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Noise Characterization for Laser Interferometer Gravitational Wave Detectors

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This work incorporates a review of the status, in Australia, of data analysis for gravitational wave detection using laser interferometers, within an overview of the present state of such research in the world generally. In this context, data analysis refers not so much to signal simulation as to what might be called the thorough process of noise characterization and the subsequent, quality-controlled signal extraction. To the extent that problems identified here arise for all currently planned instruments, there is necessarily a global component to the discussion presented. In Australia, there are unique circumstances, associated with attempting to carry out work in gravitational wave detection, which demand also a local aspect to the ensuing discussion.

KEY WORDS : Data analysis for gravitational wave detectors

1. INTRODUCTION

This paper briefly reviews the current global effort to detect gravitational radiation and attempts to put the Australian contribution to that effort into perspective. Within Australia, as elsewhere, the data analysis aspect of this effort has gained considerable momentum only very recently. It has been found that source analysis, detector characterization and detection confidence are all areas now requiring attention, along with evaluation of

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the network and computational requirements for bringing that work to fruition. Preparation for analysing these latter requirements within Australia has now begun at the Australian National University (ANU), where a small group has also been brought together to investigate specific aspects of detector characterization, within both the global and local contexts. It is anticipated that this work will have an integral rôle to play during the commissioning of currently planned detectors.

The next section gives an overview of the scientific case for wishing to detect gravitational radiation, and a brief discussion of current plans to achieve that goal. Following that, the rôle of noise in the overall performance of these proposed instruments is discussed, covering in particular, its sources, a brief outline of its character, and its potential for interference in the detection process. Then a description of the work being done to overcome these obstacles to detection is given, concluding with reference to several other fields of data analysis which have had to face similar technical difficulties. In the latter part of the paper, emphasis is placed on an evaluation of the current situation within Australia. In particular, instrumentation plans, networking and computational requirements, and advances in developing a group in detector characterization are all described. Finally, a summary of the greatest needs in detector characterization progress is presented.

2. SCIENTIFIC BACKGROUND

Light from the stars is generated at the atomic level, but is often masked from our sight by dust or other intervening matter. By contrast, gravitational waves originate from the motion of large, stellar sized lumps of matter, and travel through the rest of the universe essentially unhindered. It is the scale of their source, coupled with the fact that they may arise in areas practically invisible by any electromagnetic means, such as deep within collapsing stars or at the centre of galaxies, that gives the detection of gravitational waves such enormous potential in the fields of astrophysics and even cosmology. While indirect evidence already exists, the direct detection of gravitational radiation stands to place our present theories of gravitation on an entirely different observational foundation from that which currently exists, since General Relativity is a field still sparse in fundamental experimental verification.

Active research into the direct detection of gravitational radiation has been going on now for more than thirty years. Throughout most of that period, global scientific effort has been channelled into two main avenues: i) investigation of possible sources and calculation of the expected signal strengths, so that relevant sensitivity requirements and corresponding rate estimates can be provided, and ii) development of appropriate design concepts and prototype instrument testing with the ultimate view of achieving the maximum possible sensitivity using the most advanced available technology. After initial investigations into the use of resonant bar detectors, several proposals have now arisen for the employment of long baseline (in the km range) laser interferometry.

The key to gravitational wave detection is the very precise measurement of small changes in distance. For laser interferometers, this is the distance between pairs of mirrors hanging at either end of two long, mutually perpendicular vacuum chambers. Gravitational waves passing through the instrument will shorten one arm while lengthening the other. By using an interferometer design, the relative change in length of the two arms can be precisely measured, thus signalling the passage of a gravitational wave at the detector site. Long arm lengths, high laser power, and extremely well controlled optical and mechanical stability are essential to reach the requisite sensitivity, since the gravitational waves will be faint and will interact only weakly with matter in the detector (see Saulson, Ref. 1).

Within the last few years, the full scale construction of several large instruments has commenced. These include LIGO, composed of a total of three Laser Interferometer Gravitational-wave Observatories situated in the United States, two with baselines of 4km and one of 2km [2]; VIRGO, an Italian/French project located near Pisa with a baseline of 3km [3]; GEO600 a British/German interferometer under construction near Hannover with a baseline of 600m; and TAMA in Japan, a medium-scale laser interferometerwith a baseline of 300m [4]. In all cases, the specification of these instruments has been based on the detailed experience obtained from the operation of large scale prototypes (with up to 40m arm lengths), combined with the extensive modelling of all aspects which could not be fully tested prior to final construction. While this painstaking preparation has led to confidence that the instruments being built will be able to function as planned, it is generally realized that, after the occurrence of first light, an extended shake down period will be required before each instrument can become scientifically operational.

