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LIGO Science Benchmarks

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1. Introduction

Changes in the LIGO IFO design (laser, optics, materials, suspension and seismic isolation) lead to changes in the overall noise power spectral density for the detectors. These changes affect the LIGO sensitivity to different sources and, ultimately, the science LIGO can accomplish. To aid in understanding how changes in the IFO design change the science accessible to LIGO, I propose that the project adopt a small number of carefully chosen scientific benchmarks, based on the target science. The relative performance of different IFO designs, as measured against these benchmarks, should then play a role in evaluating different designs and their evolution, both for the initial IFOs and any IFO enhancements.

This note describes briefly the implementation of a prototype benchmark, based on the anticipated rate of detection of a hypothetical cosmological population of inspiraling compact binaries.

2. Neutron star binaries

LIGO is closely associated with the detection of inspiraling compact binary systems. While we do not anticipate that the initial LIGO IFOs will be sensitive enough to observe these with any reasonable rate, observation of inspiraling binary systems is an important LIGO science goal and sensitivity of LIGO to this source is an appropriate benchmark against which IFO designs can be measured.

For definiteness, I adopt the following hypothetical, cosmological population of inspiraling compact binary systems:

- each binary system consists of two identical compact objects (neutron stars or black holes), with a system intrinsic chirp mass of $1.2\,\mathrm{M}_\odot$;
- the source population is cosmological (*i.e.,* homogeneously and isotropically distributed) with a rate density on the current cosmological surface of homogeneity of $1.1 h_{100} \times 10^{-7}\,\mathrm{Mpc}^{-3}\,\mathrm{yr}^{-1}$;
- the source population has constant co-moving rate density per unit co-moving (cosmological) time out to the limit of the detector sensitivity;
- the cosmology has a Hubble constant of $65\,\mathrm{Km/s/Mpc}$ (Hubble parameter h_{100} equal to 0.65), is spatially flat (deceleration constant q_0 equal to 1/2), and has vanishing cosmological constant (Λ equal to 0).

The IFO noise is assumed to be Gaussian-stationary and thus described completely by its strain noise power spectral density. “Detection” of a source is assumed if the expectation value of its strain amplitude signal-to-noise exceeds a threshold ρ_0 (assumed here equal to 8).

With these assumptions, [**?**] describes how to calculate the expected rate of detections, the distance to the furthest detectable binary, the distribution of the signal-to-noise as a function of frequency, and the accumulated signal-to-noise below a frequency f. The latter two quantities are important for data analysis. Since only those parts of the IFO bandwidth that contribute significantly to the signal-to-noise are important for detectability, the full bandwidth of the IFO need not be processed when searching for inspiraling binary systems. When the mass of the signal-to-noise is concentrated in a bandwidth narrow compared to the IFOs full bandwidth, as is generally the case, this can allow a substantial reduction in the computational resources required for data analysis.

3. Implementation

The benchmark described above has been prepared as a c function for evaluation and possible integration into the LIGO modeling software.

4. Results

Four LIGO noise models have been evaluated by this benchmark. The results are summarized in table 1 and figures 1–12. Briefly, the present LIGO noise model shows the current design to be nearly 50% more sensitive (as measured by observed rate) to neutron star binary inspiral than the noise model which the project committed to in the LIGO Science Requirement Document. Previous LIGO noise models did not meet the sensitivity goal implicit in the LIGO Science Requirement document, in large measure because of the differences between the noise amplitude and its dependence on frequency for viscous and structural damping.

5. Conclusions

This note describes the need for uniform, well-documented “science benchmarks” for LIGO instrument design. The primary purpose of the proposed benchmarks is to compare alternative designs; since they may rely on unknown source or source population characteristics they are not meant to be used as absolute measures of performance, although they may do so if those caveats are kept in mind.

As a single example, a benchmark relating instrument design characteristics to neutron star binary inspiral detection sensitivity is described. Variations on this benchmark as well as other benchmarks, related to different target science, can be similarly constructed. The proposed use of these benchmarks, however, requires that the project adopt a small number of well-defined and documented benchmarks, which adequately explore the instruments sensitivity to the target science, and that all proposed instrument designs be evaluated against this set (and, subsequently, against each other) uniformly and without variation.

