Getting Ready for GEO600 Data

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Data of good quality is expected from a number of gravitational wave detectors within the next two years. One of these, GEO600, has special capabilities, such as narrow-band operation. I describe here the preparations that are currently being made for the analysis of GEO600 data.

§1. Introduction

After 4 decades of development, gravitational wave detectors are finally reaching the level of sensitivity where the first detections could occur. Within one year, the TAMA [1] detector could detect short bursts of radiation with an amplitude smaller than 10^{-20}, and by 2001 both LIGO [2] and GEO600 [3] should be sensitive to bursts of amplitude around 10^{-21}. Within a further year, VIRGO [4] could come on-line with an even better sensitvity.

Detections at this level are by no means certain, but a strong supernova in a nearby galaxy could be seen. In addition, these detectors can be used to look for other sources with smaller amplitudes. Since their sensitivity increases roughly as the number of cycles of radiation they observe, a long-lived source like an irregular spinning neutron star could be detected with an amplitude as small as 10^{-26} in one year of observing.

The possibility that these detectors can be used to search for different kinds of signals makes them very versatile, but it also complicates the analysis of the data. Each detector produces a single data stream that may contain many kinds of signals. Detectors do not point, but rather sweep their broad quadrupolar beam pattern across the sky as the Earth moves. So possible sources could be anywhere on the sky. Data analysis algorithms need to be able to find signals from any location.

Since the first detectors will barely cross the threshold of detectability, the early detections will be weak, with small signal-to-noise ratios. There is therefore a premium on applying the best signal analysis methods to this detection problem. The best linear method, for example, is matched filtering, in which the computer looks for a correlation in the noisy data with a template, which is an expected waveform. For some sources, such as coalescing compact-object binary systems [5] and spinning neutron stars, [6] we believe we have good theoretical templates. However, in all cases the waveform templates depend on parameters, such as the masses of the binary stars or the location on the sky of the neutron star, that may not be known ahead of time. Using these templates becomes a compute-intensive job, and the algorithms must be

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implemented as efficiently as possible.

For other sources, such as the last phase of the merger of two black holes [7] or the burst of radiation from the gravitational collapse event that leads to a supernova, [11] our understanding of the astrophysics does not at present permit us to construct accurate templates. Other methods that are more robust than matched filtering must be used in order to recognize signals of an unexpected shape. Such methods must be chosen with care, since they are not optimal and some may perform better than others on specific sources.

In this paper I will review the progress being made within the GEO600 project to design a data analysis system that is capable of performing sensitive searches for all of these sources within the project's limited computing budget. The data analysis programs are being developed jointly with scientists in the LIGO Science Collaboration (LSC) and with VIRGO scientists, so much of what I say will also apply to those projects. But GEO600 has, unlike the other first-generation detectors, the ability to do signal recycling, [8] which is a form of narrow-band observing. I will discuss the impact of signal recycling on our plans for data analysis.

Since expected signals are weak, there has been significant interaction between designers of the experimental hardware and data analysis specialists in GEO600. I will give examples of how some experimental features were modified or improved, and others specified in detail, after studies of data analysis showed the benefits of taking these steps.

The plan of the paper is as follows. After a review of the current status of the GEO600 detector, I will outline the plans for data analysis, both within GEO and in collaboration with LIGO. I will then address the detection algorithms needed for specific sources: chirps, known pulsars, searches for unknown neutron stars over wide areas, the X-ray binary Sco X-1, and unexpected signals. The first source detected might fall in any of these categories, and it might come at any time from the moment detectors begin operating.

§2. Status of GEO600

GEO600 is a collaboration among three institutions in Germany — the Max Planck Insitute for Quantum Optics, the Max Planck Institute for Gravitational Physics (Albert Einstein Institute — AEI), and the University of Hanover — and two in the UK — the University of Glasgow and Cardiff University. The detector, with 600 m arms, is under construction near a village called Ruthe, south of Hanover. Its vacuum system is fully constructed and tested, the first mode cleaner cavity is locked and working, and the data acquisition system is installed. Currently work is going on to lock one arm as a single optical cavity, and this is planned for the end of 1999. By mid-2000 there should be interferometry with the test optics, and full interferometry with the final optics the following year.