During that shakedown period, a comprehensive program of fully characterizing the individual instruments will be undertaken. This will play a role not only in providing diagnostics while an instrument is being brought into service, but also, once an instrument is commissioned, in allowing realistic confidence limits to be placed on the processing of any subsequent detection of gravitational radiation. Given the urgent drive, in the major research undertaken so far, to overcome serious technical obstacles, and the lack of a working full scale instrument, relatively little has been done to date on the task of detector characterization. To compensate for this, an international cooperative effort has recently been established within the LIGO Scientific Collaboration (LSC). Accordingly, the limited data available from prototypes operated as production interferometers has been made available to interested participants, including a new group being built up at the ANU as part of Australia's wider activity in the field.

3. NOISE AND ITS ANALYSIS

The analysis of data for gravitational wave detectors can be divided into two parts.

(i) Characterising the noise: this means thoroughly studying the detector output noise for colour, stationarity, statistical properties and periodicity, to allow realistic modelling of the noise. Such a characterisation will serve as a very powerful diagnostic tool for instruments during the commissioning phase and will also lay the foundation for signal extraction techniques as described in the next item.

(ii) Extraction and validation of signals: understanding and characterising the noise is important for devising reliable signal extraction techniques which filter the signal out with a specified level of confidence. Detection procedures can be tested by embedding simulated signals of well-known astrophysical sources, such as coalescing binary chirps, in the available output noise and then endeavouring to re-extract them.

Ground-based interferometers are ultimately limited by three noise sources: seismic, thermal and photon shot noise [1], with the importance of each source depending on the relevant frequency range of the detector (see Figure 1). It is clear from both direct and indirect evidence, however, that the detector output also consists of noise from other than these sources (see Figure 2, and the section on observations from existing data, below). The origin of some of this additional noise is already understood, and has been identified as non-stochastic [5] or non-stationary [6,7]. To help minimize the impact of other noise sources, certain environmental monitors are being put in place, while other system status monitoring channels are also being allocated. All these additional monitors contribute to total the data stream from a fully functioning instrument.

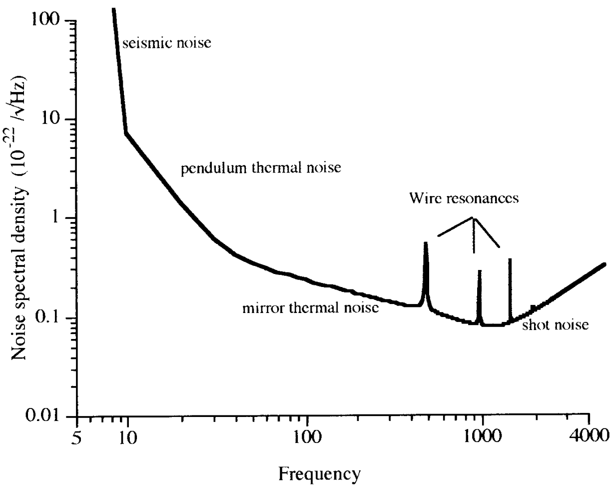

Figure 1. Fundamental noise limits for an hypothetical long baseline laser interferometer (including the effects of support wire resonances). It has been assumed that the effects of quantum light pressure are negligible at the predicted power level.

Other types of noise sources are not yet fully understood. Two sources which have received considerable attention are the effects of stray light within the beam tubes [8–10], and effects from the sudden and unpredictable releases of tension in the suspensions [11]. As is already evident from extensive experience with bar data, noise will appear for which the origin and character have yet to be identified. It has become paramountly clear that it is rare events, which occur as part of the unpredictable functioning of the instrument, that pose the greatest threat to the risk of false detection and the greatest challenge in the process of correctly characterizing the detector output.

In order to have compatible outputs from the several detectors around the globe, the international community has accepted a new data format — the Frame format [13], developed jointly by LIGO and VIRGO — which standardises the storage of data from gravitational wave detector sites. There are expected to be up to 1000 data channels for each interferometer [14], most of which simply record the current operation of the detector. A data analysis package GRASP (Gravitational Radiation Analysis and Simulation Package) is currently being developed by participating research centres around the world, and is being coordinated by Bruce Allen and his colleagues [12] in close collaboration with Caltech. The package contains routines for determining template placement within available parameter space, matched filtering, and spectral analysis. It is designed to run in a parallel processing environment supported by MPI (Message Passing Interface).

