Proposed Control Room Figures of Merit for Monitoring LIGO Sensitivity to Continuous Waves

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As we prepare for the S4 Science run in late 2004, we should plan to provide real-time figures of merit (FOM's) in the LIGO control rooms of sensitivity to continous wave gravitational radiation sources. Ideally, the figures of merit should be generated by a Data Monitoring Tool (DMT) program running continuously in the background and providing graphical display of current sensitivity and its recent history, along with summary information on an html web page. Writing out trend files of sensitivity history would also be desirable.

This note describes a proposed set of DMT figures of merit, based on ideas suggested by members of the Pulsar working group.

1 Strain sensitivity - Fixed time intervals (FOM 1)

The first figure of merit is simply a rescaled power spectral density where the vertical scale is in pulsar-relevant units. As described in [1, 2, 3], the amplitude of the average signal that we could detect in Gaussian stationary noise with a false alarm rate of 10% using the F-statistic[1], is given by

$$< h_0 > \quad = \quad 11.4\sqrt{S_n(f_s)/T}$$

where f_s is the frequency of the detected signal, $S_n(f)$ is the single-sided power spectral density, and T is the observation time. The first figure of merit proposed is a display, updated once per minute, of this amplitude sensitivity function over the bandwidth 10 Hz to 2.0 kHz for a variety of assumed observation times T [1 day, length of data run (*e.g.,* 70 days for S3, and 1 year)]. This figure of merit is simply a pulsar-calibrated version of the raw power spectral density estimate, *i.e.* with no change in shape.

2 Time required to reach energy conservation limit - Known pulsars (FOM 2)

For known isolated pulsars with measured periods P, spin-downs $\dot{P}$, and distances r one can set a bound on the rate of gravitational radiation emission from energy conservation. The second figure of merit would be the observation time required at present sensitivity at the pulsar's GW frequency to set an upper limit on gravitational radiation emission that is lower than that inferred from energy conservation. The figure of merit that would be most interesting (and challenging to address) is that for the Crab pulsar with a period of 33.37 ms, a radiation frequency of 59.93 Hz, a spin-down rate of $\dot{P} = 3.3 \times 10^{-13}$ s/s, and a distance from us of 2 kpc. The expected upper limit on amplitude of radiation from a source of inertial moment I, rotation frequency $f_{rot} = \frac{1}{2} f_s$, spin-down rate $\dot{P}$, and distance r is

$$
\begin{aligned}
h_{EC} &= \frac{1}{r}\sqrt{\frac{5}{4}\frac{G}{c^3} f_s \dot{P} I} \\
&= \frac{5.7 \times 10^{-24}}{[r/(1kpc)]}\sqrt{(\frac{f_s}{1\,\mathrm{kHz}})(\frac{\dot{P}}{10^{-13}s/s})(\frac{I}{10^{45}g \cdot cm^2})}
\end{aligned}
$$

The corresponding observation time to attain sensitivity to this h_{EC}, given the detection criteria above, is therefore:

$$
T = \frac{(11.4)^2 S_n(f_s)}{h_{EC}^2}
$$

For reference, at LIGO I design sensitivity of $\sqrt{S_n(60\mathrm{Hz})} = 10^{-22}/\sqrt{\mathrm{Hz}}$, the observation time required for the Crab ($h_{EC} = 1.3 \times 10^{-24}$) is about nine days.

A display of the required observation time to reach energy conservation would be plotted as a strip chart vs time over the last six hours for selected pulsars. The data would also be written to trend files. In addition, the monitor's html summary page would display the present readings and the averages over the last 10 minutes, 1 hour, and 6 hours..

3 Ellipticity sensitivity - Known and unknown pulsars (FOM 3)

For known isolated pulsars, the strain sensitivity figure of merit 1 can be converted to a sensitivity to ellipticity via the formula:

$$< \epsilon > \quad = \quad \frac{c^4}{4\,\pi^2\,G} \frac{r}{I} \frac{1}{f_s^2} < h_0 >$$

The third figure of merit is a graph and html table of the above quantity for the same pulsars treated in figure of merit 2. The graph would show data points for the known pulsars (ϵ *vs* frequency), along with dashed horizontal lines at 10^{-5} and 10^{-6} to indicate the band of theoretically favored upper limits on ellipticity for the same observation times considered in figure of merit 1. A related figure of merit is a set of generic curves of ellipticity sensitivity vs frequency for unknown rotating neutron stars at a fixed distance of 1 kpc, again, for different assumed observation times. These curves would *not* have the same shape as the strain sensitivity curve, since they are weighted as $1/f^2$.

4 Cumulative actual sensitivity to known pulsars (FOM 4)

At the start of a data run, *e.g.*, the monitor will start accumulating ideal sensitivity to known pulsars, displaying for each (graphically and in a table) the quantity

$$< h_0(f_s) > \quad = \quad 11.4\sqrt{\frac{1}{N\Delta T}(\frac{1}{N}\sum_i^N S_{n_i}(f_s)}$$

where N is the number of time strides of length ΔT (*e.g.,* 1 minute) of length of science mode data since the start of the run, and S_{n_i} is the power spectral density estimate from time stride i. This figure of merit will improve slowly with time and serves as a cumulative performance evaluation, not as a rapid-feedback diagnostic to guide operators and scientists.

5 Presentation

The sets of FOM's above will serve mainly as references to consult when specific questions arise. It is not practical to watch all of these every five minutes or so (as is done, for example, for the binary neutron star inspiral range). Instead, only a small subset should be prominently displayed as guidance to operators and scientists on shift. We propose the following choices for prominent display:

- (FOM1) Pulsar strain sensitivity for an observation time equal to the present data run.
- (FOM2) Time required to reach energy conservation limit for the Crab.
- (FOM3) Ellipticity sensitivity for known pulsars for an observation time equal to the present data run

References

[1] P. Jaranowski, A. Kroólak, and B.F. Schutz, Phys. Rev. D **58** 063001 (1998).

[2] B. Abbott *et al.*, to appear in Phys. Rev. D, gr-qc/0308050 (August 2003).

[3] A. Abramovici *et al.*, Science **256** 325 (1992).