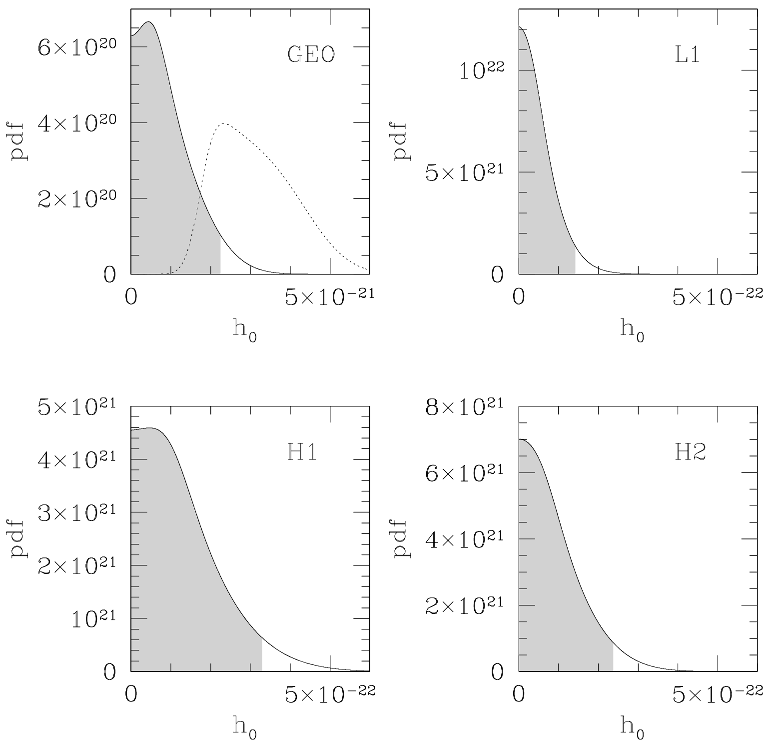

Figure 3. Marginalized posterior pdfs for h_0 (PSR J1939+2134) derived from S1 data taken by the GEO and LIGO interferometers. The shaded regions extend to the 95% upper limit points. The dotted line in the GEO plot shows the effect of adding a simulated pulsar signal into the GEO data stream (from Abbott et al.[27]).

which gives a 95%-credible upper limit on h_0.

It is straightforward to extend this analysis method to include data from n interferometers, not necessarily taken at the same time, to give

$$p(\boldsymbol{a}|\text{all data}) \propto p(\boldsymbol{a}) \times p(\text{IFO1}|\boldsymbol{a}) \times p(\text{IFO2}|\boldsymbol{a}) \times \cdots \times p(\text{IFO}n|\boldsymbol{a}). \tag{11}$$

4. RECENT PULSAR SEARCHES

The first science run of the GEO and LIGO interferometers, denoted S1, took place between 23 August and 19 September 2002.[7] General astrophysical search work within the LSC has concentrated on looking for signals from compact object inspirals such as neutron star binaries,[28] the gravitational stochastic background,[29] burst signals[30] and continuous wave sources[27] using a range of matched filter methods.

We performed a targeted search for gravitational wave emission from PSR J1939+2134 in S1 data using both the time domain heterodyne method described above and a version of the $\mathcal{F}$-statistic search method, to demonstrate consistency.[27] Probability distributions for h_0 derived from the three LIGO (H1, H2, L1) and one GEO interferometers are shown in Fig. 3, with shaded regions showing the 95% probability region. The corresponding 95% upper limits are 2.2×10^{-21} for GEO, 1.4×10^{-22} for L1, 3.3×10^{-22} for H1 and 2.4×10^{-22} for H2. The dotted line in the GEO plot shows the posterior pdf of h_0 in the presence of a simulated signal injected into the GEO S1 data stream using $h_0 = 2.2 \times 10^{-21}$, $\phi_0 = 0°$, $\psi = 0°$ and $\iota = 0°$. A joint analysis, combining data from all the interferometers, was not possible during S1 because of uncertainties in the relative phase offsets between sites, now resolved.

