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Appendix xx. Multiple Interferometer Coincidence Detection and the Half Length Interferometer.

The optimum search detector configuration, based on considerations of expected noise in laser interferometers and economy, consists of a full-length/half-length interferometer pair at one site and a full-length interferometer at the second site.* By operating a search detector with three interferometers in triple coincidence we gain a significant suppression factor for uncorrelated spurious noise pulses over that afforded by a double coincidence detector using one interferometer at each site. The use of a half-length interferometer allows a special check for the unique signature of a gravitational wave, that the interferometer responses are proportional to their test mass separations. This will not only be important to basic physics but will allow us to discriminate between events due to gravitational radiation and events due to spurious correlations between interferometers. This alone will allow us to reject events globally correlated between the two sites due to noise sources or rare exotic physical phenomena. In the case of locally correlated noise at the first site, the half-length interferometer not only improves noise rejection, but provides important diagnostic information — the length dependence of the offending noise source.

A. Rejection of uncorrelated spurious bursts by multiple coincidence detection:

The LIGO facilities will consist of a two site network, the minimum required to distinguish a gravitational wave burst from noise and extract astronomical information from the burst. It is possible in principle to search for bursts using a single interferometer at each site and operating the pair in double coincidence mode. The simplest method would be to record data from each interferometer whenever an event occurs (the output exceeds a preset threshold value), and then look for coincidences between events from the two interferometers. For instance if an event is recorded at time t_0 in interferometer 1, then the double coincidence criterion is true if an event is recorded in interferometer 2 at time $t_0 \pm \tau_W/2$, where τ_W is the duration of the acceptance window. In practice this double coincidence method will work provided that the rate of spurious double coincidences due to noise events in the two interferometers is sufficiently low.

The noise distribution in a single interferometer is a superposition of gaussian distributed pulses and a non–gaussian distribution of pulses which occur infrequently but have large amplitude. The gaussian noise has contributions from sources such as photon shot noise, thermal noise, etc., which are discussed in sections III.A and IV.B. An impulse given to a test mass due to a sudden release of strain in a suspension wire is an example of a physical mechanism which can contribute to the non–gaussian noise distribution. Experience with operating interferometers in long duration runs shows that the non–gaussian noise can be described by a flat distribution of pulse amplitude versus frequency of occurrence.

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* A full-length interferometer has test masses at each end of the 4 km vacuum tubes. A half-length interferometer has its central masses in the corner building and its end test masses in mid station buildings located near the middle of each 4 km tube.

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For double coincidence operation of two interferometers, the rate of spurious coincidences due to the noise is given by:

$$R_{12} = \tau_W R_1 R_2 \tag{1}$$

where R_1, R_2 are the noise event rates for interferometers 1 and 2, respectively. To allow detection of a pulse of duration τ_P, we set

$$\tau_W = \tau_P + 2l/c \tag{2}$$

where l is the separation between the two interferometers and c is the speed of light. The second term in equation 2 degrades the rejection of noise pulses but is necessary to allow for differences in arrival times of a real gravitational wave burst due to time of flight between the two interferometers. The rate of spurious coincidences can be greatly reduced by operating in triple coincidence mode with a third interferometer operating at one of the two sites. In this case the spurious coincidence rate is given by:

$$R_{123} = (\tau_P + 2lc)\tau_P R_1 R_2 R_3 \tag{3}$$

For detection of gravitational wave bursts at a rate of 1/yr to be signicant we require the spurious coincidence rate to be much lower than 1/yr. For comparison, Table 1 gives the allowable rate of noise events in each interferometer (assuming $R_1 = R_2 = R_3$) to achieve a spurious coincidence rate of 0.1 /yr if the noise is uncorrelated between the interferometers. As detectors become more sensitive we expect larger detection rates for bursts, but there will always be a component to the signal rate arising from bursts occurring rarely.

We see from Table 1 that triple coincidence detection affords approximately two orders of magnitude better supression of noise events than a double coincidence between two sites. Experience with prototype data runs has shown that the spurious event rate for a single interferometer without extensive auxiliary vetoes to account for external perturbations is of the order of 20/hr. It is conceivable that the vetoed rate could be reduced to less than 1/hr with appropriate vetoes, but this has not been accomplished in practice. Also there is no experimental evidence upon which to estimate the rate of spurious events which are correlated between interferometers operating at anticipated LIGO sensitivities. Presumably the degree of correlation would be greatest for interferometers at the same site, although one could envisage mechanisms which could correlate between interferometers at the two sites.

B. Rejection and diagnosis of interferometer correlations using a half length interferometer:

One can provide further discrimination against spurious events by using data on pulse heights when coincidences occur. This is most effective when the third interferometer has a different length from its complement at the same site. Since gravitational waves produce an effective displacement of test masses proportional to their separation, one can predict in advance the ratio of signals in two adjacent interferometers which differ in arm length. Observation of such a signature in a coincidence event provides a positive confirmation that the event produced the response expected by a gravitational wave. The probability that such a response could have been produced by noise decreases rapidly as the signal to gaussian noise level increases, even in most cases where the interferometers are correlated.

A triple coincidence detector will have two interferometers at site 1 that share the same physical environment. One can therefore expect some degree of correlation in the response of these two interferometers to perturbations of the local environment, especially if the interferometers are equal in length. The auxiliary environmental monitoring system can be used to veto such correlated events when the mechanism of correlation has been anticipated beforehand. One can tolerate a certain rate of correlated spurious events at site 1, provided the noise event rate for the interferometer at site 2 is sufficiently small, and still satisfy the spurious triple coincidence rate of 0.1/yr. Furthermore one can measure the event rates for both interferometers at site 1, and predict the expected double coincidence rate for an arbitrary degree of correlation at site 1. By comparing this rate with the measured double coincidence rate one can determine if locally correlated noise is a problem.

If the locally correlated noise at site 1 exceeds a safe threshold the noise mechanism must be vetoed or preferably eliminated. By having the two different length interferometers at site 1 we acquire two advantages in this effort. First of all, length scaling information provides an additional and important veto criterion. Secondly, it provides diagnostic information—we can identify how the correlated noise mechanism depends on interferometer length.

A crucial requirement to include a half-length interferometer in a triple coincidence detector arises due to the possibility that globally correlated events could occur that are not due to gravitational radiation. We would expect events correlated over the large separation between sites to be rare. Unlike the case of locally correlated noise, however, we cannot use statistical methods to identify whether global correlations are a problem, since a single such spurious event automatically satisfies the triple coincidence criterion. Data from auxiliary monitors will allow us to identify such an event as spurious if we have correctly anticipated its cause in advance. For some real events, like supernovae, we may have corroborating data from some other astronomical instrument. However the LIGO project goal, to open a new window on the universe, requires the ability to positively confirm the existence of radiation from sources invisible to other instruments. The inclusion of a half-length interferometer in a detector is, alone, capable of providing a positive signature that the event behaved like a gravitational wave – namely, it produced responses in each of the interferometers proportional to the separations of their test masses. This information will be critical to establish a claim for discovery of gravitational radiation; without it any such claim will be open to question.

Choosing one of the interferometers in a triple coincidence detector to be half-length will degrade the sensitivity of the detector. In practice this degradation factor will depend on the exact noise event rates of the individual interferometers. We have modelled a number of scenarios for operation of such a detector and determined that in the worst case the overall strain sensitivity is degraded by less than 30%. We have also found that useful length scaling information is provided for any events which satisfy the triple coincidence criterion, although this information obviously becomes more constraining as the signal to (gaussion) noise ratio becomes larger.