Model	Detection rate ($\times 10^{-3}\,\mathrm{yr}^{-1}$)
Science Requirements	0.79
Original seismic stack, old suspension Qs	0.63
DHS modified seismic stack, old suspension Qs	0.76
New HyTec stack design, current suspension Qs	1.1

Table 1. Detection rates for four different LIGO noise models. The first model is taken from the LIGO Science Requirements document and represents the noise performance that LIGO has committed to acheiving. The second model represents the original design of the seismic stack and the original assessment of the suspension quality factors. The third model is identical to the second except for a modification in the seismic stack materials and design proposed by David Shoemaker. The fourth and final model represents the current seismic stack design by HyTec as well as the current assessment of the suspension quality factors. the model source population is as described section 2.

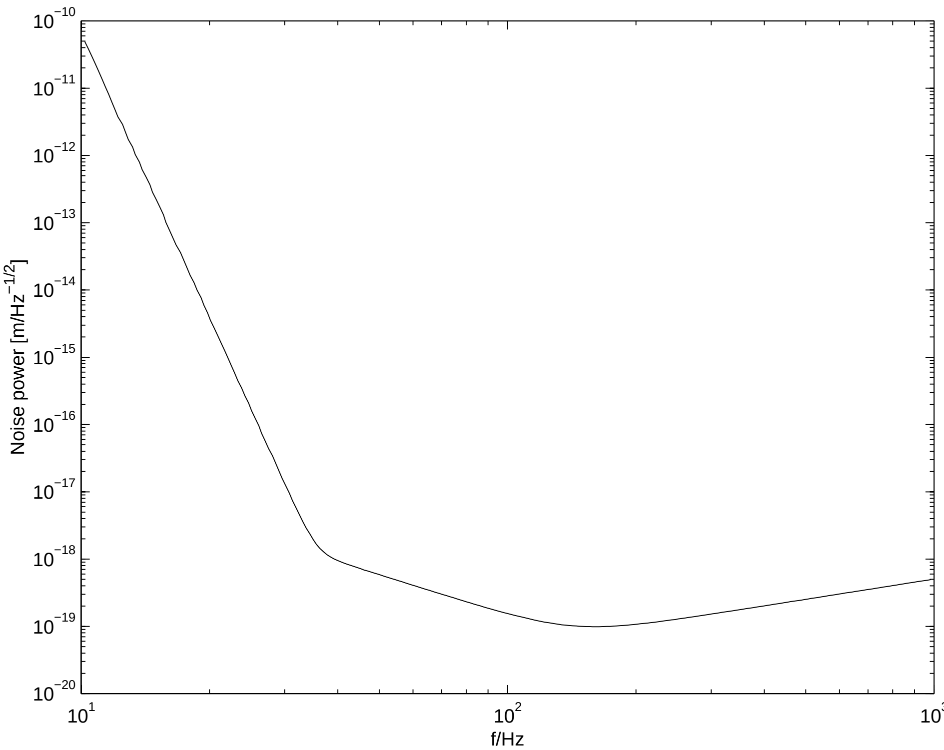

Figure 1. The model noise PSD drawn from the LIGO Science Requirements Document. Only the bandwidth from 10 Hz to 1 KHz is shown.