4. DATA AND ITS CHARACTERIZATION

A key aspect of carrying out data characterization involves having access to actual data. In so far as no full-scale interferometer is currently working, no real data is as yet available. This lack has occasionally been put forward as an argument against the longterm value of any tools developed prior to the completion of final construction. But, as many of the attributes of real data *are* present in a sufficiently similar form in data from working test models, it is indeed appropriate to be working with test data such as that shown in Figure 2 as a step towards developing generic analytical and diagnostic tools for future application.

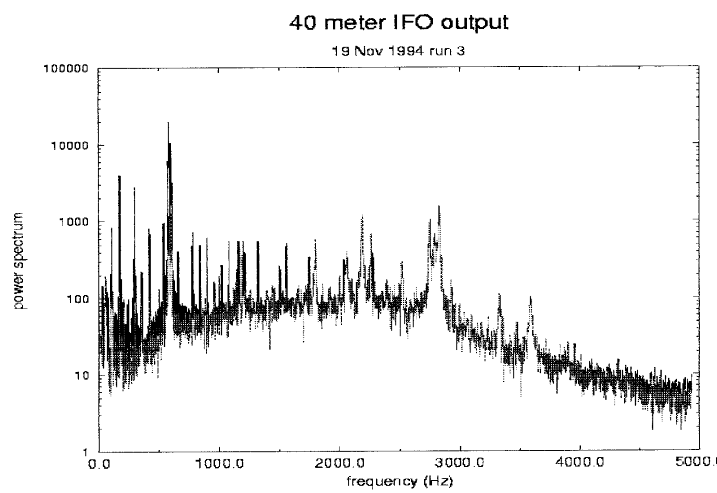

Figure 2. Sample noise spectrum from the Caltech 40m interferometer (Fig. 75 in Ref. 12).

Gravitational wave detectors produce an enormous volume of output (e.g., of the order of 16MB/sec for the LIGO instruments), consisting mainly of noise, from a host of sources both environmental and intrinsic. Buried in this noise will be the gravitational wave signature. Experience in handling large volumes of data and in the development of sophisticated analysis algorithms, to permit the confident identification of any gravitational wave component [15], will therefore play a vital role in the eventual success of gravitational wave detection.

Existing resonant bar detectors have now accumulated several years of detector output signal at appreciable sensitivity. Even so, recent coincidence runs between bar detectors located in Australia, Italy and the USA (see Pizzella, Ref. 16) have highlighted several potential difficulties in trying to avoid false detection events with reasonable confidence. Current interferometer analyses have been focussed on the data from the 100 hour coincidence run on the Glasgow/Garching prototype interferometers (see Nicholson, Ref. 17) and more recently on the existing small body of interferometer output from the 40 m instrument located at Caltech [12]. Most significantly, the Caltech data is now being distributed to interested research groups around the world so that intense work can begin on algorithm development.

5. OBSERVATIONS FROM EXISTING DATA

The design criterion of maximum sensitivity, coupled with the weak strength of known gravitational wave sources, dictates that the predominant component of any output signal will essentially be noise. Experience, to date, in operating such sensitive instruments shows that there is always a large store of rather unexpected internal sources of detector output which have to be properly understood before an instrument will operate effectively close to its design sensitivity. The process of identifying which features of a detector output may warrant closer attention often involves a fairly hands-on approach. Part of our effort will be to build up tools so that this task may be carried out more systematically, since the ability to identify *all* non-gravitational components in the detector output must be an essential part in the detection of gravitational waves.

In a particular stretch of the Caltech data, Bruce Allen has documented 169 distinct ‘events’ which arise in the detector output. Close inspection of data shows that the corresponding disturbances often have well-defined characteristics in both the temporal and spectral domains. It is phenomena like these, not so much in detail as in principle, for which a noise characterization program should be effective, in systematizing their treatment. But there are other features, too, such as the high-Q violin resonances of mirror suspension wires, and the ever present, multiple occurrence of disturbances introduced from the power mains [18,19]. The plethora of such narrow line features collectively detracts significantly from detector efficiency unless they can be systematically and effectively modelled. The high volume of data from any working instrument necessitates a scheme for carrying out this process which is as automatic as possible. Ultimately, it is rare events, clearly among the hardest to categorize, which are the most urgent to identify correctly, in order to avoid a false detection of gravitational radiation.

