BAR-INTERFEROMETER OBSERVING

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We examine the opportunities for joint observations between interferometric and bar (more generally, solid-mass) gravitational wave detectors in the near and more distant future. We give simple formulas to estimate the sensitivity of joint searches, and we present results of more detailed calculations for certain combinations. Bars and interferometers can do searches for pulsars with competitive sensitivity, and can therefore confirm each other's observations. Cross-correlation of two detectors permits searches for a stochastic background. Restricted to higher frequencies, bar-interferometer pairs are less sensitive than two interferometers for stochastic backgrounds of constant energy density (the Harrison-Zel'dovich spectrum), but they are competitive for backgrounds that have constant spectral density, as are predicted by recent calculations in superstring cosmologies. Particularly interesting are the NAUTILUS detector with the VIRGO or GEO600 interferometers, and even more sensitive would be a spherical solid-mass detector built at the site of VIRGO, LIGO or GEO.

1 Introduction

Gravitational wave observations require joint observing by a network of detectors, both to increase confidence in a detection and to provide information on the direction and polarisation of the waves. There have already been coordinated observations using networks of bar detectors [1] and interferometers [2], but coordinated observing between bars and interferometers has not been discussed much until recently [3,4,5]. Given the difficulties inherent in gravitational radiation detection, it is worthwhile exploring all realistic possibilities that involve all kinds of detectors, and especially considering these questions when decisions are made about locating new detectors.

In this paper we survey what seem to us to be worthwhile possibilities for joint observations between bars and interferometers in the near future and further away, for the three main classes of gravitational wave signals: short bursts (including binary coalescences), pulsars and other continuous sources, and a stochastic background of gravitational waves from the Big Bang. In the latter case we give simple ways to estimate the sensitivity achievable by any pair of detectors, and we summarise the results of detailed computations performed elsewhere [6] for certain promising pairs.

1.1 Detectors

We will consider a number of detectors. In many cases, they are taken simply as examples of a class of similar detectors. Among the bars we consider

- NAUTILUS, a milliKelvin bar at Frascati [7]. When we refer to this bar, our remarks can usually refer equally well to other examples, such as AURIGA [8]. These bars will operate at good sensitivity in the very near future, and can be improved even more over the next 5 years.
- TIGA, the icosahedral design for an omni-directional detector [9]. Again, our remarks would apply to any of the new class of spherical solid-mass detectors. Such detectors are not likely to operate until after the next 5 years.

Interferometers include

- First generation interferometers: GEO600 [10], LIGO I [11], and VIRGO [12]. These differ in important details, but all should reach a sensitivity for bursts of near 10^{-21} by about the year 2000. They are of course not the first generation of interferometers to have been built, since prototypes have operated at Glasgow [13], Garching [14], Caltech [15], and elsewhere for many years, and have even conducted joint observations [2]. But they are the first generation to be capable of reaching astrophysically interesting sensitivities.
- Second generation interferometers. Sometimes called "advanced detectors", or in the American context LIGO II, they can be designed on paper but are not yet funded [5]. GEO600 and TAMA300 [16] are expected to play important roles in developing some of the techniques needed to make them possible, but are probably too short to reach second-generation sensitivity themselves.
- Narrow-banded detectors. By using resonant optical techniques, such as signal recycling [17], it will be possible to improve the sensitivity of interferometers in selected bandwidths, at the expense of their broad-band sensitivity. This could be desirable when working with bars. Narrow-banding is anticipated for GEO600.

Among these instruments are a number of natural bar-interferometer pairs, geographically near one another. The LIGO detector in Louisiana is near LSU, where a TIGA bar might be built. The NAUTILUS and AURIGA bars are near to both GEO600 and especially VIRGO. We will look carefully at what these pairs can do together.

1.2 Types of observing

Gravitational wave signals may be divided into three classes: bursts, which are short enough that the motion of the detector is not a consideration; continuous waves, which can be detected with maximum sensitivity only by correcting for the motion of the detector as the Earth turns and orbits the Sun; and a stochastic background, random gravitational waves left over from the early Universe.