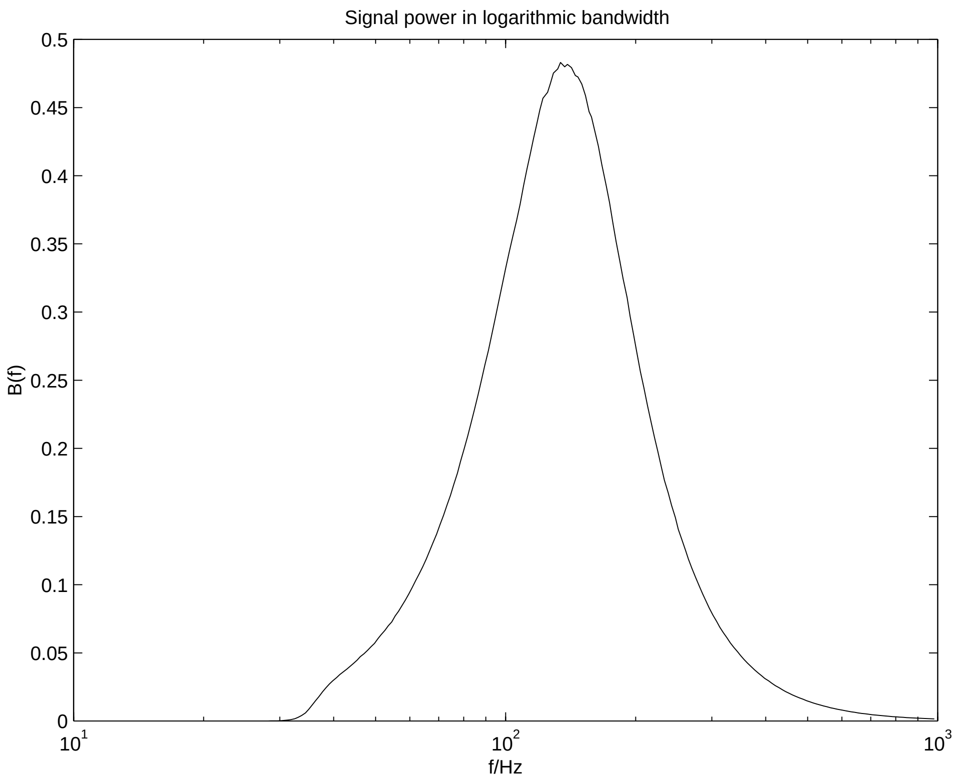

FIGURE 2. The fractional signal to noise ratio contributed per unit logarithmic bandwidth for binary inspiral observations in a detector whose noise is described by the figure 1.

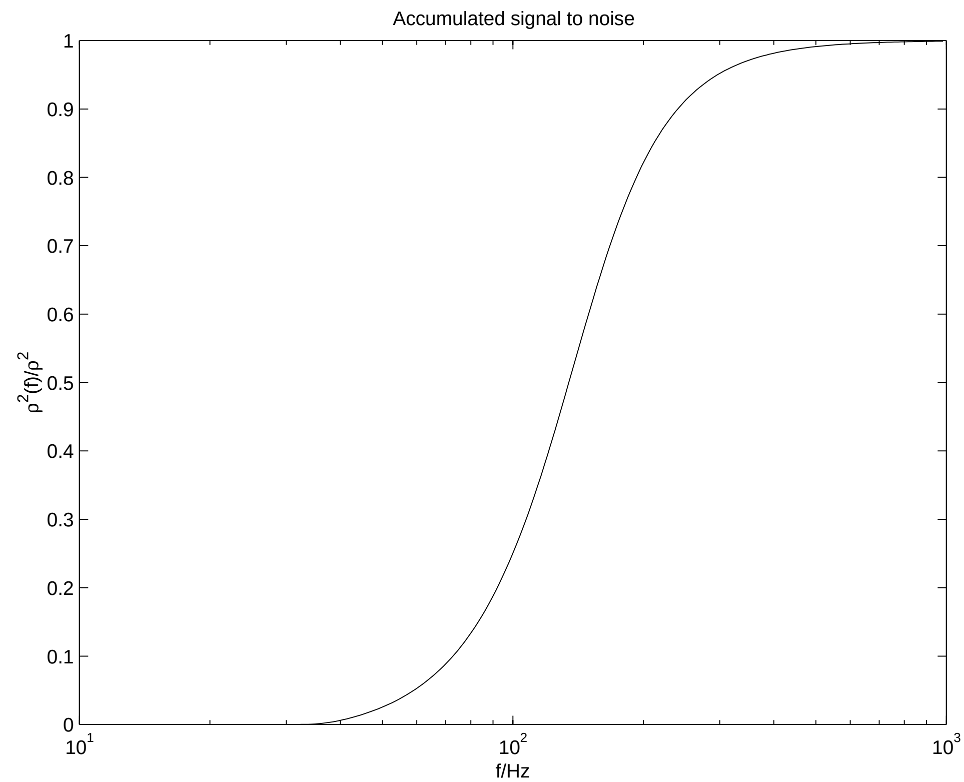

Figure 3. The accumulated signal to noise ratio up to frequency f for binary inspiral observations in a detector whose noise is described by the figure 1.

