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Virgo Detector Characterisation: Adaptive and Fractal Time Series Analysis

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Outline

Adaptive Time Series Analysis

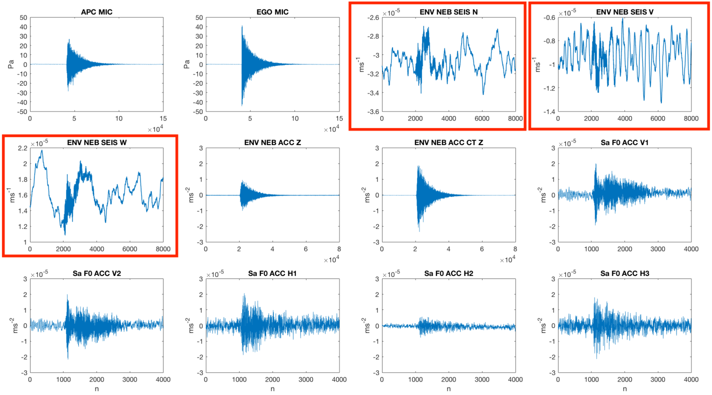
- Adaptive denoising of 4 acoustic noise injections performed at Virgo Interferometer.
- Scattered Light Noise Hunting

Fractal Time Series Analysis

- Hurst Exponent of Seismometer Array
- $1/f^{2.5}$ Noise Hunting

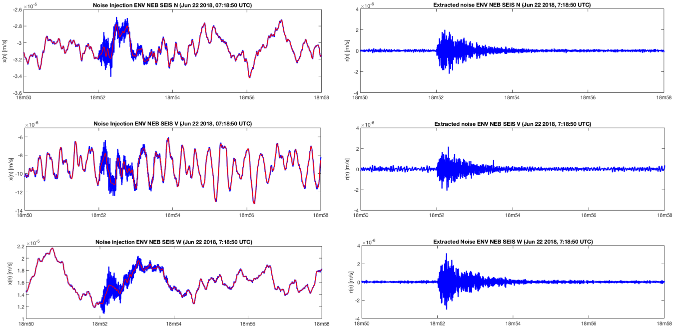
Adaptive denoising of acoustic noise injections

Seismic noise due to acoustic noise injections at Virgo



Acoustic noise injection as sensed by ENV sensors in NEB: Microphones (MIC), North/West/Vertical **SEISMOMETERS (SEIS N/W/V)**, and Accelerometers (ACC).

Seismic noise due to acoustic noise injections at Virgo



Left: Original **SEIS** data $x(n)$, signal plus trend: $s(n)+T(n)$.
Right: Seismic perturbation, $r(n)$ due to acoustic noise injection separated from underlying nonlinear/nonstationary seismic noise[1].

[1] **Alessandro Longo** et al., Adaptive denoising of acoustic noise injections performed at Virgo Interferometer, Pure and Applied Geophysics (submitted)

Scattered Light Noise Hunting

Background: Scattered Light

- Fraction of laser light diffused by **moving reflective surfaces, e.g. mirrors**

$$\delta x_{surface}(t)$$

located along the beam path Z, couples back to the main laser beam.
- The recombined scattered light forms **arch-shaped figures or fringes DARM spectrograms**
- **Scattered light phase angle** after reflecting once from the scattering surface is

$$\phi_{scattering}(t) = 2\frac{2\pi}{\lambda}(x_0 + \delta x_{surface}(t)) \quad (1)$$

- x_0 is the static optical path, as sensed by Position Sensing Devices:
- **Predictors**: Fringes frequency computed with time derivative of the scattered light phase angle