Figure 2 shows the expected performance of GEO600 in its broadband configuration and Fig. 2 in a possible narrow-band configuration. The total noise is shown as a quadrature sum of the expected noise from different sources. Notice that the photon shot noise even in the broadband case is tuned by signal recycling. This

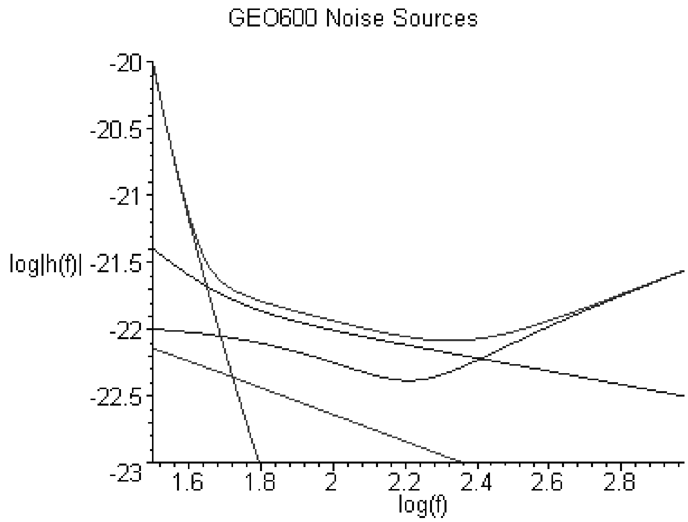

Fig. 1. GEO600 expected noise curve in broadband mode.

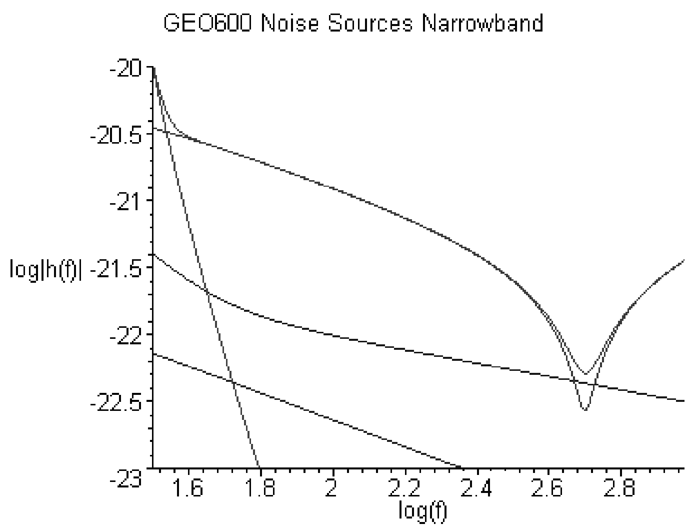

Fig. 2. GEO600 expected noise curve in a particular narrowband configuration.

allows the shot noise to be adapted to the best form to fit with other noise sources, and it also makes the interferometry cleaner. The narrow-band curve on the right is shown for a specific frequency near 500 Hz. The bandwidth is selected to allow the best sensitivity to be limited only by the thermal noise. This mode is useful in looking for signals of known frequency, or in performing searches for narrow-band signals at high frequency.

The GEO600 project has its own data-analysis team inside the project, distributed among Cardiff, the AEI, and Glasgow. This is in contrast to LIGO, which provides support and coordination for data analysis within the project but relies on the LSC to provide the algorithms and much of the software. The present author is the principal investigator with responsibility for data analysis and acquisition within GEO. B. Sathyaprakash at Cardiff has overall responsibility for data analysis coordination, and he is assisted by research scientist I. Taylor, postdoctoral scientists B. Balasubramanian, and D. Churches, and programmer M. Lewis.

At the AEI the current GEO support group includes staff members C. Cutler, M.-A. Papa, and A. Vecchio, plus postdoctoral scientists E. Chassande, B. Owen, A. Sintes, C. Ungarelli and P. Williams. The staff at the AEI work on a mixture of roughly 50% preparation for data analysis and 50% theoretical work on gravitational wave sources, including template prediction. At Glasgow a new group consisting of staff member C. Davies and postdoctoral fellow P. Boyle is expected to grow by at least one further member soon. In addition, the GEO team has strong collaborations with individuals outside the project, including S. Frasca (Rome), A. Krolak (Warsaw), and S. Dhurandar (Pune).

§3. Approach to data analysis

3.1. *Data storage and distribution*

Data from dozens of control, monitoring, and signal points will be acquired on the site and distributed around the site or to more distant points in real time, as required by the experimentalists. The experiment site is connected to Hanover University by a high-speed radio link, so no data is stored at the site (apart from a disk buffer capable of storing 3 days of the archive data set). Twin redundant workstations control data distribution from Ruthe to Hanover and beyond.

In Hanover a cluster computer with a total processing capacity of about 5GFLOPs will clean and calibrate the data, and perform initial searches for burst sources and coalescing binaries. Wide-area searches for signals from unknown neutron stars will be performed on a cluster computer at the AEI, which should have a speed approaching 20 GFLOPs, with 40 GB main memory. A similar cluster is planned in Cardiff, which will perform similar searches for different ranges of parameters. We are currently testing CPU chips to determine what kind of machine would be best suited for these clusters.

