Noise and Signal Reconstruction and Characterization in the AURIGA Detector

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Abstract. Both the noise power spectrum and signal transfer function must be well known to reliably extract candidates of gravitational wave (GW) signals using linear Wiener filters. We review AURIGA data analysis techniques relative to post-filtering statistical tests and validation.

The experimentally measured power spectrum density (PSD) of the noise $S(\omega)$ in AURIGA detector is closely fitted by assuming a model of two coupled harmonic oscillators (the bar and the transducer) plus the amplifier wide band electronic noise. The complex poles and zeros $\{p_k, q_k\}$ are just what we need to build the *whitening filter* $L(\omega)$ for this noise (defined by $S(\omega) \equiv S_0 L(\omega) L^*(\omega)$), and also the complete Wiener-Kolgomorov (WK) filter $F^{(\delta)}(\omega)$ matched to a δ-like gravitational event:

$$L(\omega) = \prod_{k=1}^{2} \frac{(i\omega - p_k)(i\omega - p_k^*)}{(i\omega - q_k)(i\omega - q_k^*)}, \quad F^{(\delta)}(\omega) = N(q_k)\, L(\omega) \prod_{k=1}^{2} \frac{i\omega}{(i\omega + q_k)(i\omega + q_k^*)}, \quad (1)$$

where $N(q_k)$ is a normalization factor.

Granted that a two-poles-and-zeroes model is appliable in the first place, we need to check that we guessed the true parameters. The mode frequencies $\omega_k = \operatorname{Im} p_k \approx \operatorname{Im} q_k$ are followed with digital lock-ins in the raw data, while the quality factors of the modes ($Q_k \approx \omega_k / 2\operatorname{Re} p_k$) are just measured once per acquisition run, as they depend on major setup parameters of the detector. The post-filtering bandwidths ($\approx 2\operatorname{Re} q_k$) are corrected on an hourly basis by a feedback on the residual 'color' around the modes in the whitened data PSD (see FIGURE 1*d*). A big short-lived excitation that enters the system –either GW signal or spurious– spoils the whitened noise PSD estimate, but also the histogram of WK filtered data (FIGURE 1*e,f*), so we take care of this by freezing the parameters estimation when non-gaussian behaviour is detected.

Event search is model dependent as well. A candidate δ-like event is a pattern in the WK filter output with a specific mix of an exponential decay ($\tau \equiv -\max_k \{\operatorname{Re}(q_k)\}$) a beat modulation ($\omega_* \equiv \operatorname{Im}(q_2) - \operatorname{Im}(q_1)$) and a carrier wave ($\omega_0 \equiv \frac{1}{2}[\operatorname{Im}(q_2) + \operatorname{Im}(q_1)]$):

$$f_{WK}(t) \approx A e^{-t/\tau} \cdot \cos(\omega_* t) \cos(\omega_0 t) \quad (2)$$

We locate precisely its maximum by interpolation (FIGURE 2), and then wait at least 3 decay times before accepting a new event.