Bursts seem to offer only limited opportunities for cooperation among bars and interferometers in the near future. Unstructured bursts, such as one might expect from a supernova explosion, might be much stronger in one detector's band than in the other's. If the two detectors have rather different burst sensitivity, then the weaker one also does not add much to the confidence of the detection. Coalescing binaries are more promising, because their signal rises in frequency in a predictable way from the natural bandwidth of interferometers to the natural operating frequencies of bars. It has been observed in many places that bars might be used to discover important information about the last stages of a coalescence that had been identified by interferometers [5]. This matter will be discussed elsewhere at this meeting (the talk by Coccia), so we will not consider it further in this paper.

Pulsars and other continuous sources offer better prospects for joint observing. We will see that bars and interferometers can have similar sensitivities in their common bandwidths, and joint observing can add confidence to a detection. There are many interesting kinds of sources. Searches should target not only known pulsars but also X-ray binaries and Be-giant stars [18]. All-sky, all-frequency searches for unknown sources should also be undertaken, to a sensitivity limit set by available computer resources,

A stochastic background can only be found by cross-correlation of two detectors, and here bars and interferometers work surprisingly well together [3,4]. We will calculate just how well for a number of cases.

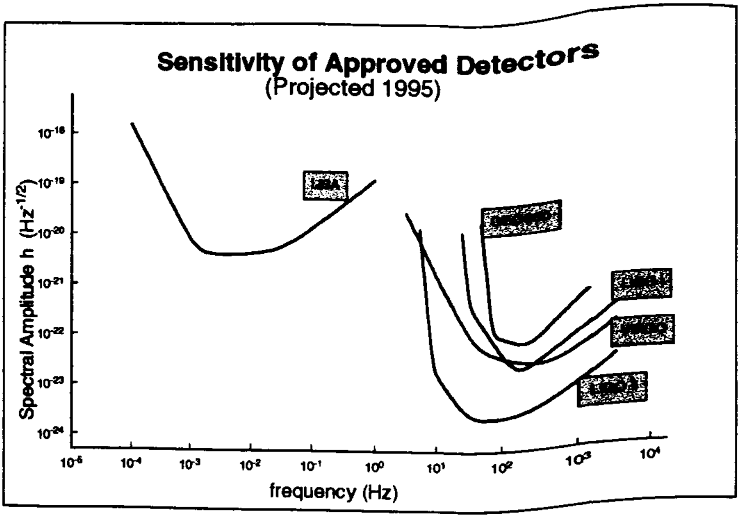

Figure 1: The expected sensitivity of several approved interferometers. For us the most interesting part is the sensitivity of the ground-based instruments above 100 Hz.

2 Approximate Characterisation of the Sensitivity of Different Detectors

For the rough estimates of working sensitivity in what follows, we need approximate characterisations of various detectors. We will use these only to generate our rough estimates. The more accurate calculations of Compton [6] are done with accurate sensitivity curves.

Bar detectors can be roughly approximated as having a square spectral noise density $S_h(f)$, with a constant value $S_h(f_b)$ in a bandwidth B_b about a central frequency f_b. (Many bars are instrumented to output data at two or more frequencies. We ignore this.) For our two example bars we have

Example	f_b	B_b	$S_h(f_b)$
NAUTILUS	900 Hz	2 Hz	$8 \times 10^{-45}\,\mathrm{Hz}^{-1}$
TIGA	1 kHz	1 Hz	$1.6 \times 10^{-47}\,\mathrm{Hz}^{-1}$ per mode

Both of these bars may operate with much larger bandwidths at these sensitivities, perhaps up to 100 Hz. This particularly affects correlation searches.