At present, all groups (including that at the ANU) active in data characterization have access to the Caltech data, currently being distributed in the Frame format, and to the GRASP subroutine Library. At the moment, no other data, either from bars or interferometers, is available in the Frame format. Nevertheless, high quality data does exist from both Glasgow and Munich, as well as from several of the bar detectors. Even in this situation, when access to the data is possible, it is often sufficiently labour intensive to adapt some specialized method of analysis from one instrument to another, that the full potential for this is likely to remain under-developed within the foreseeable future. However, it has already been possible to conduct coincidence experiments between interferometric and resonant bar data [20], with a view to determinine the most optimal search types for further investigation.

6. BORROWING OF TECHNIQUES?

Since the problem of data analysis has already been encountered in many other experimental fields, it has been suggested that, even for the detection of gravitational waves using laser interferometers, the task cannot really be intrinsically new. The techniques required must already exist in other fields of research. While this is partly true, both pooling them togetherfor this application, and even fine tuning them for that purpose are indeed new, while the computational demands challenge global resources.

One field of astronomy in which large quantities of data are already examined in the hope of finding periodic signals is the search for pulsar sources in radio astronomy. However radio antennae are highly directional whereas, as an antenna for gravitational radiation, a laser interferometer is almost omnidirectional, having no forward to back gain and only a few db difference in gain between the forward and sideways directions. This lack of directionality plays against gravitational wave detection of weak periodic sources in two distinct ways. Compared to a radio telescope, the effective wide beam-width of a laser interferometer gives increased noise (unsuppressed from all other directions) against which to try to find a signal, adding to the requisite processing time.

Furthermore, the subtle phase changes, which arise as the earth rotates about its axis and revolves about the sun, are different for each direction. Whereas radio astronomers can choose to examine different directions by sequencing different telescope observational time, gravitational wave astronomers looking for weak periodic sources must sequence different (and larger) computational search time — for a given set of data. On the basis of prior experience with pulsar data, Lyne [21] argues that each of data storage, computing speed and main memory size can present potential difficulties, as practical examples have amply demonstrated.

Another attribute of the expected output of the laser interferometers currently under construction for the detection of gravitational radiation is that their final bandwidth is in the human audio range. Thus the highly technical capability of the human ear can be put to use in both identifying interesting sources (or noises not to be confused with gravitational wave sources), and in the process of developing practical algorithms for their automatic identification. Yet again, many existing techniques for this task rely on properties which are less evident for laser interferometers.

The field of underwater sonar has developed the capability of detecting and analyzing specific weak signals buried in noise. It has been realized that noises generated by underwater creatures or vessels all have a direct mechanical origin, and this greatly facilitates the construction of a small basis dictionary from which to build templatesfor more complicated sounds. In laser interferometers, violin resonances of the suspension wires and seismic vibrations are indeed of mechanical origin, and often present little difficulty in identification. But other vibrations, such as of the vacuum chamber walls, enter into the detector output through both coherent and incoherent scattered light paths. As such, this effect is often subject to an unpredictable path through the internal control loops of the interferometer and, due to the modulation of the light beam in use for the functioning of those loops, may become evident at frequencies quite removed from those at which it originates.

Another technique, *adaptive control* [22], this time borrowed from control engineering, would appear at first sight to possess great potential for adaptation in reducing the overall motion of suspended mirrors. This is an important issue in principle because typical mirror movement is many times the size of the signal expected to be induced by the passage of gravitational waves. While there is no conceptual barrier to the introduction of the method, it turns out that a series of practical limitations severely curtail its practical utility. These practical limitations are tied up with the dynamic operating range of available transducers and the power capability and intrinsic noise floor characteristics of effective transducer amplifiers.

There is already at least one way in which interferometer installations may benefit directly from techniques used in the operation of cryogenic bar detectors. Bars are effectively high-Q, narrow band devices, and the violin modes of mirror suspension wires in interferometers have similar properties. Though not a desired part of interferometer output, they can nevertheless be looked upon as giving a separate measure of system performance, through being treated in a similar manner to the bar detector output.