A subset of the total available data will be archived to tape at 0.5 MB s^{-1}. This may be done in Hanover, but we are currently examining the possibility of sending over the internet to Berlin and writing it to tape there. This archive, some 15 terabytes per year, will be stored in two places: in Germany, by the Albert Einstein Institute, and in Britain by Cardiff University. It will be available to all members of the GEO project, all close collaborators, and (under an agreement described below) to members of LIGO and most of the LSC, but the size of the data store suggests that it will not often be accessed, nor will it be distributed to other sites.

By contrast, most of the real work will be done using a reduced set of data, containing the cleaned and calibrated signal data and a summary of the monitoring and environmental data. This will be the foundation of most of the subsequent data analysis within GEO, and it will be distributed to all the GEO partners, collaborators, and LIGO. The reduced data set will probably amount to a much more manageable size of 0.5 terabytes per year.

3.2. *Software*

Within GEO we have been designing two kinds of data analysis software. The first is quick-look software for commissioning, which will help scientists track down trouble spots and diagnose them as they try to get the detector working. The second is our main data analysis system.

These two kinds of analysis have different requirements. For the quick-look system we have designed a new computational environment called Triana. [9] A preliminary version of this software has been running for almost a year at the Caltech 40 m prototype interferometer in the LIGO project, and is now running at the Ruthe site for GEO. This software, written in Java, has a simple graphical user interface, in which a user assembles a data analysis program from a set of pre-programmed components (FFTs, correlators, etc.) by dragging the components from a toolbox into a workspace and then wiring them together to direct the data through them. The rapid re-configurability of the system, its intelligent built-in data types, its ability to work over networks, its ability to take several data streams from the acquisition system at the same time, and its suite of powerful applications take it well beyond the usual functions of oscilloscopes and spectrum analyzers. Using Triana and the computer-based control system manager, scientists will be able to sit in Glasgow or Hanover and troubleshoot technical problems. Although Cardiff University will be selling Triana commercially, it will be free to the gravitational wave community from the Triana website. [10] The first public release is expected in late 1999.

For the full data analysis programs, Triana is not a full solution. Programs must be written in a compiled language (C or FORTRAN) for maximum speed, and algorithms need to be optimized for efficiency; ease of reconfigurability is not a requirement. Nevertheless, Triana is planned to be used by GEO for the top level, supervisory program. This is because this program does very little computation, so Java is no disadvantage. Triana's efficient networking abilities allow the program to be controlled from, say, Cardiff while it runs at Hanover, despite the relatively slow internet bandwidth between the two locations. And finally, Triana's built-in data types, which were designed for looking quickly at the data from the detector, are perfectly suited for passing information between steps in a larger analysis algorithm. So the present plan is to use Triana to control and manage the communication between the C/FORTRAN functions or subroutines that will perform the data analysis.

3.3. *Cooperation with LIGO*

GEO and LIGO have signed an MOU that provides for full access from each project to the other's data. This will last as long as the LIGO I project takes data. Rules are currently being discussed for managing the access and exchange of the data. The expectation is that any members of the projects or their collaborators (e.g., LSC members who contribute to LIGO I) should be able to get access to the data of both projects for analysis. Publication on the basis of such analysis would have to be approved by both project managements, and important papers would have authorship consisting of the entire collaborations.

Because of the size of the data sets, full access to non-signal data streams, such as environmental monitors and so on, will only be practical at the archive centers. But the smaller signal data streams will be distributed and shared between the projects.

This agreement is not exclusive. Both projects see this as a model for an enlarged agreement that will hopefully involve TAMA and VIRGO as well. The goal of gravitational wave astronomy is best served by data exchange and joint observing programs.

§4. Specific sources: sensitivity, algorithms, priority

4.1. *Chirps*

The first interferometers will not have good sensitivity for detecting coalescences of neutron-star binaries, unless there are orders of magnitude more such systems in nearby galaxies than in our own. Figure 3 shows the sensitivity of GEO600 to a neutron-star chirp in the Virgo cluster. This is not really detectable, yet on current statistics only one such event would be expected every 1000 years. We will therefore have to wait for detectors in the class of LIGO II before we see these.