Interferometers have a more complicated spectrum. Figure 1 shows the spectral noise density of several detectors. For observing above about 200 Hz, which is mainly the region of interest for joint observing with bars, the interferometers may be characterised by a "knee" frequency f_k, where they have their best sensitivity, and by a rising shot-noise curve above this in which S_h is proportional to $(f/f_k)^2$. In fact, underlying this shot noise is a thermal noise from the vibrations of the test masses on which the mirrors are mounted. The interferometer's sensitivity is usually optimised so that this noise roughly equals the shot noise at f_k, and then it falls as $(f/f_k)^{-1}$. This is important, because when a detector is narrow-banded, the thermal noise sets the minimum on the achievable S_h at any frequency. Examples of the thermal noise expected in some detectors are shown as the dotted lines in Figure 2.

From Figure 1 we find the following simple characterisations of our example interferometers:

Example	f_k	$S_h(f_k)$
GEO600	200 Hz	$3 \times 10^{-45}\,\mathrm{Hz}^{-1}$
LIGO I	200 Hz	$4 \times 10^{-46}\,\mathrm{Hz}^{-1}$
VIRGO	200 Hz	$1 \times 10^{-46}\,\mathrm{Hz}^{-1}$
Advanced	100 Hz	$8 \times 10^{-48}\,\mathrm{Hz}^{-1}$

$S_{\rm shot} = S(f_k)(f/f_k)^2$, $S_{\rm th} = S(f_k)(f/f_k)^{-1}$

3 Looking for Neutron Stars

Provided that one correctly removes Doppler and amplitude modulation produced by the motion of the detector, as well as other effects such as any measurable proper motion of the source or its change of frequency during the observation, then the sensitivity limit on a continuous source during a time T_{obs} is

$$h^{1\sigma}_{PSR} = \left(\frac{S_h}{T_{obs}}\right)^{1/2}. \tag{1}$$

Targets of joint searches between bars and interferometers must be at a frequency near 1 kHz. Let us suppose that T_{obs} is about 1 yr. Then the sensitivity limits that our previous approximations for detector sensitivity give are

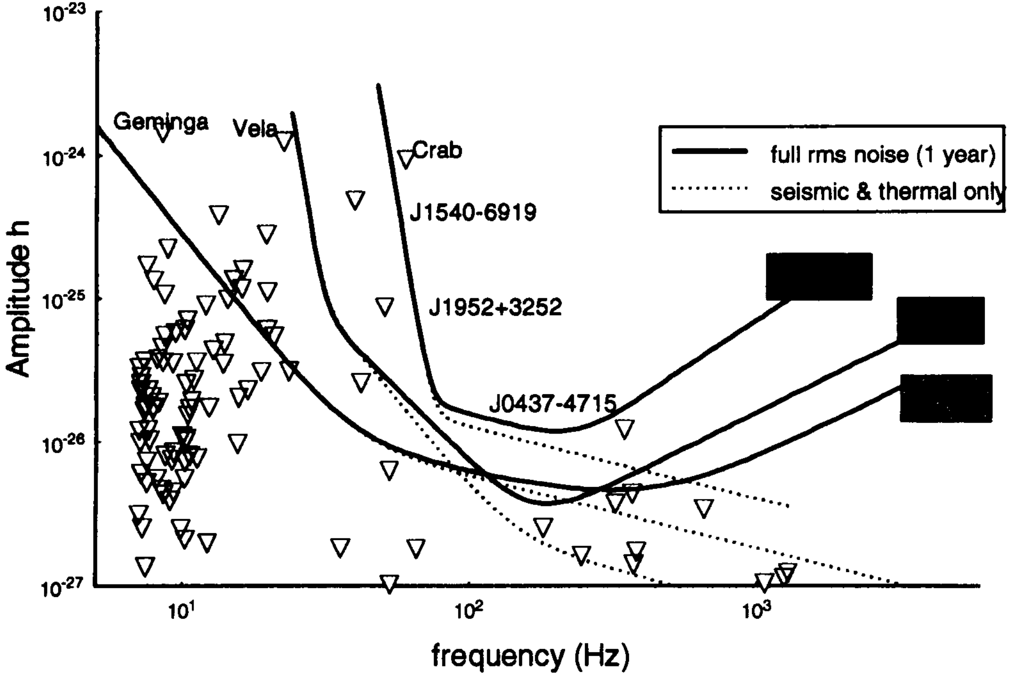

Figure 2: Upper limits on gravitational wave amplitudes from known pulsars, set by assuming all their spindown can be accounted for by the emission of gravitational wave energy. The points represent all pulsars in the November 1995 version of the database of Taylor *et al* [19], with gravitational wave frequencies above 7 Hz and amplitudes above 10^{-27}. Also shown are the expected sensitivities of three first-generation interferometers in a one-year observation, and the thermal noise limits on narrow-banding (dotted lines).