It's useful to think of these upper limits on strain as upper limits on the equatorial ellipticity of the pulsar, ϵ, given by

$$\epsilon \simeq 0.237 \left(\frac{h_0}{10^{-24}} \right) \left(\frac{r}{1\,\mathrm{kpc}} \right) \left(\frac{1\,\mathrm{Hz}}{f_{\mathrm{rot}}} \right)^2 \left(\frac{10^{45}\,\mathrm{g\,cm}^2}{I_{zz}} \right) \tag{12}$$

where r is the distance to the pulsar, f_{rot} is its rotational frequency and I_{zz} its principal moment of inertia, parallel to the axis of spin. The tightest upper limit on h_0 from S1 gives an ellipticity limit of

$$\epsilon^{95\%} = 2.9 \times 10^{-4} \left(\frac{10^{45}\ \mathrm{g\ cm}^2}{I_{zz}} \right), \tag{13}$$

for PSR J1939+2134, which compares with the (considerably lower) upper limit derived from the pulsar's measured spindown rate of $\epsilon \leq 3.80 \times 10^{-9} (10^{45}\,\mathrm{g\,cm}^2/I_{zz})^{1/2}$. The difference in magnitude of these limits reflects the low spindown rate of this millisecond pulsar, and the consequentially low gravitational luminosity it could support under a simple flywheel model.

5. PULSAR INJECTIONS

More recent science runs have included coherent pulsar injections into the hardware of the interferometer control systems, making the arms change length slightly in a way that exactly mimics the effect of a pulsar signal.

During the S2 science run (Feb 14 to April 14 2003) two such signals were injected coherently into the three LIGO interferometers. The injected pulsars signal were relatively strong, imposing strain amplitudes of 2×10^{-21} in the interferometers, corresponding to oscillatory mirror motion of amplitude about 10^{-17} m.

The artificial signals were injected for a period of 12 h and the data processed using the heterodyne technique described above. Fig. 4 shows the results of recovering the four parameters (h_0, ϕ_0, ψ and $\cos\iota$) of the first injected pulsar (P1) from the individual interferometers (grey background curves) and the joint coherent solution (thicker black curves). Again, these curves represent posterior pdfs for the parameters, so we would expect the true injected values, shown by the vertical dotted lines in each graph, to fall within the bulk of the curves, and similarly we would expect the curves from each interferometer to overlap significantly. Although there is some spread the results are sufficiently consistent to demonstrate the technique and to show that any real, suitably strong, pulsar signal in the data stream conforming to our expectations would be picked up successfully. The graphs showing the pdfs for ϕ_0 are particularly important as they demonstrate the relative coherence between the interferometers and show that we can truly operate the detectors in a "phased array mode", increasing our sensitivity accordingly.

6. OUTLOOK

Spinning neutron stars remain a tantalising source of continuous gravitational waves, although the strength of those waves remains rather uncertain. There are however good reasons to believe that some sources could have sufficient flux at the Earth to be detected by the present, or next, generation of ground-based gravitational wave detectors and several groups are already performing both targeted and general searches in current detector data.

The LIGO and GEO detectors have recently completed their S3 run and results from this and S2 will be available shortly. Further tests have been carried out to check the effectiveness of the search methods, including ten pulsar injections into S3 with a range of strengths. Looking to the future, further science runs promise to improve significantly low-frequency sensitivity and running time, so that the gravitationally-based upper limit on the Crab pulsar is shortly expected to fall below the spindown limit, a threshold that for many heralds the start of gravitational neutron star astronomy.

