LIGO - T890055-00-R

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(Corrected Version)

Comparison of Attributes and Liabilities of a LIGO with three Full-Length Interferometers, with those of a LIGO with two Full-Length and one Half-Length Interferometers, in the Initial Phase

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To avoid confusion, we first define the operation of a half-length interferometer.

1. Operation of a Half-Length Interferometer

A half-length interferometer has central test masses in the corner building, and end test masses in an auxiliary building located about half way along each arm. For convenience here we will assume that the ratio of lengths is exactly 2:1, although this is not essential in practice. In operation, the storage time in the arms of the half-length interferometer is made equal to that of the corresponding full-length one by having double the number of bounces of light in the half-length one. Thus a given gravity wave gives equal sizes of optical phase output signal in both the half and full length interferometers - although the motions of the test masses are smaller in the half-length one. With this arrangement the frequency response of the half and full length interferometers are also the same.

For this discussion we will assume that half and full length interferometers give equal outputs for a given gravity wave signal.

Noise

We summarize the ratio of output noise, n_h and n_f, from half- and full-length interferometers for different situations (for equal gravity-wave output):

	n_h/n_f
Photon shot noise limited, non-recycling	equal
Photon shot noise limited, fixed number of recycles	equal
Photon shot noise limited, broadband recycling, limited by mirror losses	$\sqrt{2}$
Photon shot noise limited, narrowband resonant recycling	2
Thermal noise limited, seismic noise limited, stochastic noise limited, or at standard quantum limit	2

Operational Modes for Burst Searches with half-length interferometer

1.1. In general the data analysis system would be arranged to impose a requirement for acceptance of signals from the two interferometers at site 1 if the signals are equal in amplitude and shape to within a suitable factor of the accuracy expected from the noise of the two interferometers. This can impose a tight restriction on signals large compared with noise, and a looser restriction on signals near noise, without reducing acceptance of gravity-wave signals significantly.

Analysis has shown that good rejection of spurious signals due to gas bursts, or due to motions common to adjacent test masses, can be obtained in this way (see LIGO Report # 46, by P. Saulson; also Report # 12 by R. Drever and Report # 12R by P. Saulson).

1.2. In general the data analysis system would be arranged to impose acceptance thresholds for signals from the half and full length detectors which would depend on primarily on their noise levels, and would be chosen to give optimum experiment sensitivity for an accidental coincidence rate appropriate for the rate of gravity wave bursts sought. This situation has been analyzed recently (see accompanying reports by R. Drever, Y. Gursel and M. Tinto), and it is shown that use of a half-length interferometer with noise greater than that of the two full length ones by factors of $\sqrt{2}$ and 2 respectively reduces experiment sensitivity by factors of only 1.09 and 1.20 respectively.

2. The Comparisons

Features of System (A) a LIGO with three full-length interferometers, two at one site sharing the vacuum pipes, and one at the other site

2.A.1. This system may provide a possibility of a two-fold coincidence burst search between one interferometer at site 1 and the one at site 2, with the third interferometer for a test station or a separate periodic experiment – but ONLY if singles rates of spurious pulses are very low.

For this to be viable, the singles rate would have to be less than about 3 pulses per hour. I regard this as much lower than it would be reasonable to expect in the LIGO: other less sensitive experiments have given about 20 pulses per hour (see Report # 12).

I would regard it as extremely risky to plan on this type of operation as the main mode for the LIGO.

2.A.2. This system may provide a possibility of a triple coincidence burst search between the two full-length interferometers at site 1 and the one at site 2. However any phenomena which gives simultaneous similar pulses in the two interferometers sharing the same pipe would render the local coincidence requirement ineffective for those pulses, and could lead to a high accidental rate for the whole experiment.

This is a serious risk. Let us take as an example a single spurious rates of 20 pulses per hour from each interferometer (similar to those found in other experiments, see Reports # 12, 12R). Let us assume that only 1% of this rate is due to a common phenomena, such as gas bursts. In this case the expected accidental rate is 0.3 per year, which I regard as too high (it would make it impossible to claim that one potential gravity-wave pulse found in a one-year search was statistically significant). And it is quite possible that the gas burst rate could be much higher than 1% of the total spurious rate – the surface area of the LIGO vacuum pipe is 600 times that of the 40 m system which was the largest of those that gave the burst rate quoted above.

In fact with no real data to sufficiently limit gas bursts or similar phenomena I think we would be taking a significant risk to depend on this mode of operation. Further, with this system we would not even have any good diagnostic tool to help find out the source of spurious pulses which could so easily ruin the rate sensitivity of the system. If we could see no way whatever of avoiding this danger we might just have to take this risk – but fortunately installing a half-length instead of a full-length interferometer in one of the locations at site 1 may give us a way out, and provide a powerful insurance and diagnostic tool against this danger.

Features of System (B) a LIGO with two full-length interferometers, one at each site, together with a half-length interferometer at site 1

2.B.1. The system provides the possibility of an effective triple-coincidence burst search between the full and half-length interferometer at site 1 and the full-length interferometer at site 2.