But other binaries may be seen earlier. We do not know the rate of black-hole/black-hole binaries. Being stronger, if they are as abundant as neutron-star

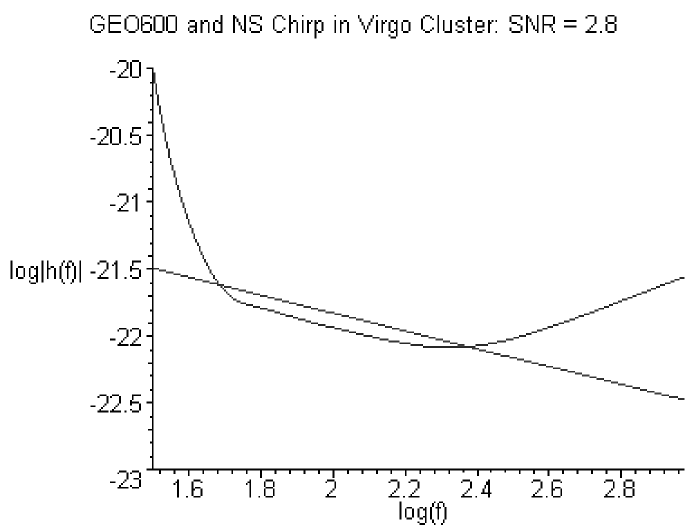

Fig. 3. Sensitivity of GEO600 vs the effective signal from a binary system consisting of two 1.4 $M_\odot$ neutron stars in the Virgo cluster. The noise is plotted as $S(h)^{1/2}$. The signal is plotted as $f^{1/2}|\tilde{h}(f)|$. In this form, the difference between the curves in this logarithmic plot is a visual indication of the contribution to the SNR from any frequency. In this case, the signal is barely above the noise, leading to a SNR of 2.8. This is not enough to identify a detection without other coincident observations.

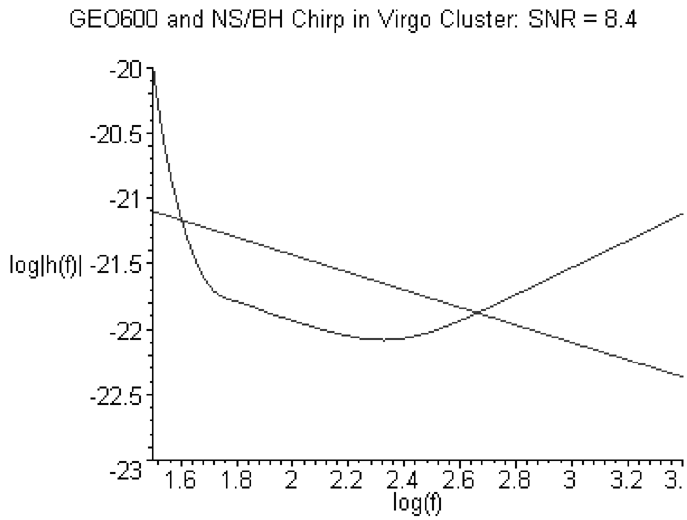

Fig. 4. Signal and noise for GEO600 and a binary coalescence consisting of a 1.4 $M_\odot$ neutron star and a 15 $M_\odot$ black hole in the Virgo cluster.

binaries, then there may be one or two near enough to the Earth to be detected by the first detectors. Figure 4 shows, for example, that binary stellar black holes could be visible to GEO600 out to 100 Mpc with SNR of 5. Given the small numbers on which rate estimates are based, this offers a real possibility of detection. But if the black holes are even more massive, then things get less certain. The observable frequency region may include only the merger radiation itself, and we do not have good models of this at present. Detection will rely on more robust methods.[11)]

An interesting idea is the possibility of binary systems formed by MACHOs.[12)] If these objects are compact enough to generate gravitational waves in the observable region, then these binaries could be very abundant. For this reason, GEO is planning to search for binaries with a total mass as low as 0.5 $M_\odot$.

Correlations with unusual events may also help, such as gamma-ray bursts. But the rate of bursts suggests that, if they are correlated with neutron-star binaries, they are quite far away. However, if bursts can arise from a number of different systems, then some, such as hypernovae, may be nearer.

4.2. *Continuous waves from known objects*

If a pulsar is known through radio or X-ray observations, then searching for it in gravitational wave data will normally not be very challenging. The position of the source will be known, and the frequency of the radiation must be closely related to the pulsar frequency. It will be important to search at frequencies of the pulsar frequency ($m = 1$ quadrupolar radiation, which might come from free precession), twice the pulsar frequency ($m = 2$ quadrupole radiation, which would be generated by mass asymmetries built into the spinning star), and 4/3 the pulsar frequency (which would come from an unstable r-mode). Indeed, free precession can make

