Daily monitoring of scattered light noise due to microseismic variability at the Virgo interferometer

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Abstract
Data acquired by the Virgo interferometer during the second part of the O3 scientific run, referred to as O3b, were analysed with the aim of characterising the onset and time evolution of scattered light noise in connection with the variability of microseismic noise in the environment surrounding the detector. The adaptive algorithm used, called pytvfemd, is suitable for the analysis of time series which are both nonlinear and nonstationary. It allowed to obtain the first oscillatory mode of the differential arm motion degree of freedom of the detector during days affected by scattered light noise. The mode’s envelope i.e. its instantaneous amplitude, is then correlated with the motion of the West end bench, a known source of scattered light during O3. The relative velocity between the West end test mass and the West end optical bench is used as a predictor of scattered light noise. Higher values of correlation are obtained in periods of higher seismic noise in the microseismic frequency band. This is also confirmed by the signal-to-noise ratio (SNR) of scattered light glitches from GravitySpy for the January–March 2020 period. Obtained results suggest

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that the adopted methodology is suited for scattered light noise characterisation and monitoring in gravitational wave interferometers.

Keywords: scattered light, detector characterisation, Virgo, pytvfemd

(Some figures may appear in colour only in the online journal)

1. Introduction

Virgo is a ground-based gravitational wave (GW) detector located in Cascina, near Pisa (Italy) having a detection frequency band ranging from 10 Hz to a few kHz [1, 2]. Environmental noise characterisation and mitigation are of key importance for detectors such as Virgo. A relevant example in this regard is seismic noise, affecting the detector in the 0.1–200 Hz band [3–7]. In the 0.1–1 Hz frequency range, the seismic noise induced by sea waves interacting with the shore is referred to as microseism [8, 9]. Its reduction is fundamental to achieve the design sensitivity of third generation GW interferometers, which aim at enlarging the detection bandwidth at 1 Hz [10–12]. For ground-based detectors such as Virgo, the microseismic noise frequency is lower than the resonant frequency of the seismic isolation systems. Hence, an excess of microseismic noise can couple to the detector in the form of scattered light, showing up at the output of the detector i.e. in the differential arm motion (DARM) degree of freedom (DoF) [13, 14]. Scattered light occurs when stray beams bounce off reflective surfaces having a relative motion w.r.t optics of the detector and recombine with the main light beam through phase and amplitude coupling [15]. Its distinctive characteristics are arches, or fringes, appearing in DARMs’ spectrograms (see appendix A). The time at which these arches appear and their frequency $f_{arch}(t)$ is related to the motion $x_{sc}(t)$ of the object responsible for the noise i.e. the culprit, and in particular to its velocity as described by the so-called predictor (Hz)

$$f_{arch}(t) = \frac{2N}{\lambda} |v_{sc}(t)|,$$

where $N$ is the number of round trips occurring before recombination with the main beam, $\lambda$ is the Virgo laser wavelength, and $v_{sc}$ is the velocity at which the detector component is moving. Scattered light is a noise both nonlinear and nonstationary, and adaptive algorithms [16–19] are well suited for its characterisation. Equation (1) for the culprit is found to be well correlated with their output [20–22]. Days in which high microseismic noise induced scattered light in the DARM DoF of Virgo were analysed to quantify the contribution of the optical bench located at the end of the West arm, a known source of scattered light during the third scientific run (O3). Pytvfemd [23], the Python version of the time varying filter empirical mode decomposition (tvf-EMD) algorithm [19], was employed to this end. The analysis focused on the last part of O3 (O3b), the most affected by scattered light, to take advantage of the computing framework at Cascina. The adopted methodology allowed to monitor the onset and time evolution of scattered light noise and link it to the variability of environmental conditions at the detector location.

2. Methodology

Adaptive algorithms allow the extraction of nonlinear, nonstationary modes, referred to as intrinsic mode functions (IMFs), from the data. For this reason, they are suitable for scattered light noise characterisation. When analysing noisy time series with adaptive algorithms such as empirical mode decomposition, mode-mixed IMFs are possibly obtained [16]. To mitigate
mode mixing, the recently developed tvf-EMD algorithm uses a threshold on the instantaneous bandwidth (IB) of the modes to be extracted to stop the sifting iterations, employing the bandwidth threshold ratio parameter $\xi$. It calculates a local bisecting frequency, used for the spline approximation step which is carried out using B-splines of order $n$ [24]. The order $n$ affects the frequency response of the spline approximation (see figure 1 in [19]). This bisecting frequency is also realigned (see algorithm 2 in [19]) to mitigate the effect of noise on the algorithm output. Sifting iterations stop when the oscillatory mode to be extracted is a local narrow band signal, based on a threshold put on the Loughlin IB [25, 26]. The relevant parameters of the tvf-EMD algorithm, used for this scattered light data analysis, are $\xi = 0.1$ and the B-spline order $n = 26$. The Python version of tvf-EMD, referred to as pytvfemd, was used. The adopted methodology is based on the one described in [20, 21], and it was extended taking into account days worth of data. Is hereafter summarised.