7. AUSTRALIA AND AIGO

All the current construction of km baseline interferometers is taking place in the Northern Hemisphere. The Australian Consortium for Interferometric Gravitational Wave Astronomy, ACIGA, has in mind the eventual construction of a full-scale instrument in Western Australia, on land set aside for this purpose by the Western Australian Government. Funding for a 12m advanced research interferometer (ARI), to be a future corner station for the AIGO500, the proposed 500m Australian International Gravitational Observatory project sponsored by ACIGA [23], has already been obtained. ACIGA currently encompasses expertise related to all major components of the full scale interferometer: the injection bench; seismic isolation suspensions and thermal noise suppression; and the detection bench and global control. However, through lack of human and fiscal resources, most aspects of gravitational wave data analysis have been largely ignored to date. With the availability of high quality interferometer data, the establishment, within Australia, of a data analysis facility at the ANU, is thus particularly timely.

Data management and signal extraction problems arise for all gravitational wave detectors. In Australia they do so more acutely because the country's low total population, coupled with a sparse population density, means that both requisite personnel and national infrastructure are not present to the same degree that occurs in conjunction with all the other currently planned detectors. National infrastructure includes, in particular, funding, as well as communications and computing network components. Personnel are required for the development, design, planning and building phases of the ACIGA project, and its theoretical backing.

LIGO expects a total of around 16 MB/sec from three detectors which, with the overlap at Hanford, corresponds to about 6 MB/sec for one interferometer. Although AIGO is likely to have overall fewer than the 1000 channels proposed for LIGO, it will be predominantly some of the lower bit rate channels which are most likely to be absent, perhaps leaving Australia with an effective data acquisition rate closer to 5 MB/sec. While some of that may be compressible, such will not be the case for the higher bit rate, mostly noisy, channels. Thus, while compression may bring the net rate down, to say 3 MB/sec, the optimal form of compression is unlikely to be known until some time after work with the data has commenced. Evidently, modelling data throughput at up to 5 MB/sec would appear necessary, while anything over 3 MB/sec may prove satisfactory in the long run — for one way data transfer.

Due to the expected large rate of data accumulation and the extensive subsequent analysis, AIGO will require access to high speed networking, massive data storage and high speed computing. At the present time, within Australia, the only site with the full range of facilities required for this project is at the ANU Supercomputer Facility (ANUSF). The post-analysis code currently written has been ported to several machine architectures already, including both scalar and vector memory machines. In addition, the code parallelizes well, and is thus able to make effective use of Beowulf clusters[3] of commodity workstations. These clusters are potentially serious, competitive, economical, future alternatives to powerful machine architectures. Along with existing supercomputing facilities, these are also being investigated at the ANUSF.

The siting of AIGO at Gingin in WA, while the requisite computing and data storing facilities reside at the ANU, poses a severe challenge to Australian network infrastructure. Tests are currently underway to evaluate existing capability, as part of a step towards helping to shape bandwidth requirements of the proposed AARNET2 network [24], which is destined to take Australia well into the 21st century.

The initial thrust of the work proposed to be carried out at the ANU will be in the spectral domain, using efficient approximation schemes and extensive statistical analysis. While the most sophisticated schemes for characterising noise and identifying signals work optimally when all noise sources are Gaussian, we will work especially on the non-Gaussian component, which limits detection efficiency. Given Australia's extensive experience operating bar detectors [25], one possible first step is to make use of specific techniques which have already been developed for the analysis of bar data, by treating the high-Q violin resonances of the mirror suspension wires in an interferometer as a probe of overall system performance. These techniques have played a major role in the identification, and sometimes elimination, of non-Gaussian noise sources in bar detector output. We will be adapting these methods from the narrow band application for bars to the wideband output of interferometers.

The approach to noise characterisation envisaged is based on well

[3] Beowulf clusters are described at http://www.beowulf.org.

established expertise in the field of spectral analysis [26]. An advantage of this approach is that although the characterisation itself can be quite slow, it can be carried out off-line, generally during commissioning, and then provides an effective and robust tool for signal interpretation which can be very efficiently implemented.

7. FUTURE PLANS

Analysis of rare events is perhaps the most urgent and demanding problem facing data characterization efforts. Here, the meaning of rare is determined on the basis of some prior expectation. Most typically, it refers to events which occur far more frequently that would be anticipated from pure noise, distributed with Gaussian statistics. Experience with running bar detectors has shown that the knowledge required to be able to properly identify such signals accumulates gradually over rather long time-frames. Inspection of the available 40m data from Caltech clearly indicates that non-gravitational events dominate the non-Gaussian aspects of the detector output, and there is no reason to suppose that this will not be the case again when large-scale instruments first begin operation. Thus, the global effort to understand these predominantly instrument-based signals must continue.