$$f_{fringe}(t) = \frac{2}{\lambda}|v_{surface}(t)| \quad (2)$$

- $v_{surface}(t)$ velocity at which scattering surface is moving

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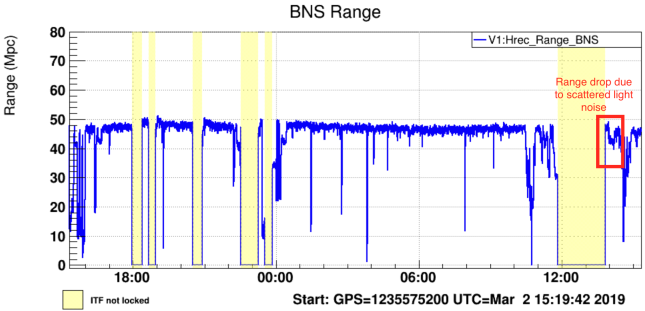
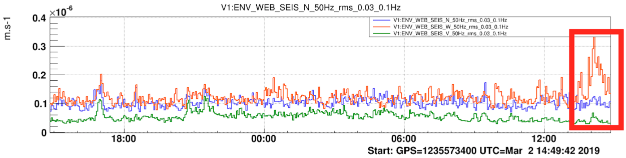
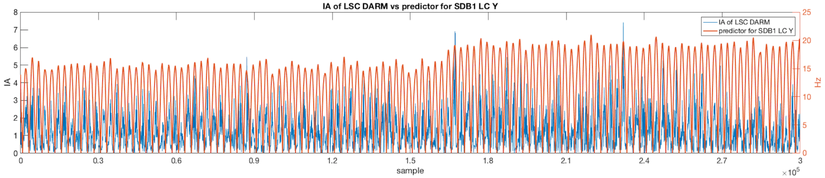
Drop in BNS range due to scattered light noise





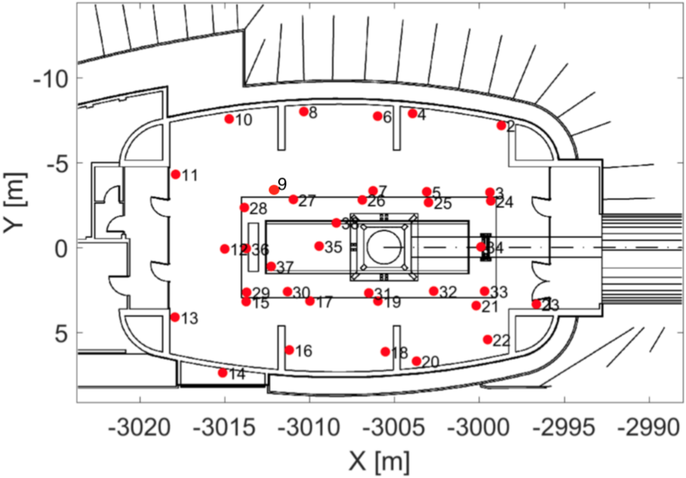
Tool for Scatterers identification

- Tool: Crosscorrelate Instantaneous Amplitude (IA) of strain, i.e. DARM (blue) with predictor for different auxiliary channels.
- Highest correlation: Suspended Detection Bench (SDB) (red)
- IA obtained with adaptive algorithm Empirical Mode Decomposition

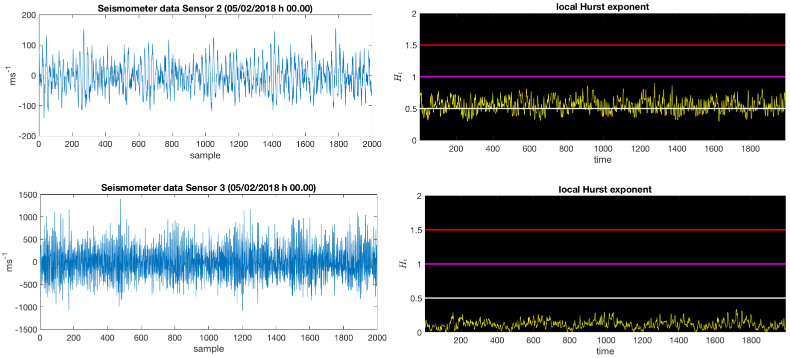


Hurst Exponent of Seismometer Array

Seismometer Array for Newtonian Noise Characterisation

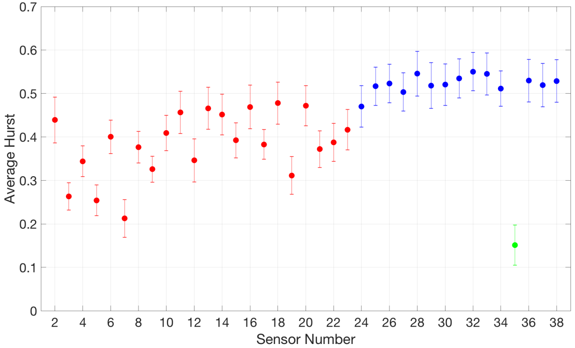


Hurst Exponent of Seismometer Time Series



Seismometers in different positions (left plot) exhibit different persistency (right plot)