- Periods of scattered light noise in the DARM time series were identified looking at daily Omicron [27] trigger plots such as the one shown in figure 1.
- DARM data were low-pass filtered based on the frequency of the clusters of short transients of excess of power (glitches) with SNR $>$ 20, visible in the daily Omicron triggers plots. Then low-passed data were decomposed with pytvfemd, obtaining a set of IMFs.
- The envelope of the first mode (IMF1) i.e. its instantaneous amplitude $IA(t)$, is correlated with equation (1) computed for the suspended West end bench (SWEB), the most frequent culprit of scattered light in Virgo during O3. The Pearson correlation coefficient is used to this end.

The relative motion in the direction of propagation of the beam ($z$) of SWEB and of the West end test mass (MIRROR) was used, referred to as BENCH-MIRROR. For each day, intervals of 60 s were considered. Hence, the output of the analysis is a time series of 1440 values of
correlation $\rho$ for each day. The $\rho$ time series is indicative of the time evolution of scattered light noise due to the West end bench. Its dependence on the microseismic noise, as measured by environmental sensors deployed at the Virgo location, can then be investigated.

3. Results

This section presents the results of the daily analysis. In total 1440 intervals of 60 s of data were analysed for each day. As the winter period is typically characterised by higher sea activity and microseismic noise, the following days of the last part of O3b, were chosen:

- 18 January 2020
- 1–2, 9–10, 29 February 2020
- 1–2 March 2020

For these days in O3b, a larger number of low frequency triggers were observed in the Omicron trigger data. Figure 1 shows the daily Omicron triggers of DARM DoF of Virgo during 18 January 2020. Two distinct clusters of scattered light glitches with a high SNR $> 20$ can be seen. The first cluster has frequencies centered around 20 Hz, and lasts from 00:00 UTC to approximately 11:00 UTC. The second cluster has frequencies centered around 15 Hz and it lasts until the end of the day. Figure 2 shows the correlation $\rho$ between the BENCH-MIRROR predictor $f_{arch}(t)$ and the IA$(t)$ of DARM’s IMF1, as extracted by pytvfemd. For the 18 of January, a low-pass frequency of $f = 20$ Hz was used for the 00:00–11:00 UTC interval while $f = 10$ Hz was used from 11:00 UTC to the end of the day. This combination
Figure 3. Correlation values between the predictor $f_{\text{arch}}(t)$ for BENCH-MIRROR and the $IA(t)$ of DARM’s IMF1, obtained for the 1–2 February period (top) and the 9–10 February (bottom). Also shown, time evolution of the root means square of the West end building seismometer data in the 0.1–1 Hz frequency band.
Figure 4. Correlation values between the predictor $f_{\text{arch}}(t)$ for BENCH-MIRROR and the $IA(t)$ of DARM’s IMF1, obtained for the 29 February 1 March period (top) and the 2 March (bottom). Also shown, time evolution of the root means square of the West end building seismometer data in the 0.1–1 Hz frequency band.
of values was found to give the best results i.e. higher values of $\rho$. It can be seen that the $\rho$ values obtained are consistent with the times of occurrence of high SNR glitches in figure 1, in the UTC time intervals 01:00–07:00, 11:00–14:00, and 14:00–23:00. The moving average of $\rho$ with a window of 60 points, hence 1 h, shown in red highlights this.