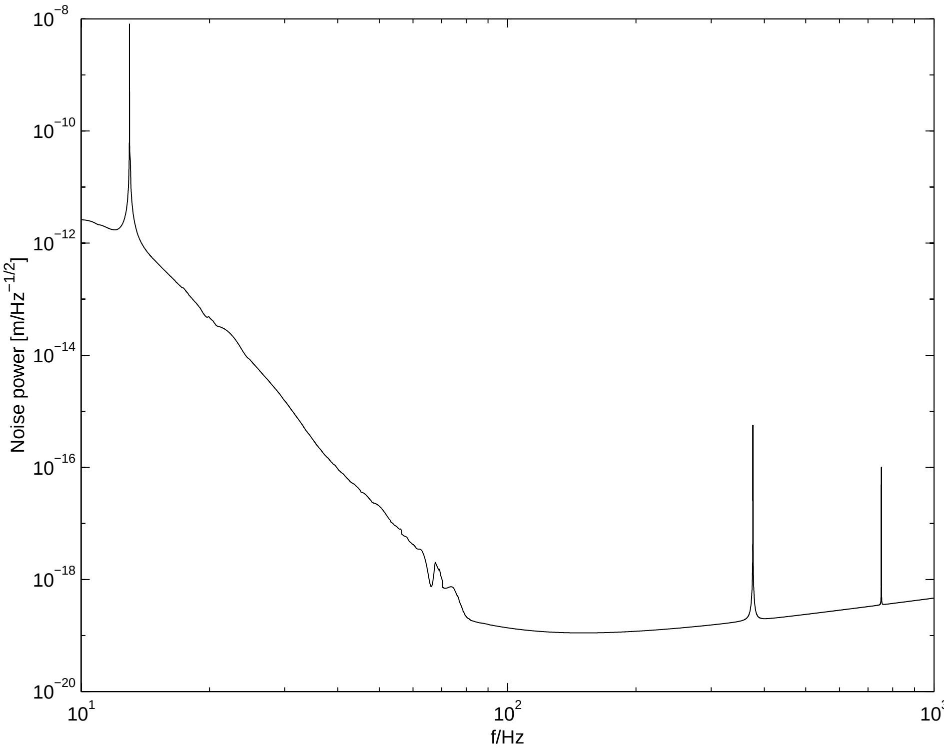

FIGURE 4. The model noise PSD with the original seismic stack design and old suspension quality factors. Only the bandwidth from 10 Hz to 1 KHz is shown.

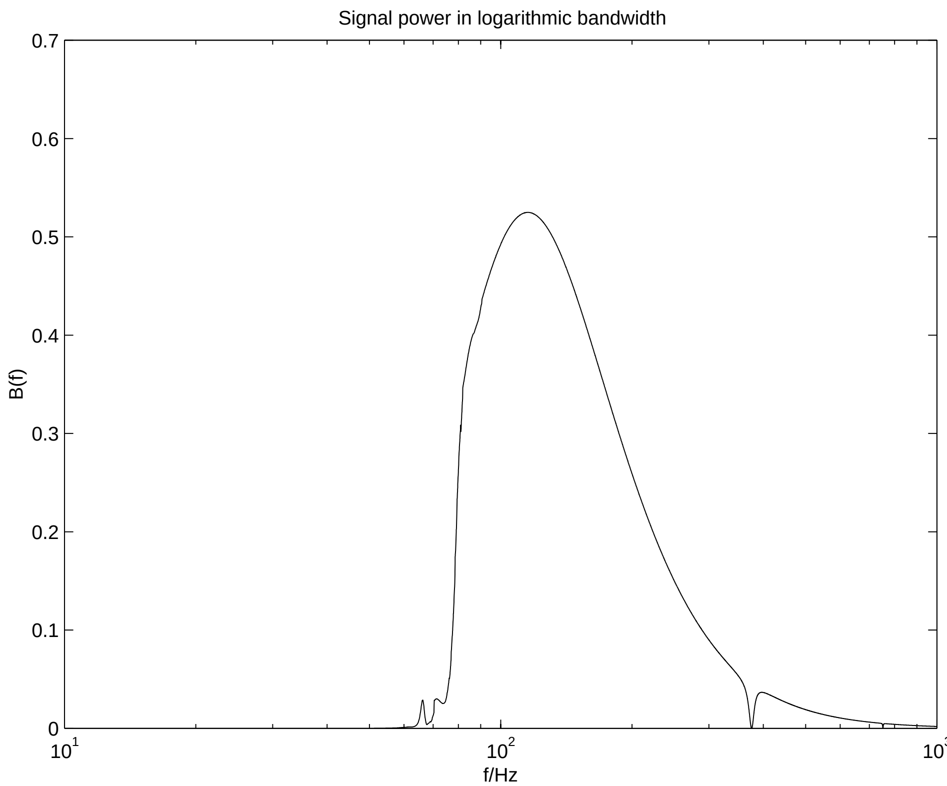

Figure 5. The fractional signal to noise ratio contributed per unit logarithmic bandwidth for binary inspiral observations in a detector whose noise is described by the figure 4.