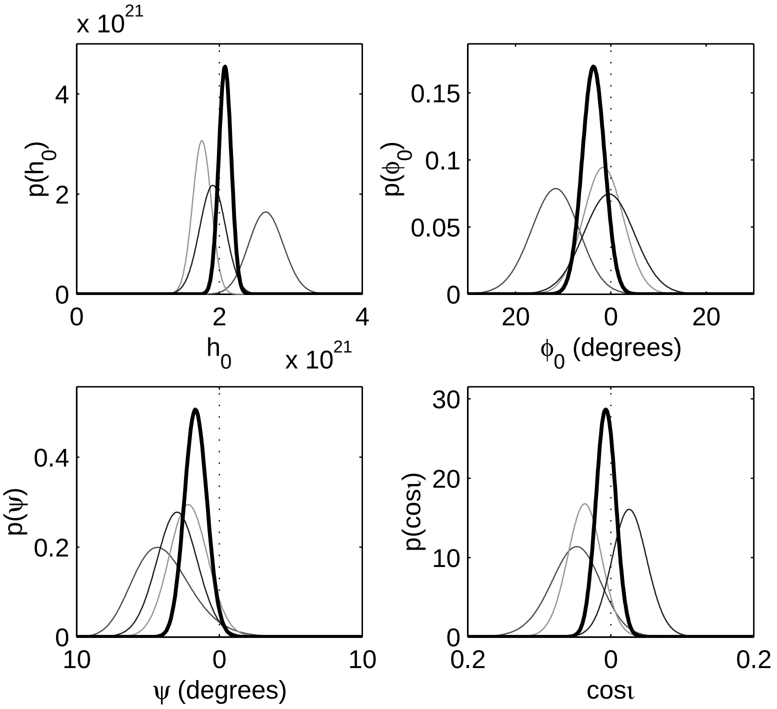

Figure 4. The parameters of the artificial pulsar P1, recovered from 12 h of IFO strain data from the one Livingston and two Hanford interferometers. The results are displayed as marginal pdfs for each of the four signal parameters. The vertical dotted lines show the values used to generate the signal, the grey lines show the results from the individual IFOs and the black lines show the joint result from combining the three IFOs coherently.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory and the Particle Physics and Astronomy Research Council of the United Kingdom, the Max-Planck-Society and the State of Niedersachsen/Germany for support of the construction and operation of the GEO 600 detector. The authors also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the Natural Sciences and Engineering Research Council of Canada, the Council of Scientific and Industrial Research of India, the Department of Science and Technology of India, the Spanish Ministerio de Ciencia y Tecnologia, the John Simon Guggenheim Foundation, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

REFERENCES

1. R. A. Hulse and H. J. Taylor, "Discovery of a Pulsar in a Close Binary System," *Bull. Am. Astr. Soc.* **6**, p. 453, Sept. 1974.
2. J. H. Taylor and J. M. Weisberg, "Further experimental tests of relativistic gravity using the binary pulsar PSR 1913 + 16," ApJ **345**, pp. 434–450, Oct. 1989.
3. D. J. Champion, D. R. Lorimer, M. A. McLaughlin, J. M. Cordes, Z. Arzoumanian, J. M. Weisberg, and J. H. Taylor, "PSR J1829+2456: a relativistic binary pulsar," MNRAS **350**, pp. L61–L65, June 2004.
4. M. Burgay, N. D'Amico, A. Possenti, R. N. Manchester, A. G. Lyne, B. C. Joshi, M. A. McLaughlin, M. Kramer, J. M. Sarkissian, F. Camilo, V. Kalogera, C. Kim, and D. R. Lorimer, "An increased estimate of the merger rate of double neutron stars from observations of a highly relativistic system," Nature **426**, pp. 531–533, Dec. 2003.