Figure 2, bottom panel, shows the time evolution of seismic noise in the microseismic frequency region 0.1–1 Hz at the Virgo West end building on the 18 January. Higher values at the beginning of the day are observed, related to the higher frequency scattered light glitches. The decrease of microseismic noise is consistent with the observed lower frequency of the second cluster of glitches of figure 1. Figure 3 shows the $\rho$ values obtained for February 1–2 and February 9–10. A higher correlation, indicative of scattered light noise in the data, is visible in the middle region of the plot. Also shown is the seismometer data, which are highly correlated with the $\rho$ time series of the top panel. Figure 4 reports the $\rho$ values obtained for the 29 February–2 March period, along with seismometer data. Sudden drops in the values of $\rho$, are obtained from data following lock loss of the detector i.e. when not all the optical cavities are resonant, and correspond to periods in which the full lock is not yet achieved. More details on the lock acquisition procedure are in [28]. Figures 2–4 show that an increase of microseismic noise leads to an increase in scattered light noise witnessed in DARM due to the West end bench i.e. high correlation values between the SWEB predictor and the instantaneous amplitude of DARM’s IMF1. Regarding the 2 March, an increase in seismic noise in the 0.03–0.1 Hz is also measured by the seismometer in the West end building (not shown), coincident with the increase of $\rho$ in the middle part of the plot. To further investigate the relationship between scattered light glitches and microseismicity, figure 5 shows histograms of the signal-to-noise ratio (SNR) of Virgo glitches classified as scattered light by GravitySpy [29] with SNR < 50 during January, February and March 2020. Scattered light glitches with peak frequency $f < 40$ Hz and for which the duration is shorter than their separation in time were considered. It can be seen that February has the highest number of glitches, followed by March and January. Changes in the amounts of scattered light glitches are possibly due to different levels of microseismicity during the considered months.
To verify this, figure 6 reports histograms of the West end building seismometer data, horizontal components, in the microseismic band i.e. 0.1–1 Hz, for the same period. Velocities greater than $v = 5 \mu m \ s^{-1}$ are more frequent in February followed by March and January 2020, as expected.

4. Conclusions

The pytfeamd adaptive algorithm was applied to the DARM DoF of the Virgo detector to extract the oscillatory mode related to scattered light noise, from which its instantaneous amplitude $IA(t)$ can be obtained. The $IA(t)$ time series is known to correlate with the predictor computed from the velocity of the optic generating scattered light. Daily analysis were carried out, using the relative motion of the West end bench w.r.t. the West end mirror to obtain the predictor from equation (1). The analysis obtains a total of 1440 values of Pearson correlation coefficients $\rho$ each day. The time evolution of $\rho$ values is consistent with the clusters of scattered light glitches in the Omicron triggers plot of 18 January, shown in figure 1. Omicron triggers for the other days considered are in appendix B. Furthermore, the obtained values of $\rho$ are found to be correlated with seismometer data in the microseismic frequency band. The data
considered are from the winter period, during which higher microseismic noise is expected. This excess of low frequency noise can couple to the detector in the form of scattered light as it possibly affects the suspended optical benches. Obtained results indicate that the adopted methodology, based on the pytvfemd adaptive algorithm, is suitable to monitor the onset and evolution of scattered light noise, related to environmental noise variability in GW interferometers. As the source of scattered light during O3 was known to be the West end bench, this noise was mainly removed during the online noise subtraction using the relevant photodiode as a witness channel [30]. This allowed to remove the scattered light noise so that it would not significantly affect the GW strain data. The issue concerning the West end bench control was identified and cured after O3, and its residual motion is expected to be similar to the one of the other terminal bench, located at the end of the North Arm of the detector. To make the adopted methodology automated, the expected peak frequency of the scattered light glitches could be used as low-pass frequency cutoff. One daily analysis takes approximately 1.5 h on Condor [31]. This allows to foresee a daily monitoring of possible scattered light culprits during the pre-O4 noise hunting phase and then during the run itself.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.
Figure A1. Shown in red is the predictor $f_{\text{arch}}(t)$ computed for the West end bench and overlapped on the spectrogram of the DARM DoF of the detector. The scattered light arches are visible in yellow, having frequency up to 15 Hz.

**Appendix A. Scattered light arches in DARM spectrogram**

The distinctive feature of scattered light noise in the data is the presence of arches appearing in their spectrogram. Equation (1) is indicative of the frequency and time of occurrence of such arches. Hence, if the source of scattered light has been correctly identified, the predictor overlaps with the arches in the spectrogram. Figure A1 shows the spectrogram of DARM and the predictor for the West end bench for the 1 February 2020, as obtained for 1 min of data. The starting time is 20:01:00 UTC. It can be seen that the predictor overlaps with the arches, confirming that the West end bench is the culprit of the observed scattered light noise.
Figure B1. The daily Omicron plots for the 1 of February 2020 (Top) and for the 2 of February 2020 (Bottom) are shown.

Appendix B. Daily Omicron plots

Shown are the Omicron daily triggers of Virgo DARM DoF for the days considered in this study. The onset and time evolution of low frequency glitches is visible. The colour scale indicates the SNR of the glitches. The green and red bar on top indicates periods in which the detector is locked or unlocked, respectively (figure B1–B3).
Figure B2. From top to bottom, reported here are the daily Omicron plots for the 9, 10 and 29 February 2020.
Figure B3. Daily Omicron plots for the 1 (Top) and 2 (Bottom) of March 2020 are shown.

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