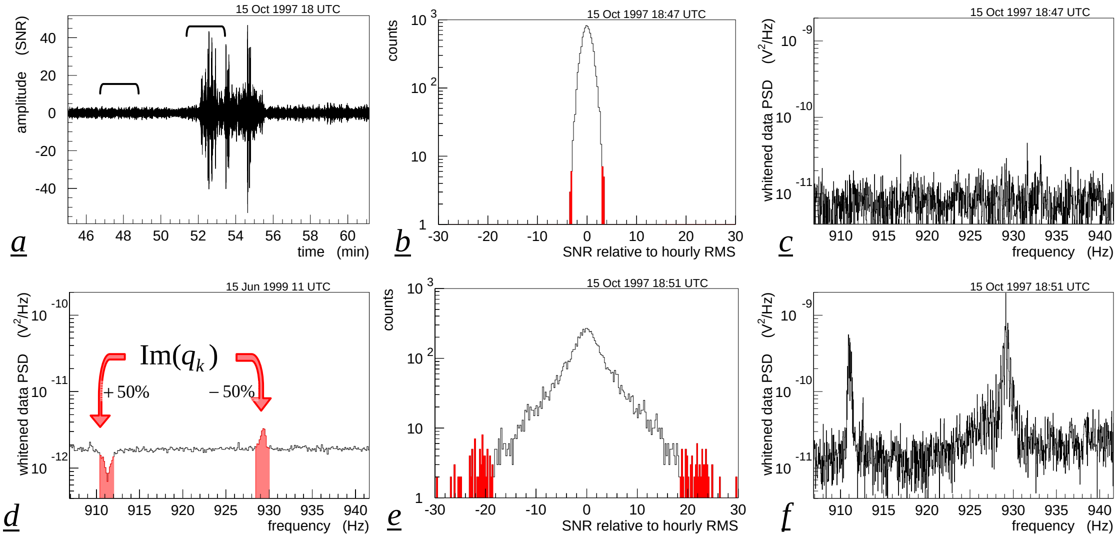

FIGURE 1. The filtered data (*a*) are divided into buffers of 2 minutes. The two marked with brackets have quite different statistical distributions (resp. *b* and *e*), particularly on tails beyond 3 times the Root Mean Square (*in gray*). The non-gaussian buffer is not let enter the effective noise temperature estimate (which is a RMS moving average). Notice that in the same 'bad' buffer it seems that the whitening filter is no more working properly (see *c* and *f*), in particular it mimics a displacement of the zeros q_1 and q_2. Compare it with the effect on whitened PSD of a ±50% error on the post-filtering bandwidth (*d*).

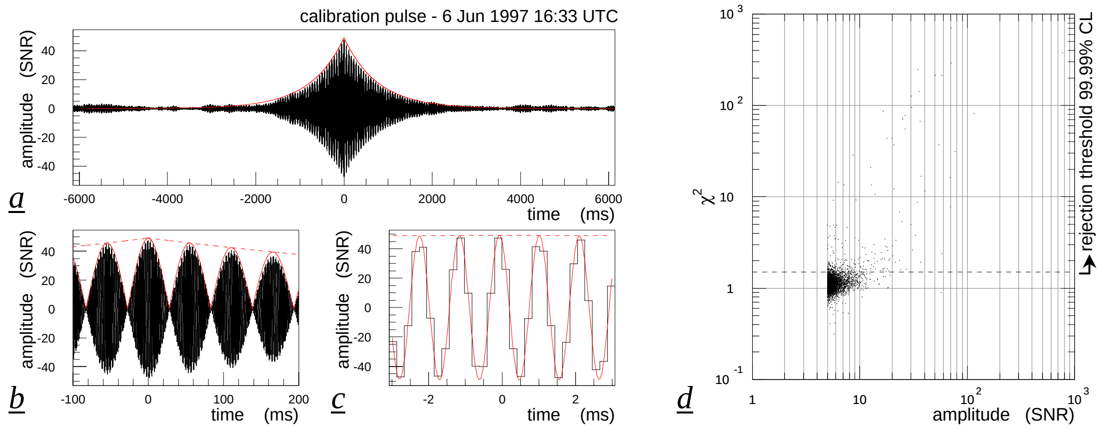

FIGURE 2. – *a*,*b*,*c*: A high SNR event extracted in AURIGA normal operation data. A good match with the model is found at different scales (*gray line*). – *d*: Thresholds on SNR and χ^2 are necessary to select from candidate events those with reliable time of arrival and amplitude estimates.

WK filtering is a maximum-likelihood fit based on models for both the noise and the signal, so if we can trust the first one, then passing a χ^2 test is a necessary and sufficient condition for time-of-arrival and amplitude estimation to make sense. The χ^2 test is used to discriminate between fast mechanical (or gravitational) bursts on the bar and other spurious events –e.g. electromagnetic pulses on the amplifier– with an efficiency which has a quadratic dependence on Signal-to-Noise-Ratio (FIGURE 2*d*).

REFERENCES

1. G.A. Prodi *et. al.* elsewhere in these proceedings.
2. A. Ortolan *et. al.* in 2nd *E. Amaldi Conf. On Grav. Waves* (World Scientific, Singapore, 1998), p.204.