Hurst Exponent of Seismometer Time Series

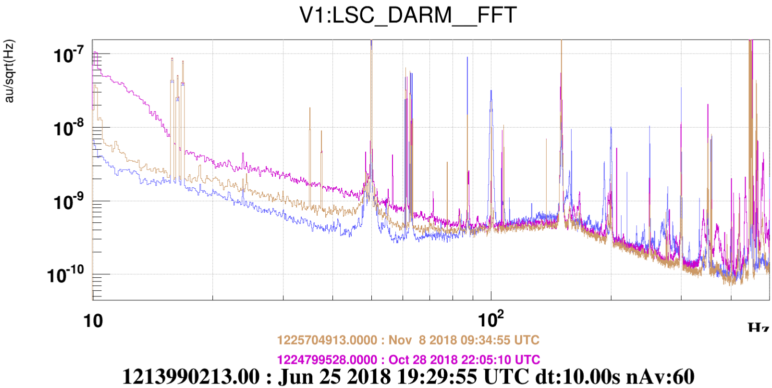


Average Hurst for the array: Seismometers on top of tower platform (blue) have higher persistency[2]

[2]Fractal analysis of data from seismometer array monitoring Virgo Interferometer, VIRGO Internal Review

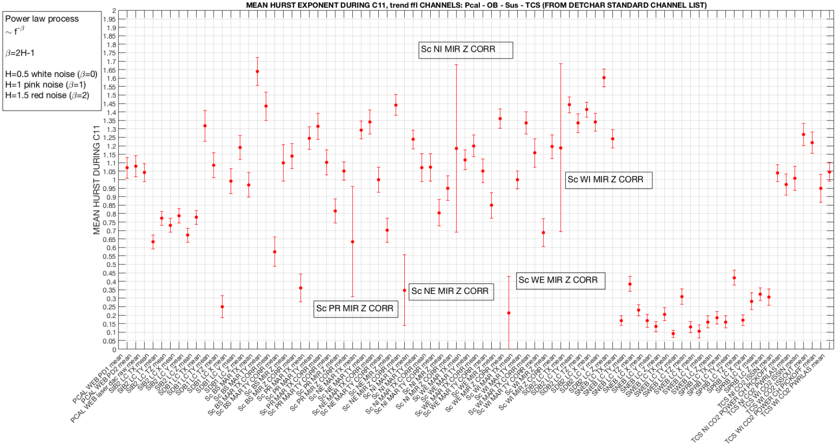
$1/f^{2.5}$ Noise Hunting

$1/f^{2.5}$ Fractal Broadband Noise



Broadband noise affecting the sensitivity from 20 to 100Hz, worth around 15MPc

$1/f^{2.5}$ Fractal Broadband Noise



Fractal Analysis of data from Commissioning run C11.

Classify noises with variable persistent behavior

References

Applications of Adaptive Algorithms

- **Alessandro Longo** et al., Adaptive denoising of acoustic noise injections performed at Virgo Interferometer, Pure and Applied Geophysics (submitted).
- **Alessandro Longo** et al., tvf-EMD based time series analysis of ^{7}Be sampled at the CTBTO-IMS network, Physica A 523 (2019) 908-914

tvf-EMD algorithm

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Empirical Mode Decomposition

- Norden E. Huang et al., The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis, Proc. R. Soc. Lond. A (1998) 454, 903-995.
- EMD package `http://perso.ens-lyon.fr/patrick.flandrin/emd.html`

Detrended Fluctuation Analysis

- Peng, C.K., Havlin, S., Stanley, H.E., Goldberger, A.L., 1995. Quantification of scaling exponents and crossover phenomena in nonstationary heartbeat time series. Chaos: An Interdisciplinary Journal of Nonlinear Science, 5.1, 82-87.

Local Hurst and Multifractal Detrended Fluctuation Analysis

- Espen A. F. Ihlen, Introduction to multifractal detrended fluctuation analysis in Matlab, Front Physiol. 2012; 3: 141.