Detector	$h^{1\sigma}_{PSR}$ at 1 kHz for 1 yr
NAUTILUS	2×10^{-26}
TIGA	7×10^{-28}
GEO600 broad[a]	5×10^{-26}
GEO600 narrow[b]	5×10^{-27}
LIGO I broad	2×10^{-26}
(LIGO I narrow	2×10^{-27})
VIRGO broad	1×10^{-26}
(VIRGO narrow	1×10^{-27})
Advanced broad	3×10^{-27}
Advanced narrow	3×10^{-28}

We have placed the sensitivities for LIGO I and VIRGO operating in narrow-band modes in brackets because present plans for these detectors do not appear to envision implementing narrow-banding.

By comparing this table with Figure 2, we see that there are several pulsars whose spindown limits are above these sensitivities, and even a few that are in the right frequency range. The advanced bar detector TIGA has nearly as good a sensitivity as an advanced interferometer near 1 kHz. And NAUTILUS has respectable sensitivity, comparable with that of first-generation interferometers at this frequency. The NAUTILUS group does indeed plan to search for pulsars (see the talk by Astone at this meeting).

3.1 Narrow-banding interferometers as a strategy for pulsar searches?

A simple argument suggests that interferometers might do better at searching for unknown pulsars by narrow-banding. Narrowing the interferometer to a bandwidth B reduces the number of pulsars available to the instrument, to a number proportional to B if the distribution of pulsars in frequency is uniform (a strong and probably wrong assumption). But it also reduces the spectral noise density in this bandwidth by a factor proportional to B. This increases the range of the detector by $B^{-1/2}$. If pulsars are distributed in a plane, then the increase in range increases their numbers by B^{-1}, and the net effect of narrow-banding is neutral. But if pulsars are distributed more spherically, their number will be proportional to $B^{-3/2}$, and narrow-banding improves the number of detections in proportion to $B^{-1/2}$.

However, this argument is naive, and if we take into account other factors then we can reach the opposite conclusion. One difficulty is that narrow-banding must be done on the rising part of the shot-noise curve, since it is limited below by thermal noise. In order to make B smaller, one must go higher in f, and therefore in the base level of S_h. When this factor is taken into account, the number of pulsars available (if they are distributed spherically) is proportional to $B^{1/4}$, so it is a disadvantage to narrow-band. This assumes a uniform distribution in frequency, which is also almost certainly bad: as we push up in f, the density of pulsars is likely to decrease.

Finally, we mention a factor that should also be considered, but which has not yet been adequately studied. The range of a search for unknown pulsars is likely to be limited by computer power rather than observing opportunities: the computer power required to search a data set taken over a length of time T is proportional to [20] T^4. The range of the search, which is proportional to h^{-1}, goes as $T^{-1/2}$. But it is also proportional to bandwidth, since the computing requirements depend directly on the number of data points. So narrowing the bandwidth by a factor B allows the length of the data set to be increased by a factor of $B^{-1/4}$. The range increases, and the number of detections goes up by $B^{-3/8}$ if pulsars are distributed spherically. This wins over the factor of $B^{1/4}$ in the previous paragraph, so that the net effect is slightly favourable to narrow-banding, but not by much. This slight advantage might be overwhelmed by an unfavourable frequency distribution of pulsars.