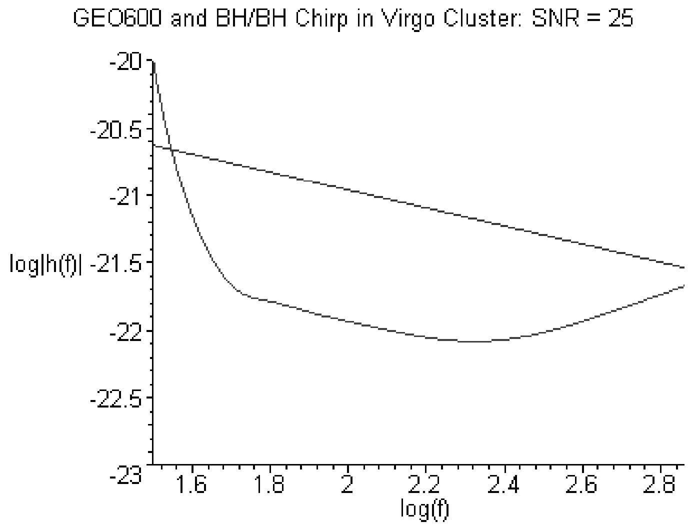

Fig. 5. Signal and noise for GEO600 and a binary coalescence consisting of two 15 $M_\odot$ black holes in the Virgo cluster.

these frequencies differ by small amounts from the pulsar frequency, so searches will have to be done in small bandwidths about these key mulitples of the spin frequency.

But to achieve a reasonable sensitivity we must accumulate signal for a year or more. This places constraints on the operations of detectors.

Known pulsar amplitudes are also constrained if the period derivative of the pulsar is known, as it is for most pulsars. The loss of kinetic energy determined by the spindow sets a maximum amplitude on the expected radiation, provided we know also the distance to the source. In most cases this maximum is itself below the GEO observing curve, but in a few cases this limit is interesting. These are illustrated in Fig. 6. The most important of these cases is the Crab pulsar, which GEO could see with SNR more than 100 in one year, provided it is radiating at its limit. However, if an eccentricity of about 10^{-5} for the source of the radiating quadrupole moment is assumed, then the radiation amplitude falls to a little below the GEO noise curve. Only observations will tell whether the Crab is detectable by GEO.

A complicating issue for the Crab pulsar is the fact that it glitches relatively frequently, so that the possibility that a glitch will occur during a one-year observation is significant. The effect of a glitch is to change the frequency of the radiation, but if the radiation depends on an asymmetry that is changed by the glitch event, then also the phase of the gravitational waveform could undergo a sudden change. This means that filtering for the Crab will not be trivial. We will have to use continuous radio observations to monitor the frequency, and if it glitches we will have to put in a parameter in the filter for the phase jump.

The Crab illustrates the interaction within the GEO project between experimentalists and data analysts. A year ago, the GEO noise curve would have been drawn with its low-frequency limit (steeply rising seismic wall) about 10 Hz higher than is

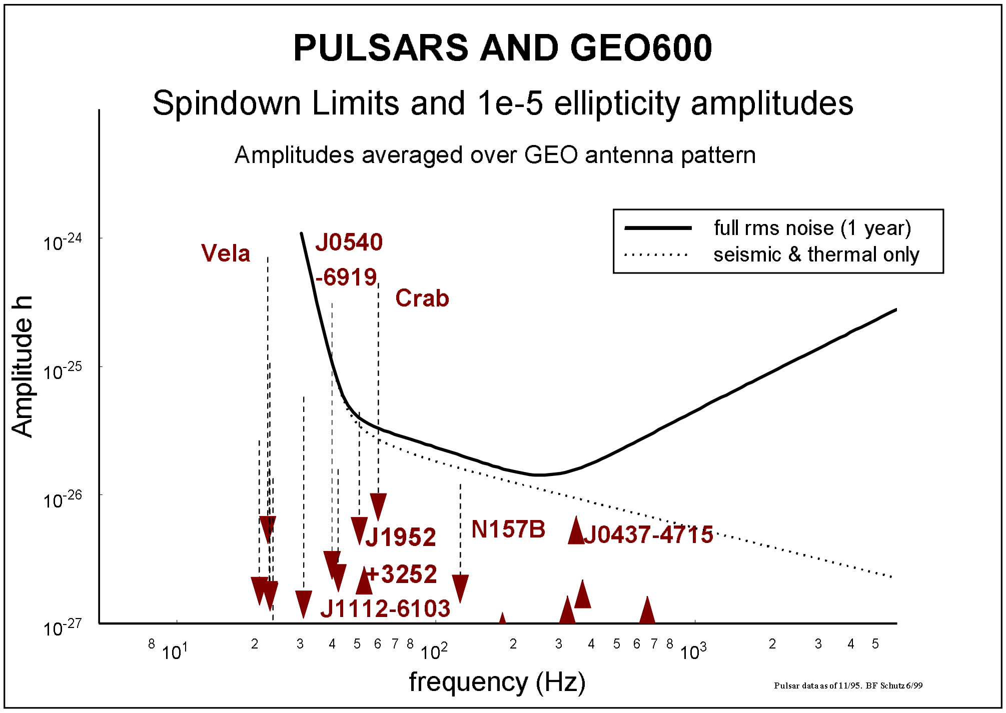

Fig. 6. Noise-curve of the GEO600 detector in broadband mode for a one-year observation, compared to signal amplitudes from a number of known pulsars. The amplitudes are shown as arrows, the top of which is at the spindown limit and the bottom at the amplitude expected for an ellipticity of 10^{-5}. The amplitudes are averaged over for the antenna pattern of GEO as it sweeps across the sky.