With several large laser interferometric gravitational wave detectors already well under construction in the USA and Europe, the international effort in gravitational wave data analysis research is gathering momentum. It now exists as a well supported, priority area within all international gravitational wave detection projects. Although the field of gravitational wave data analysis is in its infancy, it is developing and evolving at a rapid rate. It is therefore extremely important that our own data analysis program develops in close step with other international programs. At meetings of the LIGO Scientific Collaboration (LSC) detector characterisation group, the latest techniques and developments in detector characterisation are examined in detail, and future research directions are outlined. Australia already participates in this area of LSC activity.

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REFERENCES

1. Saulson, P. R. (1994). *Fundamentals of Interferometric Gravitational Wave Detectors* (World Scientific, Singapore).
2. Abramowici, A. et al. (1992). *Science* **256**, 325.
3. Bradschia, C., et al. (1991). In *Gravitational Astronomy: Instrument Design and Astrophysical Prospects*, D. E. McClelland and H.-A. Bachor, eds. (World Scientific, Singapore), p. 110–135.
4. Tsubono, K., and the TAMA collaboration (1997). In *Gravitational Wave Detection: Proc. TAMA Workshop*, K. Tsubono, M.-K. Fujimoto and K. Kuroda, eds. (Universal Academic Press, Tokyo), p. 183–191.
5. De Salvo, R. (1997). "Non Stochastic Noise in Gravitational Wave Detectors." VIRGO preprint.
6. Niebauer, T. M., et al. (1991). *Phys. Rev. A***43**, 5022.
7. Meera, B. J., and Strain, K. (1991). *Phys. Rev. A***44**, 4693.
8. Thorne, K. S. (1989). "Light scattering and proposed baffle configuration." Unpublished Caltech report. See also LIGO technical reports T940063-00, T950101 00, T950132-00 and T960012-00 by E. E. Flanagan and K. S. Thorne.
9. Vinet, J.-Y., Brisson, V., and Braccini, S. (1996). *Phys. Rev. D***54**, 1276.
10. Vinet, J.-Y., Brisson, V., Braccini, S., Ferrante, I., Pinard, L., Bondu, F., and Tournie, E. (1997). *Phys. Rev. D***56**, 6085.
11. Beccaria, M., et al. (1998). *Nuc. Instr. and Meth. in Phys. Res. A***404**, 455.
12. Allen, B. (1998). GRASP Users Manual, University of Wisconsin, Milwaukee.
13. Mours, B. (1997). In *Gravitational Wave Detection: Proc. TAMA Workshop*, K. Tsubono, M.-K. Fujimoto and K. Kuroda, eds. (Universal Academic Press, Tokyo), p. 27–30. See also the LIGO/VIRGO technical note LIGOT970130-B or VIRGO-SPE-LAP-5400-102.
14. Sigg, D., Fritschel, P. (1998). "LIGO Channel Count." LIGO Technical Document T980004-00-D.
15. Schutz, B. F. (1991). In *The Detection of Gravitational Radiation*, D. G. Blair, ed. (Cambridge University Press, Cambridge), p. 406–452.
16. Pizzella, G. (1997). *Class. Quantum Grav.* **14**, 1481.
17. Nicholson, D., et al. (1996). *Phys. Lett. A***218**, 175.
18. Sintes, A. M., and Schutz, B. F. (1998). *Phys. Rev. D***58**, 122003.
19. Allen, B., and Ottewill, A. (2000). *Gen. Rel. Grav.* **32**, 385 in this special issue.
20. Astone, P., Lobo, J. A., and Schutz, B. F. (1994). *Class. Quantum Grav.* **11**, 2093.
21. Lyne, A. G. (1989). In *Gravitational Wave Data Analysis*, B. F. Schutz, ed. (Kluwer Academic Publishers, Dordrecht), p. 95.
22. Astrom, K. J., Goodwin, G. C., and Kumar, P. R. (1995). *Adaptive Control, Filtering, and Signal Processing* (Springer-Verlag, New York).
23. Sandeman, R. J., et al. (1997). *A.I.G.O. Prospectus* (University of Western Autralia, Perth).
24. Hawick, K. A. (1998). *AARNet2 Demonstration Project: Advanced & Distributed Computing Project Plan* (University of Adelaide, Adelaide).
26. Heng, I. S., et al. (1996). *Phys. Lett. A***218**, 190.
27. Coldwell, R. L., and Bamford, G. J. (1991). *The Theory and Operation of Spectral Analysis — Robfit* (A.I.P., New York).