4 Stochastic Searches Using Bars and Interferometers

According to Flanagan [21] and Compton [6], the 90% confidence limit on the energy density per unit logarithmic frequency that any pair of detectors located at the same site can set at any frequency is

$$\Omega_{gw}^{90\%} = \frac{8\pi}{G\rho_c} f^3 \left[\frac{S_1 S_2}{2TB}\right]^{1/2}, \tag{2}$$

where $\rho_c = 3H_0^2/8\pi G$ is the closure mass density S_1 and S_2 are spectral densities at the two detectors, T is the observing time, and B is the bandwidth. Note the f^3 factor, which reduces the effectiveness of high-frequency searches for backgrounds with constant Ω_{gw} (the so-called Harrison-Zel'dovich spectrum).

Putting in typical numbers, and using $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, we find

$$\begin{aligned}\Omega_{gw}^{90\%} &= 4\times 10^{-4}\left(\frac{f}{1\,\mathrm{kHz}}\right)^3 \left(\frac{S_1}{10^{-46}\,\mathrm{Hz}^{-1}}\right)^{1/2} \left(\frac{S_2}{10^{-46}\,\mathrm{Hz}^{-1}}\right)^{1/2} \\ &\quad\times \left(\frac{T}{1\,\mathrm{yr}}\right)^{-1/2} \left(\frac{B}{1\,\mathrm{Hz}}\right)^{-1/2}.\end{aligned} \tag{3}$$

If the two detectors are not on the same site, then one divides by $|\gamma|$ as defined by Flanagan [21]. We consider this below.

We specialise this formula to the kinds of detectors whose sensitivity we estimated above:

- Two broadband interferometers:

$$\Omega_{gw}^{90\%} = 2 \times 10^{-7} \left(\frac{S_{k,1}}{10^{-46}\,\mathrm{Hz}^{-1}}\right)^{1/2} \left(\frac{S_{k,2}}{10^{-46}\,\mathrm{Hz}^{-1}}\right)^{1/2}, \tag{4}$$

  with $f_k = 200\,\mathrm{Hz}$ and $T = 1\,\mathrm{yr}$.

- One bar and one broadband interferometer:

$$\Omega_{gw}^{90\%} = 2 \times 10^{-3} \left(\frac{S_b}{10^{-46}\,\mathrm{Hz}^{-1}}\right)^{1/2} \left(\frac{S_k}{10^{-46}\,\mathrm{Hz}^{-1}}\right)^{1/2}, \tag{5}$$

  with $f_b = 1\,\mathrm{kHz}$, $B = 1\,\mathrm{Hz}$, $f_k = 200\,\mathrm{Hz}$ and $T = 1\,\mathrm{yr}$.

- Two bars:

$$\Omega_{gw}^{90\%} = 4 \times 10^{-4} \left(\frac{S_{b,1}}{10^{-46}\,\mathrm{Hz}^{-1}}\right)^{1/2} \left(\frac{S_{b,2}}{10^{-46}\,\mathrm{Hz}^{-1}}\right)^{1/2}, \tag{6}$$

  with $f_b = 1\,\mathrm{kHz}$, $B = 1\,\mathrm{Hz}$, and $T = 1\,\mathrm{yr}$.

- One bar and one narrow-banded interferometer:

$$\Omega_{gw}^{90\%} = 2 \times 10^{-4} \left(\frac{S_b}{10^{-46}\,\mathrm{Hz}^{-1}}\right)^{1/2} \left(\frac{S_k}{10^{-46}\,\mathrm{Hz}^{-1}}\right)^{1/2}, \tag{7}$$

  with $f_b = 1\,\mathrm{kHz}$, $B = 1\,\mathrm{Hz}$, $f_k = 200\,\mathrm{Hz}$ and $T = 1\,\mathrm{yr}$; note that S_{int} is limited by thermal noise.

- Single-detector noise limit (set just by its internal noise):

$$\Omega_{gw}^{90\%} = 2 \left(\frac{f}{1\,\mathrm{kHz}}\right)^3 \left(\frac{S_h}{10^{-46}\,\mathrm{Hz}^{-1}}\right)^{1/2}. \tag{8}$$

These numbers can be translated into tables of values of sensitivity in terms of Ω_{gw} and in terms of spectral noise density of gravitational radiation,

$$S_{gw} = \left[\frac{S_1 S_2}{2TB}\right]^{1/2}.$$

These are given below.