shown here. After the data analysts emphasized to the experimenters the potential importance of achieving good sensitivity to the Crab, the experimenters re-designed the suspension to improve its sensitivity at the crucial frequency of 60 Hz by a factor of almost 100. This new design was so successful that it has been adopted as part of the design for the LIGO II upgrade.

Other known objects may be sources of gravitational radiation, but we might not have as much information from them as from pulsars. For example, unusual giant stars may be Thorne-Zytkow objects, which are giants with neutron stars in the centers, the result of inspiral of a binary neutron star companion. The neutron star will be accreting strongly and may, if the giant rotates, accrete angular momentum and spin up. This could lead to instabilities or other gravitational wave radiation mechanisms, as proposed for the low-mass X-ray binaries. In such systems we will have a location to search for, but not a frequency.

Supernova remnants should also be searched. Young remnants may contain a neutron star that is a pulsar that is not beamed toward us. Recent observations by the Chandra satellite have revealed a previously unobserved point source of X-rays at its center, which is likely to be a young neutron star. GEO should search all such remnants in a small area around their geometric centers.

Globular clusters are promising sources of radiating neutron stars. Many pulsars have been found in a few core-collapse globular clusters. Some are so young that they must have formed by accretion-induced collapse of white dwarfs. They may be sources of gravitational radiation themselves, but GEO should search the rest of the field of such clusters for other neutron stars. These might be pulsars beamed in other directions.

GEO is developing a database that will include the coordinates of all such targets. The selection of systems to look at can be done at any time.

4.3. *Area searches*

Pulsar surveys do not show us all the neutron stars in the Galaxy, because of beaming effects and the limited range of such surveys. Gravitational wave observations have the potential to be more complete, at least in terms of strong gravitational wave emitters. But to become this complete, we shall have to do a wide-area survey of the sky.

The youngest star in the galaxy is probably about 10% of the age of the youngest known pulsar, the Crab. It may be nearby, hidden in a star-forming region, or it may be on the other side of the Galaxy. If young neutron stars are strong radiators, then this star should be the strongest. According to recent work on the r-mode instability, [13)] it should not be rotating faster than about 150 Hz, so its radiation should be at or below 300 Hz, where GEO and other first-generation detectors have optimum sensitivity. But its frequency will not be constant during the observation. If it has a spindown timescale of only 100 years, then in a one-year observation it will spin down by 1%, or about 3 Hz. Since we can resolve 3×10^{-8} Hz in a one-year observation, this spindown represents a drift in frequency of 10^8 frequency resolution elements (frequency bins)! The drift would be noticeable in just a one-hour observation, too short to accumulate enough sensitivity to detect radiation of a reasonable amplitude.

In fact, the situation is worse, if the second time derivative of the frequency acts on the same timescale, then it makes a change of frequency of 0.01%, or about 10^6 frequency bins. To fit the signal over one year would require including the third time derivative (10^4 bins) and the fourth time derivative (100 bins). Each different frequency bin that can be affected by the spindown parameters (derivatives of the frequency) forces one to use a different value of that parameter that needs to be searched for, so just to accommodate the spindown one needs roughly 10^{20} templates!

In addition, its position will be unknown. In a 1-year observation, the frequency modulation caused by the motion of the detector allows one to obtain a similar angular resolution on the sky to that which radio astronomers obtain with single-dish observations of pulsars, namely fractions of an arcsecond. That means that there are some 10^{13} locations on the sky that must be searched independently in order to demodulate the signal well enough to reach the theoretical sensitivity of such an observation. For each place on the sky one has to look through the full set of spindown parameters.

So a brute-force search for such a pulsar will have to cope with a parameter space consisting of some 10^{33} templates, any one of which might reveal this pulsar at any frequency. But it is easy to see that to perform demodulation and a wide-band frequency search for this many templates on a year's worth of data sampled at, say, 1 kHz (3×10^{10} samples) is simply impossible. [6]

But searches for such pulsars are not hopeless. It is clear that if one performs 10^{33} independent searches with approximately 10^{10} independent frequencies in each search, then one cannot expect to identify a pulsar right down to the 1σ noise level of the detector: one can only be confident of an identification if the probability that the noise would create a chance signal is less than about 10^{-43}. Given Gaussian noise, this requires a threshold for identification of at least SNR = 9.3. It seems safe to assume that such a search will have an effective sensitivity no better than 10 times the detector noise level. So a search does not need to examine each frequency bin down to the 1σ level. It only needs to ensure that a signal as strong as 10σ is not missed.

