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THE ISSUES IN THE ANALYSIS OF GRAVITATIONAL WAVE RECEIVER OUTPUT WHICH MAY INFLUENCE THE DESIGN OF THE INSTRUMENT

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I. INTRODUCTION

In this memorandum, I will give answers to the questions which were raised during the March 9, 1989 meeting of the data systems working group. I will follow the order of the questions as they were written in the notes taken by me during the meeting.

II. HOW TO PERFORM LONG FAST FOURIER TRANSFORMS

Fast Fourier transforms involving 10^{11} points may have to be performed in the search of continuous sources of gravitational waves which produce signals below the noise level of the instrument. Such signals can only be extracted by manipulating long sections of data. 10^{11} points in standard single precision will occupy 400 billion bytes of memory in the computer performing the fast Fourier transform. The state of the art computer with the largest amount of core memory is a CRAY 2/4-512 which contains 4.3 billion bytes of 80 nanosecond dynamic RAM memory on line at all times. This amount is 100 times too small to perform the required fast Fourier transform in the computer all at once. It is expected that the maximum amount of core memory will go up as the time progresses and in five years it may be possible to get access to a computer with a memory of 32 billion bytes. This will still fall short of computing the required transform all in the memory by a factor of more than 10. It is clear that such Fourier transforms will have to be computed with the aid of an external slow mass storage device like optical disks or high capacity magnetic tapes.

The algorithms for performing a large fast Fourier transform can be found in the literature. The references (7), (8), (9) and (10) describe several different ways of computing large Fourier transforms. The crucial point in these algorithms is that although the amount of computational work involved in calculating the large transform of size $N = 2^n$ in M pieces is about the same as M times the computational work involved in calculating a fast Fourier transform of size $\frac{N}{M}$, there is a very significant of I/O overhead associated with the process and this overhead is a function of whether the external storage is strictly serial (like a streaming magnetic tape) or random access (like an optical disk). If the number of pieces are large (greater than 10), the I/O overhead for a strictly serial device is enormous compared to a random access device. Assume that $N = 2^{36} = 10^{11}$. Let the c be such that 2^c is the largest power of two less than half of the available core size. For a work station with 8 million bytes of memory, c is about 22. With a random access device, about n computational passes and $min(2c-2, n+1) = 37$ I/O passes are required. With a strictly serial device, about n computational passes and $max(n, 2n-c-1) = 49$ I/O passes are required. Note that I/O pass for a tape device is much slower than that of a random access device since the tape may have to be rewound and fast-forwarded. These are excruciatingly slow operations. Note that all of these algorithms not only read from the mass storage device, but also write to it during the I/O passes.

Trying out other fast Fourier transform algorithms using different sorting techniques or a radix other than 2 as given in references (12) and (13) do not alter these conclusions. Hence I recommend that a random access device like an optical disk is used to store the interferometer data. These disks are much more permanent than a magnetic tape (they can not be erased by simply bringing a magnet nearby, they do not wear off with repeated use, they are totally uneffected by humidity, minor scratches have no effect on data, etc.) and their capacity is near the highest capacity magnetic tape. Their cost is higher, but that will come down in the future.

The errors associated with computing the Fourier coefficients with such a large transform have to be estimated. Given the limited precision of the data and the computing machinery, these errors may be significant. The complete error analysis of the fast Fourier transform is done in reference (11). It turns out that even in a transform of size $N = 10^{11}$ points, the round-off error is insignificant if standard single precision, rounding floating-point arithmetic is used.

The issue of large fast Fourier transforms are also addressed in reference (6) with similar conclusions. In the course of this document I will be frequently referring to (1), (2), (3), (4), (5) and (6). The copies of (3), (4), (5) and (6) are attached to this document. The contents of (1) and (2) are summarized in another ligo memorandum.

III. QUESTIONS RELATED TO CONTINUOUS SOURCE SEARCHES

There were three questions about the continuous source (pulsars, etc.) searches:

(1) How easy is the search when the source position or the frequency is known?

(2) How feasible is the search if nothing about the source is known?

(3) What is the chance of detection penalty if the computational resources are limited?

These questions are well treated in references (6) and (5). The single detector case as well as the implications of applying the Gürsel-Tinto method of correlation to a set of detectors are discussed in them. The precise implementation of the Gürsel-Tinto method in the case of continuous sources is under development by Gürsel and Tinto.

IV. COALESCING COMPACT BINARIES

This case is treated in depth in references (3), (4), (5) and (6). The references (14) and (15) point out a remarkable result: "Photon counting (shot) noise should be the main source of noise in a long baseline interferometric gravitational wave detector above a frequency of about 100 Hz. So far as seismic isolation prevents resonable sensitivity below that frequency it is accurate to consider photon-counting noise as the only noise present. But there are prospects to improve the 100 Hz seismic cut-off and reduce it to a value between 10 and 50 Hz. In such a frequency range, however, the thermal noise in the suspension of the test masses and in the masses themselves becomes dominant. We analyse quantitatively its effects and show that by reducing the seismic cut off-frequency by a factor of 2 an improvement about the square root of 2 in the signal-to-noise ratio can be achieved, under reasonable conditions, for the detection of a signal coming from a coalescing binary. Further improvement in seismic isolation is shown not to yield any significantly better performance." The precise implementation of the Gürsel-Tinto method for these types of signals detected by a set of detectors is under development by Gürsel and Tinto. We expect to produce a paper in early July.