5. A. G. Lyne, M. Burgay, M. Kramer, A. Possenti, R. N. Manchester, F. Camilo, M. A. McLaughlin, D. R. Lorimer, N. D'Amico, B. C. Joshi, J. Reynolds, and P. C. C. Freire, "A Double-Pulsar System: A Rare Laboratory for Relativistic Gravity and Plasma Physics," *Science* **303**, pp. 1153–1157, Feb. 2004.
6. J. M. Weisberg and J. H. Taylor, "The Relativistic Binary Pulsar B1913+16," in *ASP Conf. Ser. 302: Radio Pulsars*, p. 93, 2003.
7. B. Abbott et al., "Detector description and performance for the first coincidence observations between LIGO and GEO," *Nuclear Instruments and Methods in Physics Research A* **517**, pp. 154–179, Jan. 2004.
8. G. H. Sanders, "Status of LIGO," in *Gravitational-Wave Detection. Edited by Cruise, Mike; Saulson, Peter. Proceedings of the SPIE, Volume 4856, pp. 247-257 (2003)*, pp. 247–257, Mar. 2003.
9. B. Willke et al., "Status of GEO 600," *Classical and Quantum Gravity* **21**, pp. 417–, Mar. 2004.
10. M. Ando et al., "Current status of TAMA," *Classical and Quantum Gravity* **19**, pp. 1409–1419, Apr. 2002.
11. F. Acernese et al., "The commissioning of the central interferometer of the Virgo gravitational wave detector," *Astroparticle Physics* **21**, pp. 1–22, Apr. 2004.
12. M. Bejger and P. Haensel, "Moments of inertia for neutron and strange stars: Limits derived for the Crab pulsar," A&A **396**, pp. 917–921, Dec. 2002.
13. M. Bejger and P. Haensel, "Accelerated expansion of the Crab Nebula and evaluation of its neutron-star parameters," A&A **405**, pp. 747–751, July 2003.
14. A. G. Lyne, R. S. Pritchard, and F. Graham-Smith, "Twenty-Three Years of Crab Pulsar Rotational History," MNRAS **265**, p. 1003, Dec. 1993.
15. M. Pitkin and G. Woan, "Searching for gravitational waves from the Crab pulsar – the problem of timing noise," *Classical and Quantum Gravity* **21**, pp. 843–846, Mar. 2004.
16. J. C. N. de Araujo, J. A. de Freitas Pacheco, J. E. Horvath, and M. Cattani, "Gravitational waves from wobbling pulsars," MNRAS **271**, pp. L31–L33, Nov. 1994.
17. J. C. N. de Araujo, J. A. de Freitas Pacheco, M. Cattani, and J. E. Horvath, "Deformation of rapidly rotating compact stars," A&A **301**, p. 433, Sept. 1995.
18. D. I. Jones and N. Andersson, "Freely precessing neutron stars: model and observations," MNRAS **324**, pp. 811–824, July 2001.
19. D. I. Jones and N. Andersson, "Gravitational waves from freely precessing neutron stars," MNRAS **331**, pp. 203–220, Mar. 2002.
20. N. Andersson, "Gravitational waves from instabilities in relativistic stars," *Classical and Quantum Gravity* **20**, p. 105, Apr. 2003.
21. R. V. Wagoner, "Gravitational radiation from accreting neutron stars," ApJ **278**, pp. 345–348, Mar. 1984.
22. L. Bildsten, "Gravitational Radiation and Rotation of Accreting Neutron Stars," ApJ **501**, pp. L89+, July 1998.
23. G. Ushomirsky, C. Cutler, and L. Bildsten, "Deformations of accreting neutron star crusts and gravitational wave emission," MNRAS **319**, pp. 902–932, Dec. 2000.
24. C. Cutler, "Gravitational waves from neutron stars with large toroidal B fields," Phys. Rev. D **66**, p. 084025, Oct. 2002.
25. A. G. Lyne, R. S. Pritchard, F. Graham-Smith, and F. Camilo, "Very low braking index for the VELA pulsar," Nature **381**, pp. 497–498, 1996.
26. C. Palomba, "Pulsars ellipticity revised," A&A **354**, pp. 163–168, Feb. 2000.
27. B. Abbott et al., "Setting upper limits on the strength of periodic gravitational waves from PSR J1939+2134 using the first science data from the GEO 600 and LIGO detectors," Phys. Rev. D **69**, p. 082004, Apr. 2004.
28. B. Abbott et al., "Analysis of LIGO data for gravitational waves from binary neutron stars," Phys. Rev. D **69**, p. 122001, June 2004.
29. B. Abbott et al., "Analysis of First LIGO Science Data for Stochastic Gravitational Waves," Phys. Rev. D **69**, p. 122004, June 2004.
30. B. Abbott et al., "First upper limits from LIGO on gravitational wave bursts," Phys. Rev. D **69**, p. 102001, May 2004.