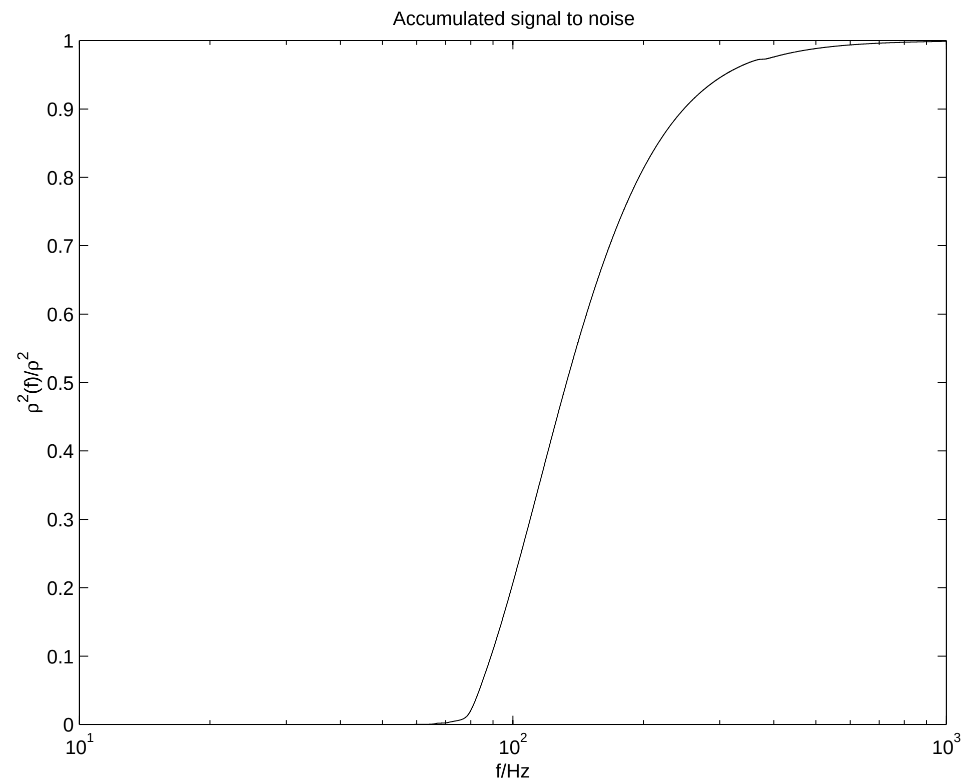

FIGURE 6. The accumulated signal to noise ratio up to frequency f for binary inspiral observations in a detector whose noise is described by the figure 4.

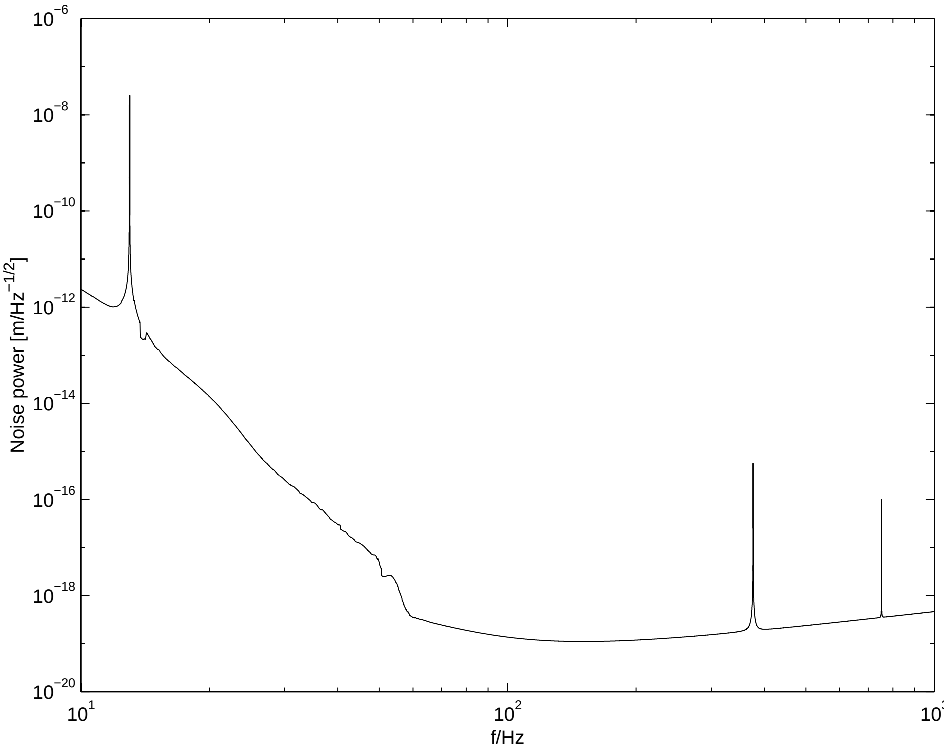

FIGURE 7. The model noise PSD corresponding to the original seismic stack design with modifications by DHS. Only the bandwidth from 10 Hz to 1 KHz is shown.