V. GRAVITATIONAL WAVE BURSTS

An overview of this case is given in references (5) and (6). The case is completely solved for 3 separated detectors by Gürsel and Tinto as described in references (1), (2) and the relevant ligo memorandum. The case of 3 detectors where two of the receivers are at the same location but rotated 45 degrees with respect to each other is also solved by Gürsel and Tinto. Our initial simulations with a moderately tuned, unoptimized program show that this case enables one to determine the source location within an solid angle of about 10^{-3} steradians. This result is 10 times worse than the 3-separated-detector case and it is likely to improve in the very near future. This means that if the rotated detector is built on one of the ligo sites, the ligo observatory will be able to determine the source location! This result may influence the site selection.

The theoretical basis for the four or more detector case is worked out by Gürsel and Tinto and we plan to publish our results with the 2 detectors only (under-determined), overlapping 3 detector case (exact number of unknowns and equations) and the four or more detector case (over-determined) at the end of April.

VI. STOCHASTIC BACKGROUND

The isotropic case is treated in references (5) and (6) which again involves correlations between the outputs of many detectors or a complete understanding of the noise in a given detector. The Gürsel-Tinto method of correlation can in principle be applied to detect any directionality in this background radiation. We do not know how to do this precisely at the moment. We may be able to solve it next year.

VII. THE NEED FOR SPECIAL COMPUTERS

For the burst case the computational requirements are rather modest. A relatively fast workstation will be able to find the direction of the source under quarter of an hour after its has been loaded by the data from the three detectors. This is a completely acceptable rate of computation since in the early days of operation the best pulse rate is about once a month. A super computer performs the same computation in a about 10 seconds. Since the speed of the computers is expected to increase in the next five years, there will be no problem associated with performing correlations involving bursts.

The special computers may be needed to perform the long fast Fourier transforms in the continuous source searches. In the searches for coalescing compact binaries, numerous filters corresponding to the different values of the parameters of the search may have to be computed in parallel. These can also be performed by a special purpose computer. However, if one has access to a fast super computer these will also be able to perform those calculations just as fast. The cost of either mode of operation should be judged when the the need arises.

This subject is also treated in reasonable depth in reference (6). At this point in time, I see no major obstacle related to this subject that may affect the design of the instrument.

VIII. NEED FOR LIVE CONNECTION

A live connection between the sites may be desired if immediate information about a burst needs to be computed. For example three sites connected by a live link will be able to compute the direction and the waveforms of the burst minutes after it has happened. The speed requirements for this is very modest: A 19200 baud serial link will be fast enough since the burst data is only a few thousand bytes long. The speed of the connection should be chosen to give the largest speed with a reasonable degree of reliability for the given amount of money.

There is no need for a live connection between the sites for other types of computations since such a connection will have to carry a huge amount of data. It is just as easy to ship copies of the optical disks which contain the relevant data. It may be desirable to have a monitor data link which displays the other sites operating parameters at each site. Again the speed requirements for this link is not very high, since most of the parameters are not expected to change during a search. A fast serial link will do fine here as well. Perhaps the answer is to rent one or more 56 kilobaud leased lines or their equivalents in five years.

This issue is lightly touched in reference (6). There is a suggestion of establishing an interferometer data network following the bar groups GRAVNET.

IX. NON-INTERFEROMETER VETOES OF PERIODIC SEARCHES

One might want to analyze the house keeping signals with the same precision in the case of periodic searches since the frequencies in question are in the range of frequencies that may be produced by local mechanical and electrical devices. This will significantly increase the amount of data which needs to be stored as well as increasing the analysis time. Since there will be multiple detectors in the observatory the local signals will disappear when the outputs of multiple detectors are cross-correlated. I do not see any need for this increased data rate in the initial phase of the operation.

X. CLOCK SYNCRONIZATION AND CLOCK REFERENCE

The initial synchronization of the clocks between the sites can be accomplished in a manner consistent with the Special Theory of Relativity. Since the gravitational field of the Earth is weak and nearly stationary, it is possible to choose a "time-like" killing vector which enables one to syncronize the clocks in the manner described above.

The real requirement is for the clocks to stay synchronized during the data taking procedure. This is not very stringent for the burst sources which only last for a few milliseconds. If the clocks stay synchronized within a fraction of a microsecond, the resulting time delay accuracy will not alter the results of the direction finding algorithm significantly. The tight tolerances are needed for the periodic searches. For a total number of 10^{11} points digitized at a rate of 10 Khz, the elapsed time is about 3 months. During that period the synchronization of the clocks should not drift more than a period of the signal that is being searched for. It should be considerably better than this value since the cross correlation between the two or more detectors will lead to a wrong value for this level of syncronization near the ends of the data stream. This will require local rubidium clock references.

XI. DATA FORMAT

As discussed above, the data format is most important for computations involving periodic searches since a cumbersome format will cause the slow mass-storage to be accessed more than it needs to be accessed. For this reason I recommend that the house keeping data and the interferometer data should be recorded on separate optical disks. The interferometer data should be recorded on an optical disk as a continuous stream. Different interferometer outputs should go to different optical disks. This gives maximum decoupling of the signals which should reduce the mass storage access time during analysis.

Fixing of a data standard is not required at the moment since this is important when different groups exchange data. This can only be decided by talking to these people, there is no other constraint on it.

XII. REFERENCES

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