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Scattered light noise from Virgo viewports: results and possible mitigations

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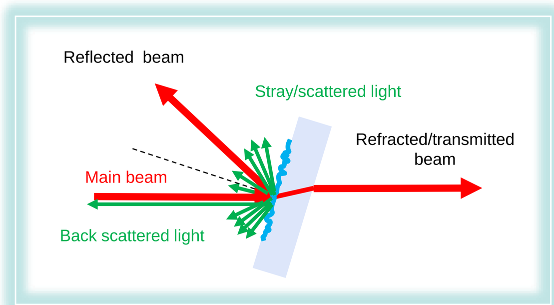
In addition to the fundamental noises (quantum noise, thermal noise, and seismic noise) affecting the sensitivity of ground-based gravitational-wave interferometers, the technical noises often limit some frequency bands. A substantial part of detector commissioning is devoted to the study and the mitigation of technical noises. Scattered light is among these noises. In this presentation, the studies of the scattered light from the main Virgo interferometer viewports, during the commissioning in preparation for the O4 run, and some preliminary results applicable for the O5 configuration will be shown. Possible mitigation suggestions will also be discussed.

What is the stray light?

- The stray light is light of the system source which has lost its indented path.
- In the gravitational-wave interferometer (ITF), the laser light travel through several optical elements.
- They can couple back some light into the interferometer port due to back reflection or scattering.
- The back propagating light enters into the instrument and can recouple with the main mode of the laser beam adding a spurious field to the main one [1].

- This coupling can happen through various processes :
  - ✓ residual reflection from anti-reflective coatings;
  - ✓ scattering from imperfect mirror surfaces;
  - ✓ scattering from surface defects (like dust, digs or scratches);
  - ✓ scattering from the enclosure of the optical system;
  - ✓ diffraction from the limited aperture of the optics.



- The amplitude and phase of the scattered light (SL) field are linked to the optical element motion [2]:

$$\phi_s(t) = \frac{4\pi}{\lambda}(x_0 + \delta x_s(t)) = \phi_0 + \delta\phi_s(t)$$

Scattered light phase

λ laser optical wavelength (1064 nm)
x_0 static optical path (depends on scattered position in the ITF)
$\delta x_s(t)$ optical element displacement

Scattered light noise

- The scattered light generates two additional noises at the interferometer [3]:

$$n_\phi(t) = C sin(\phi_s(t))$$ **Phase noise**

$$\frac{\delta P}{P}(t) = C cos(\phi_s(t))$$ **Amplitude noise**

- The **coupling factor C** is the fraction of light power exiting one of the ITF ports and coupled back into the main mode:

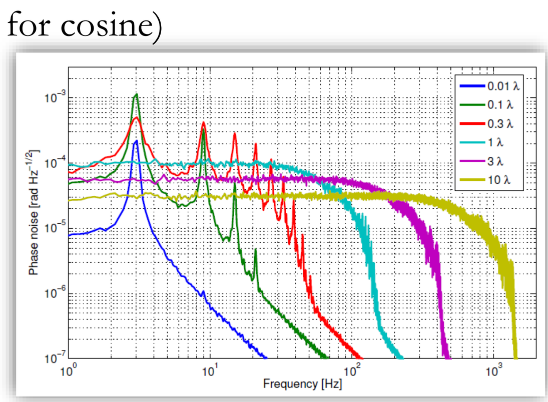
$$C = f_{sc} + f_{sp} + f_{Rayleigh}$$

f_{sc} fraction of scattered light
f_{sp} fraction of back reflected light due to specular reflection
$f_{Rayleigh}$ fraction of scattered light by atoms/molecules

- The time variation of phase and amplitude noises depends on motion of scattering element:
  - ✓ Small motion $\delta x_s(t) \ll \lambda/4\pi \rightarrow sin(\phi_s(t)) \simeq \phi_s(t)$ (same for cosine)

    The noise coupling is linear with the scattering element motion.
  - ✓ Large motion $\delta x_s(t) \gg \lambda/4\pi$

    The noise dependence is non-linear and an up-conversion occurred at low-frequency.



Simulation of coupling of stray light into phase noise. It is assumed a scattering element with a total coupling of 10^{-6}, moving as a pendulum with resonant frequency of 3 Hz and quality factor of 100, excited by white noise. The phase noise induced by stray light is shown as a function of the RMS amplitude of the motion. Figure from Ref. [3]

Scattered light noise model

- The contribution of these two noise sources to strain amplitude h is given by:

$$\tilde{h}(f) = C\left\{TF_{\phi}(f)\mathcal{F}[sin(\phi_s(t))] + TF_{\delta P/P}(f)\mathcal{F}[cos(\phi_s(t))]\right\}$$

TF. transfer function from phase and amplitude noise to detector output h
$\mathcal{F}$ Fourier transform

- **In case of the viewport**, f_{sp} and $f_{Rayleigh}$ factors are negligible and the faction of the scattered light coupling with the main mode of the laser beam is:

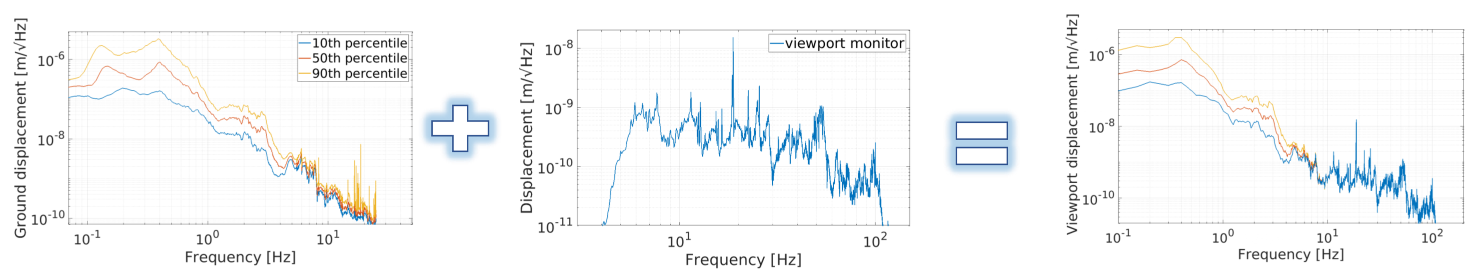
$$f_{sc} \approx BRDF\frac{\lambda^2}{\pi\omega^2} \sim TIS\left(\frac{\lambda}{\pi\omega}\right)^2$$

$$C = \sqrt{\frac{P_{sc}}{P_{in}}} \quad with \quad P_{sc} = f_{sc} \cdot P_{in}$$

For scattered angle > 4°: $BRDF \sim \frac{TIS}{\pi}$

BRDF - Bidirectional Reflectance Distribution Function
TIS - Total Integrated Scatter
ω beam radius at scattering face
P_{in} beam power on scattering face
P_{sc} beam power scattered by viewport

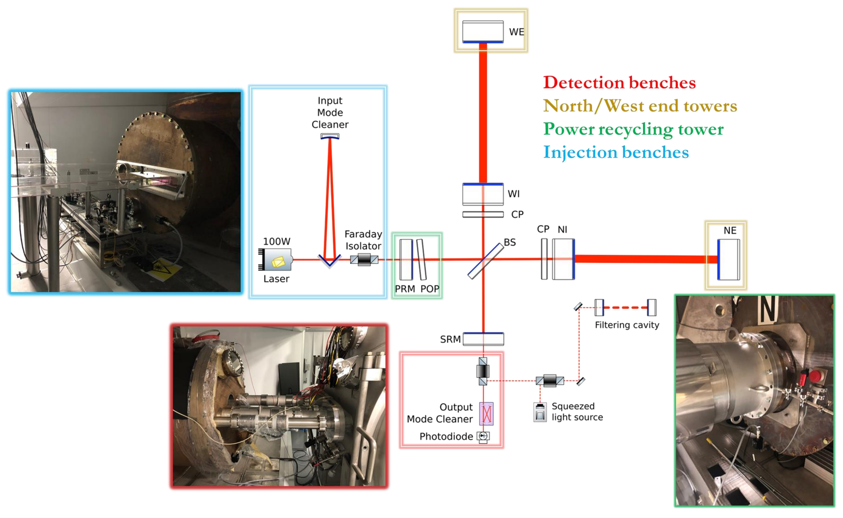
- The viewport motion is obtained blending the 10th, 50th and 90th percentiles* of the ground displacement with the displacement of the viewport witness sensor.
- The ground displacement is measured using the Guralp CMG-40T three-axis seismometer sampling the ground motion during the whole O3 run.

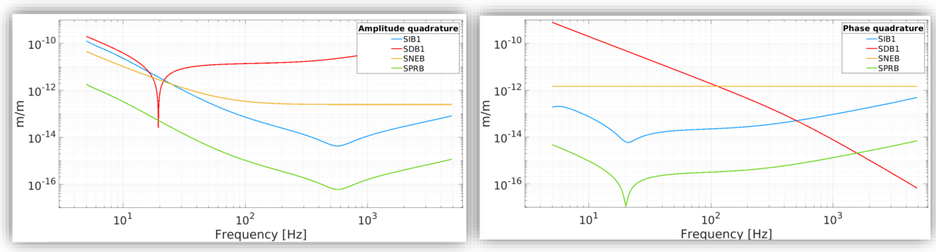


* The 10th, 50th and 90th percentiles show the upper limit of displacement noise for 10%, 50% and 90% of the considered period.