Hierarchical search strategies can address such a requirement much more efficiently, provided they are carefully designed. Two related methods are under development, one in the LIGO LSC community, [14] and the other within GEO. [15] Both begin from much shorter initial searches, lasting approximately 1 day. Since such a search has frequency bins 365 times larger than those of a 1-year search, and the modulation produced by the Earth's motion and by spindown is much less, the number of independent templates that must be searched is very much less, about 10^7 instead of 10^{33}. To perform a complete search over all these parameters in one day (keeping up with the data stream) requires a computer capable of executing a few hundred GFLOPs. The methods then knit together a succession of these short searches using an *incoherent* method. In the LIGO approach, this is done by adding power spectra together. In the GEO approach, this is done by searching power spectra for patterns of peaks, using a technique developed in particle physics called the Hough Transform.

At the end of this incoherent stage, the data are passed through a threshold chosen so that a signal that would have had a strength of 10σ would still be seen. This turns out to be at a level of $10\sigma/365^{1/4} = 2.2\sigma$ at the end of the incoherent stage. Then a third stage is required to follow up these candidates by refining parameter space, but only around the parameters that pass through the threshold, and then repeating the search over this smaller portion of parameter space. Since the parameter space is smaller the initial coherent stage of the next search can be longer, and so by the end of the second incoherent stage the threshold can be set to produce a further refinement of the space. In this way one can iterate to eliminate all the parameter space in which there are false alarms.

Even this search, just described, demands considerable computer power and is not at all optimal. Practical searches will probably have as a goal finding sources provided they are stronger than some target level that is somewhere between 10σ and 15σ over an observing period of only 10^7 s. Optimization studies by GEO [15] have suggested this is possible for some kinds of sources with a 20 GFLOPs computer. Further studies are needed when the algorithms are coded in the next few months.

Such algorithms are limited not just by the availability of computer cycles but also by considerations of memory size and input/output delays. In GEO we have developed methods of approximating Fourier transforms of data over long periods, such as one day, by building them up out of Fourier transforms of data taken on short periods of time, say an hour, and working exclusively within a narrow bandwidth of frequencies. [16] While not exact, our tests have shown us that such methods produce excellent approximations, and have the advantage that a single processor in a parallel computer can work entirely locally in frequency space, without needing to communicate with other processors. Because of these methods, GEO plans to achieve its analysis targets using clusters of workstations communicating only via fast ethernet links.

Further improvements in these algorithms seem possible. At frequencies above 300 Hz, narrow-banding is possible. This improves sensitivity in a narrow band of frequencies, allowing one to reach the same limit on the signal amplitude in a shorter time. Since the number of parameter sets is strongly dependent on the observation time, it is actually a computationally more efficient strategy to cover the high-frequency region in a number of short narrow-band observations than in a single wide-band observation.

Another improvement will be to run the GEO-designed Hough algorithm alongside the LSC-designed power-spectrum-addition algorithm. Both have similar sensitivity and performance, but they probably treat the noise in different ways. By demanding that a candidate source should pass both tests simulaneously, we should be able to further narrow the volume of parameter space in the follow-up stages, improving the sensitivity of the overall search.

4.4. *Sco X-1*

One of the surprizes of the last few years in X-ray astronomy has been the discovery that the spin frequencies of the neutron stars in low-mass X-ray binary systems lie in a narrow range around 300 Hz. [17] Since these are accreting neutron stars being spun up to the millisecond pulsar range, it would be reasonable to have expected a distribution of spins. Some mechanism must exist to limit the spins of the stars to this particular value. Magnetic effects do not seem to be a good candidate, since the stars have different accretion rates, so equilibrium with the magnetic field at the same spin for all stars would require the magnetic field to be correlated with the accretion rate.

A different suggestion has been made by Bildsten. [18] He suggests that gravitational radiation limits the spins, and in particular that accretion leads to an asymmetry in the temperature of the star, which in turn leads to an asymmetry in the density distribution. The resulting quadrupole moment would emit gravitational radiation, and at some spin this would carry off enough angular momentum to balance that which is accreted. Detailed calculations have shown that a limit at 300 Hz seems plausible in terms of neutron star physics.

This would make such systems steady gravitational wave beacons. The strongest would be the one whose X-ray flux on the Earth was strongest, since this correlates directly with the gravitational wave flux. This system is Sco X-1, the first extra-solarsystem X-ray source to have been discovered, and still one of the least understood.