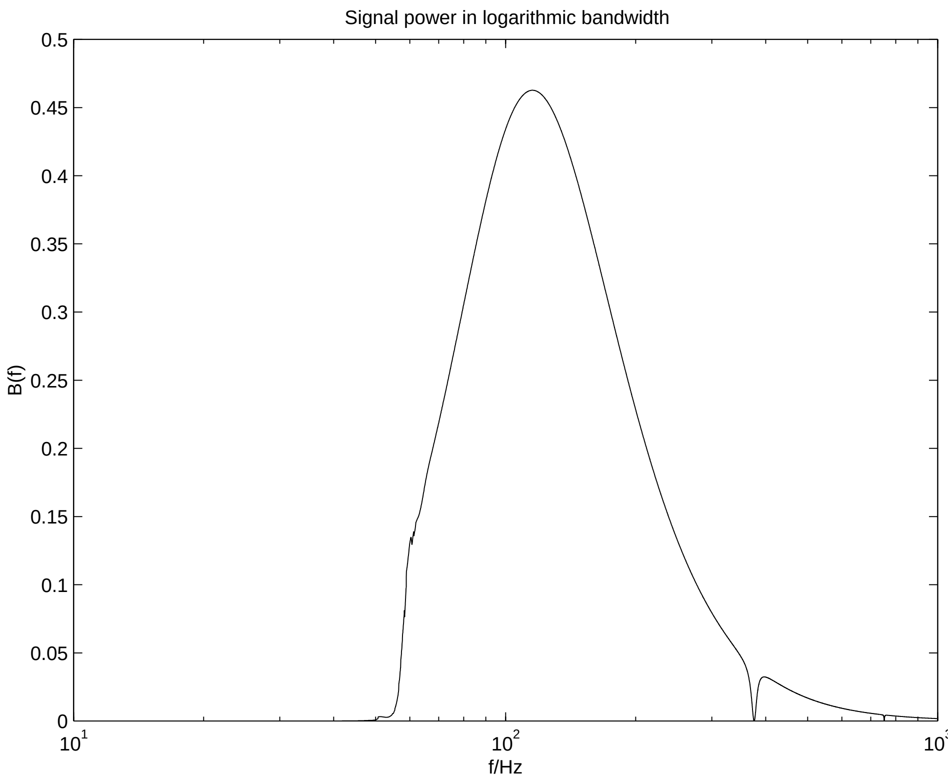

FIGURE 8. The fractional signal to noise ratio contributed per unit logarithmic bandwidth for binary inspiral observations in a detector whose noise is described by the figure 7.