Ideal (Same-Site) Limits on $\Omega_{gw}^{90\%}$

	N'LUS	TIGA	GEO600	LIGO I	VIRGO
N'LUS	3×10^{-2}	*	*	*	*
TIGA	1.4×10^{-3}	6×10^{-5}	*	*	*
GEO600	1×10^{-1}	4×10^{-3}	$[6 \times 10^{-6}]$	*	*
LIGO I	4×10^{-2}	2×10^{-3}	$[2 \times 10^{-6}]$	$[8 \times 10^{-7}]$	*
VIRGO	2×10^{-2}	1×10^{-3}	$[1 \times 10^{-6}]$	$[4 \times 10^{-7}]$	$[2 \times 10^{-7}]$
GEO nb	1×10^{-2}	4×10^{-4}	N/A	N/A	N/A

In this table, a * denotes entries that can be obtained from the symmetry of the table, "N'LUS" denotes the NAUTILUS detector, "nb" means "narrow-band", and square brackets [...] denote experiments that are not possible to perform on the same site. (Note, however, that at LIGO's Hanford site it will be possible to do a same-site experiment between a full-length and a half-length interferometer.) The TIGA results are per mode, so modes can be combined to make some improvements.

Some of these combinations were studied by Compton [6] in detail, allowing for more realistic instrumental sensitivities and, most importantly, for their geometrical separation and orientation. She found the following results for the limits on energy density:

Realistic Limits on $\Omega_{gw}^{90\%}$

Detector Pair	Realistic $\Omega_{gw}^{90\%}$, allowing for geometry
LIGO I — LIGO I	5×10^{-6}
GEO600 — N'LUS	4×10^{-2}, same site
GEO600 — N'LUS	8×10^{-1}, present locations
GEO600 (nb) — N'LUS	6×10^{-3}, same site
TIGA-TIGA	8×10^{-6}, same site, 5 modes

This table of estimates above can be converted to read spectral density limits:

Ideal (Same-Site) Limits on $|h_{25}| = \left[S_{gw}^{90\%}\right]^{1/2} / 10^{-25}\,\mathrm{Hz}^{-1/2}$

	N'LUS	TIGA	GEO600	LIGO I	VIRGO
N'LUS	9	*	*	*	*
TIGA	2	0.5	*	*	*
GEO600	7	2	[2]	*	*
LIGO I	4	1	[1]	[0.6]	*
VIRGO	3	1	[0.7]	[0.4]	[0.3]
GEO nb	2	0.5	N/A	N/A	N/A

There are a number of interesting conclusions that one can draw from these tables. For example, there is a substantial improvement in a possible GEO-NAUTILUS experiment if a NAUTILUS-type bar were built on the GEO site, and if GEO were run in narrow-band mode with it. A TIGA bar on a interferometer site, such as at the LIGO site in Louisiana, would be a little better than the GEO-NAUTILUS same-site combination, but among first-generation interferometers the best combination with a bar is a narrow-band GEO600 with a TIGA on the same site. These cannot beat, however, a same-site LIGO I experiment, using a half-length interferometer, which could do more than 2 orders of magnitude better than GEO-TIGA on Ω_{gw}, although it would be almost the same as GEO-TIGA in terms of spectral density. (The same-site experiments must be careful that they are not affected by common-mode environmental noise in the two detectors.)

When we look at the table of spectral density limits, the bars seem much better relative to the interferometers than they were in the energy-density comparison. This is because of the factor of f^3 in the energy density, which favours low-frequency observing. The best spectral limits will be set by a pair of TIGA's, but a narrow-band GEO would not be a bad companion for a TIGA.

Acknowledgements

We have been greatly helped in this work by our colleagues at Cardiff, particularly David Nicholson, John Watkins, Gareth Jones, and Chris Dickson. We also acknowledge important conversations with Pia Astone, Alberto Lobo, and James Hough.

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