Figure 7 shows the sensitivity of GEO600 to the predicted radiation from Sco X-1 if this radiation comes out at 500 Hz. By narrow-banding, GEO600 can achieve slightly better sensitivity than LIGO I, which will not be able to narrow-band. Nevertheless, the optimum SNR is not high. In a two-year observation with a perfectly matched filter, GEO600 will reach an SNR only of order 3. In a single detector this would not be enough to identify the radiation. But in three detectors (GEO600 plus the two LIGO detectors), the confidence could be sufficient.

However, the construction of a good matched filter will not be easy. The accretion rate in such systems is variable, and this will lead to small variations in the spin rate and hence in the emitted frequency. Taken over a long enough time, these may produce a random-walk-style drift in frequency that is observable. It may be that monitoring of the emissions from Sco X-1 will provide enough information to make at least a sensibly parametrized model of the signal, but this remains to be seen.

For GEO600, the decision to look for Sco X-1 will be a difficult one, since it will involve dedicating the detector to a 2-year narrow-band observation. This decision will have to be made in the light of further research on models for Sco X-1 and after it is clear whether a good filter can be developed.

In the absence of such a good filter, testing the model for Sco X-1 in this way will have to wait for LIGO II, which could detect the predicted radiation in an observation lasting a few days.

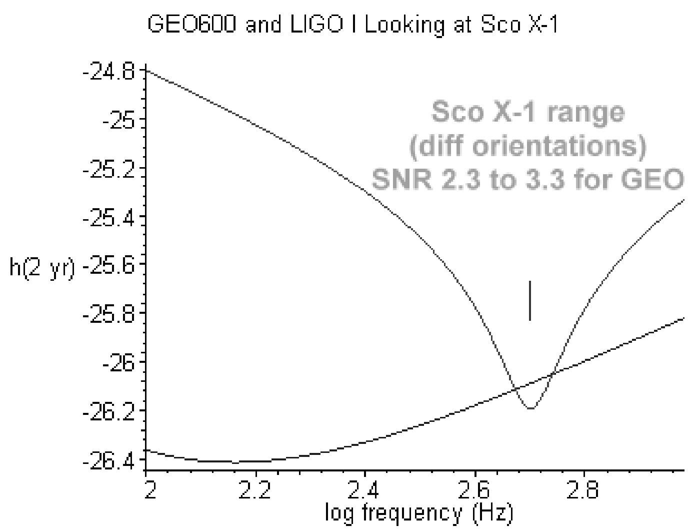

Fig. 7. Sensitivity of GEO600 and LIGO I to the predicted radiation from Sco X-1, assuming perfect filtering during a two-year observation. The antenna pattern effects have been taken into account. The range of values for the signal reflect uncertainty about the inclination of the spin axis of Sco X-1 to the line of sight.

4.5. *Bursts and unexpected signals*

Surprises, usually in the form of strong unexpected sources, have turned up in every new waveband that astronomy has looked in: radio galaxies, X-ray binaries, gamma-ray bursts, ultra-high-energy cosmic rays, infrared galaxies. At some level of sensivity, this must also happen for gravitational waves. We hope to increase the probability of finding unexpected sources early by adopting suitable signal-search methods.

It is of course not possible to perform matched filtering for a signal for which no waveform is predicted. However, it is possible to argue plausibly that there are some features to be expected even from unexpected sources. In particular, it seems to me that strong sources of radiation may be dominated by rotation, since rotation is a natural way to produce the kinds of asymmetry that are needed for gravitational radiation. Strong sources should therefore consist of bursts of radiation that are at least a few cycles long, if not longer. This might be particularly true of bursts from supernovae.

There are signal-search methods that look for short-lived signals with relatively narrow bandwidth. Linear methods such as wavelets and other time-frequency methods seem well-suited to this job. Nonlinear adaptive filtering methods that lock onto oscillations may also be useful. Both of these are under investigation within the GEO team and elsewhere, such as in the LSC. These methods should also reveal short oscillatory features of instrumental noise, which may be abundant because of the number of feedback-control systems in the detectors. They will therefore be used to clean up the noise or at least to veto sections of the data. The real problem will be to recognize which of these events, if any, comes from a gravitational wave instead of an internal system. Coincidence analysis with data from other detectors using the same filters seems essential here.

§5. Conclusions

The development of algorithms for the GEO600 data analysis is nearing completion in a number of areas, and software is being written with the goal of having a fully tested working system before the data rolls off in mid-2001. The GEO600 analysis system will use components created in-house and components imported from the LIGO LSC. Other collaborations would be most welcome. There will undoubtedly be gravitational wave signals in our first data, but will we be able to recognize them? The detector builders are doing their best to ensure that there is as little noise obscuring them as possible using our current technology. We data analysts must similarly ensure that we do the best possible job of filtering out the remaining noise numerically, as we look for recognizable signals.

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