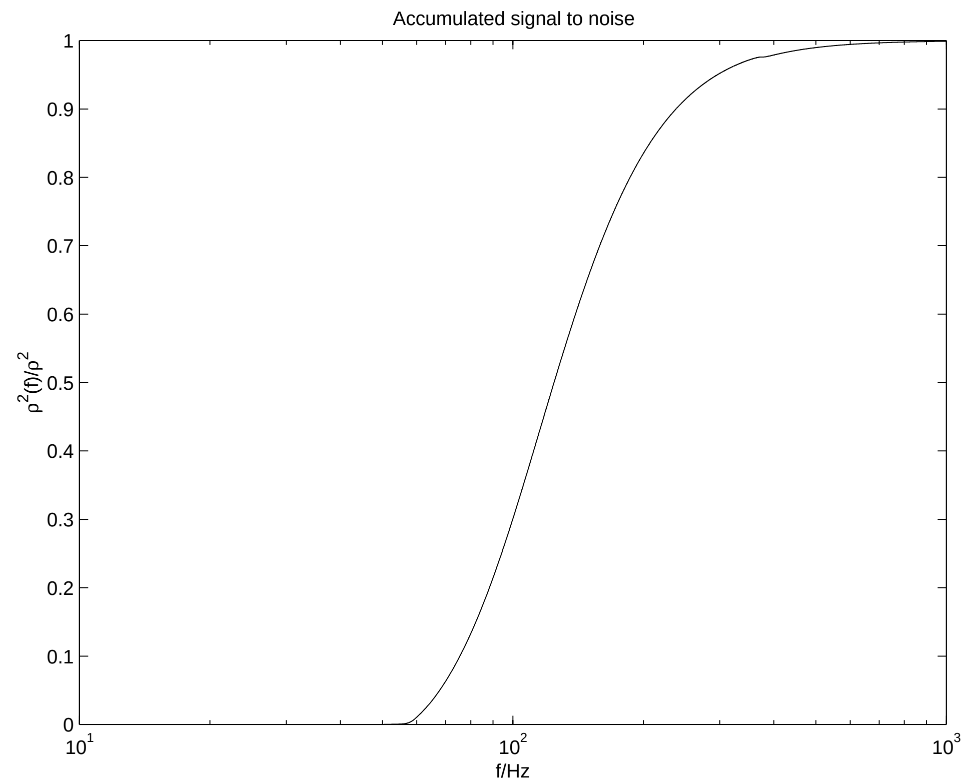

FIGURE 9. The accumulated signal to noise ratio up to frequency f for binary inspiral observations in a detector whose noise is described by the figure 7.

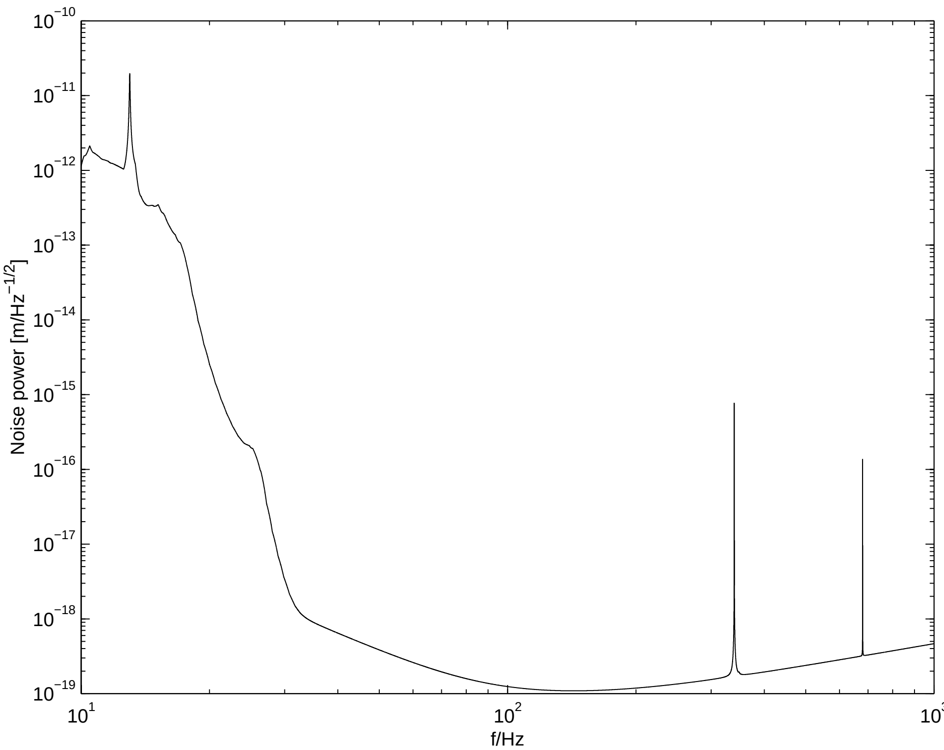

FIGURE 10. The model noise PSD corresponding to the current LIGO noise model. Only the bandwidth from 10 Hz to 1 KHz is shown.