In this case the pulse amplitude and shape criterion described in section 1.1 can give useful discrimination against almost all sources of spurious signals common to the full and half-length detector at site 1 of which we are aware. The effectiveness of the spurious signal rejection depends on the origin of the signal and on its magnitude relative to noise: this is discussed in detail in Report # 46. Here we may note that the analysis by Y. Gursel and M. Tinto of thresholds for triple-coincidence experiments indicates that for an acceptable accidental rate with just three interferometers the thresholds are sufficiently high that there will be some discrimination for even near-threshold signals. For most spurious signals, which we expect to extend to larger amplitudes, discrimination should be much more effective. Even a signal due to a phenomenon which may give almost uncorrelated pulse heights in interferometers using two adjacent test masses (such as acoustical noise or electromagnetic phenomena) can be discriminated against to a useful extent – for the window of acceptance is set by the very well-correlated response expected from a gravity wave. For gas bursts, discrimination is particularly effective, and we estimate that gas bursts as frequent as a 3 per minute in each interferometer might be tolerated without seriously degrading the triple-coincidence accidental rate for the whole system. Thus the half-length system gives a major improvement in tolerance to gas bursts and similar phenomena.

Overall this seems an effective and relatively risk-free search system for gravity wave bursts, and we would recommend it primarily for this reason. However the use of a half-length interferometer brings several other important benefits in addition.

2.B.2. The comparison of signal rates and outputs from the half- and full-length interferometer at one site provides an effective diagnostic tool for all length-associated phenomena – predicted or unpredicted. In attempting to achieve the four decades improvement in flux sensitivity planned for the LIGO we can expect unforeseen problems, and any diagnostic tool may prove invaluable. The full-length half-length system seems particularly appropriate, since the main change from the prior type of experience will be a length change. I feel that it is likely to be so difficult to get the LIGO interferometers to operate near their expected sensitivity that to sacrifice a simple and very general diagnostic tool, such as this system can give us would be to incur a serious additional risk of overall failure.

2.B.3. The system provides a distinctive signature for gravitational waves – a strain in space proportional to test mass spacing. When gravity waves are detected, this will enable the LIGO to make a unique experimental check of this fundamental property of gravitational radiation. This will be not only important to basic physics, but it will also give us a valuable signature for gravitational radiation, and enable us to discriminate it against many other types of rare exotic phenomena which may be proposed. In fact this doubles the number of attributes of gravitational radiation that we can hope to check in an early pulse experiment – the other one being the velocity of propagation, which we can hope to check is near the velocity of light. (Polarization properties may be checked later, but not at the early stage we are considering here.)

2.B.4. The half-length full-length system may provide a way of extending stochastic background searches to wavelengths short compared to the distance between the two LIGO sites, by making correlation experiments between the full and half-length interferometers at one site practicable. This is a much less important and less certain benefit than the ones just discussed, for it is probable that a certain amount of low-level correlated noise will remain even after optimum analysis, and this may limit the ultimate stochastic background sensitivity. It is likely, nevertheless, that this limit will be significantly better than that which could be set with full-length interferometers alone, and probably better than that from any other experiments of which we are aware. However we mention this point more for completeness than for its relative significance.

2.B.5. Given the major benefits 2.B.1 to 2.B.3 to be expected from use of half-length interferometers, what are the scientific costs? They are less than were expected until recently: we summarize them here.

Scientific Costs

(a) There is a slight reduction in threshold sensitivity for burst searches if there is no significant background pulse rate. However the attached analysis of Y. Gursel and M. Tinto shows that even in the worst case this reduction in sensitivity is small (not more than 20% near 1 kHz), and in most cases it is less than this. And in the presence of expected rates of spurious pulses this could be entirely outweighed by the improvement in event rate sensitivity.

(b) If the half-length interferometer were used as a testbed for a new interferometer it would not be identical to the one at the other site. Here one should assess the likelihood of wishing to make this choice. It is expected that two-fold coincidences will have such a high accidental rate as to be of little value in themselves, and the main hope of parallel development of a test system would depend on a coincidence with another detector outside the LIGO system, such as a neutrino detector, for example. In any case the two-interferometer operation would be relatively insignificant compared with a full three-interferometer one. In this situation it might be better use the full-length interferometer at site 1 for the testbed, and leave the half-length one for the continuing more routine monitoring function. So there might be little actual sacrifice in development effort in practice – although all this is hard to predict at this stage.

(c) If the half-length interferometer were used for a periodic gravity-wave search it would have half the sensitivity of a full-length one. Here, the argument just given may also be applicable. It may in practice be more important to devote a full-length interferometer to this search, and use the half-length one for routine pulse monitoring, where there is less performance sacrifice. Again, the choice would be clearer at the time.

Overall we conclude that there is relatively little scientific cost in installing a half-length interferometer instead of a full-length one at site 1: and there are likely to be very important scientific and risk-reduction advantages in doing so.

3. Conclusion

The arguments discussed above, and the many other assessments I have made, lead me to feel that the case for installing a half-length interferometer instead of a full-length one is overwhelming. If we don't do this, I feel we will be taking an enormous and unnecessary risk with a great deal of scientific and engineering effort, and with public money. Installing a third full-length interferometer corresponds to having one more of an article of which we already will have two; putting in a half-length interferometer instead corresponds to having an article which is just sufficiently different to give us quite new capabilities, a new experimental tool, and a major reduction in overall risk of failure.