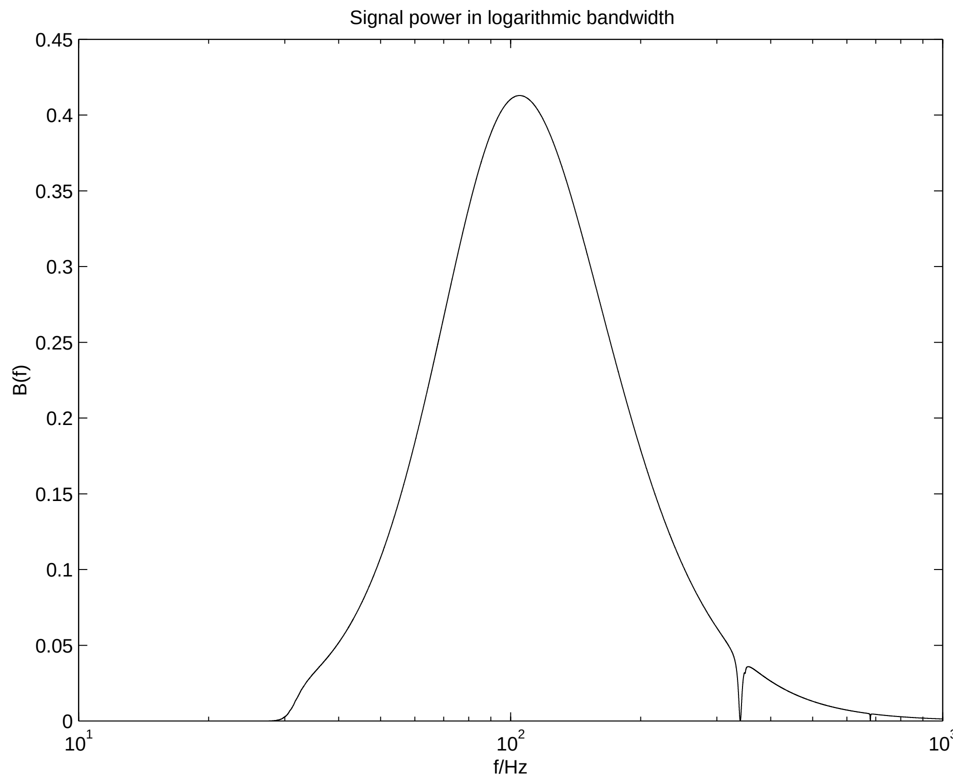

FIGURE 11. The fractional signal to noise ratio contributed per unit logarithmic bandwidth for binary inspiral observations in a detector whose noise is described by the figure 10.

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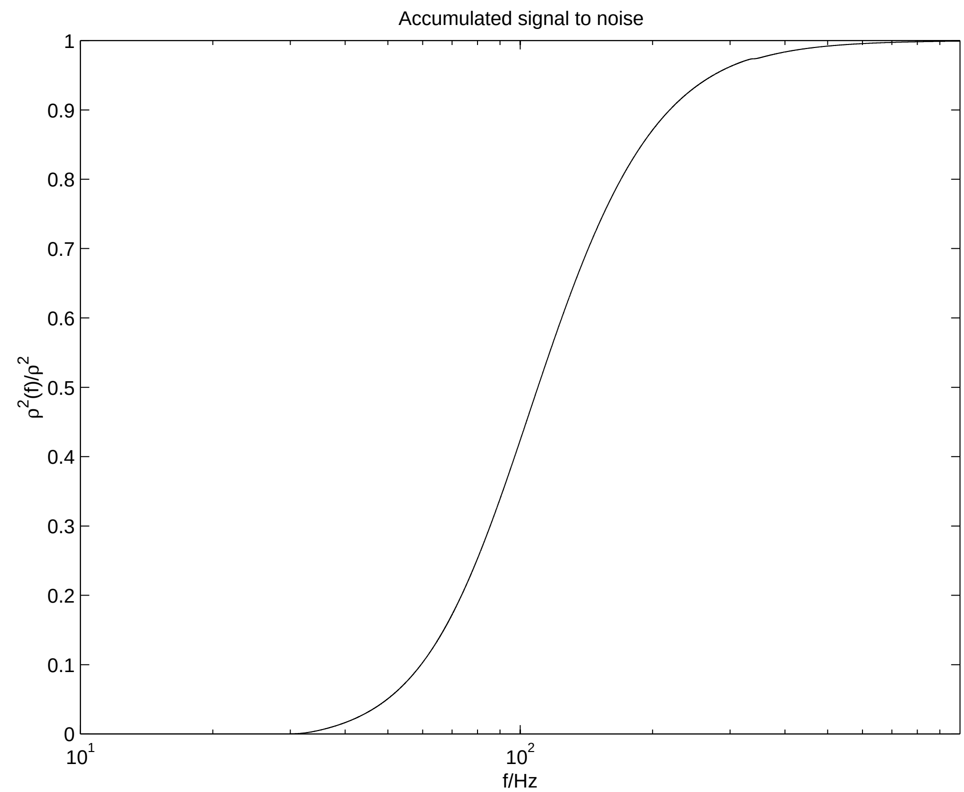

FIGURE 12. The accumulated signal to noise ratio up to frequency f for binary inspiral observations in a detector whose noise is described by the figure 10.