Main Virgo interferometer viewports

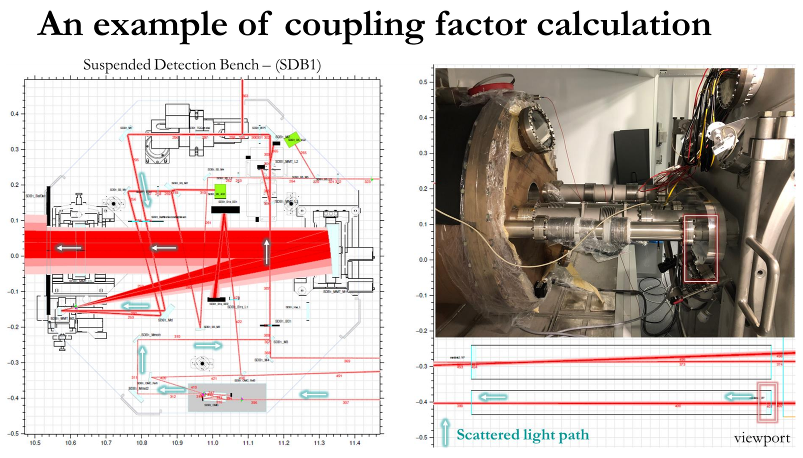
- The viewports are installed in different area of detector with the aim to connect chambers at different and not compatible vacuum levels.
- Transfer function of equivalent displacement noise of a scatter element (coupling 1ppm of impinging power to the main ITF mode) to the differential arm degree of freedom.





- Larger transfer function values mean increased sensitivity to the displacement noise.

An example of coupling factor calculation

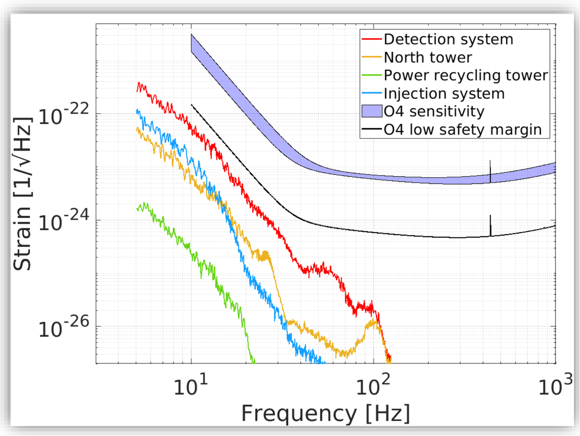


Parameters	Value
P_{B1} beam power on SDB1	1 W
ω beam radius at scattering face	2.77 mm
SDB1_M3 reflectivity	98.5 %
OMC transmissivity	96.8 %
Faraday Isolator (F.I.) attenuation	40 dB
P_{in} power impinging on viewport	953 mW
TIS (viewport tilt angle = 2°)	400 ppm

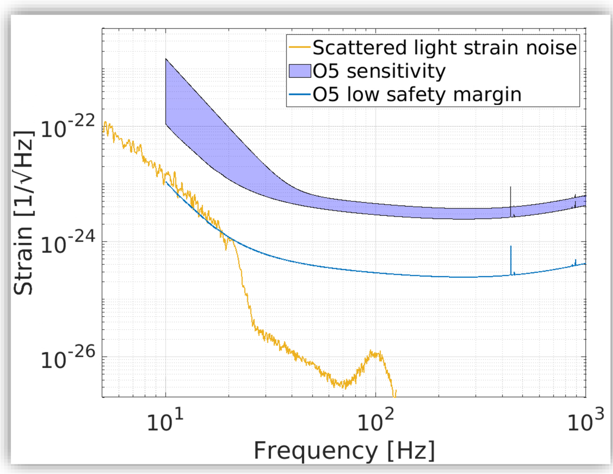
$$P_{in} = P_{B1} \cdot r_{M3} \cdot t_{OMC}$$
$$P_{sc}^{sc} = f_{sc} \cdot P_{vp} \cdot r_{M3} \cdot t_{OMC} \cdot a_{FI}$$
$$C = \sqrt{P_{sc}/P_{in}} \sim 2.39 \cdot 10^{-8}\sqrt{W/W}$$

Scattered light noise studies

- Taking into account the 90th percentiles of the viewport displacement, the SL strain noise of four systems are well below the safety margin (O4 low sensitivity divided by a factor 10).



North end minilink in O5 at 90th percentiles



$$P_{in} = P_o \cdot g_{PR} \cdot t_{BS} \cdot g_{NA} \cdot t_{NE}$$
$$P_{sc} = f_{sc} \cdot P_{in}$$
$$C = \sqrt{P_{sc}/P_{in}} \sim 6.27 \cdot 10^{-8}\sqrt{W/W}$$

- For O5 run, it is foreseen to change the beam geometry inside the detector arm cavity increasing the beam size on the end mirrors with the aim to reduce the mirror thermal noise [4].
- Calculating the SL noise contribution from the viewport linking the North tower and the minitower, it does not limit the sensitivity.

Parameters	Value
Power injected into ITF	80 W
Power Recycling (PR) cavity gain	40
P_{PR} PR arm cavity power	3200 W
Beam Splitter (BS) mirror transmissivity	0.5
North arm (NA) cavity gain	450
P_{NA} NA cavity power	$7.20 \cdot 10^5$ W
ω beam radius at scattering face	54 mm
NE mirror transmissivity	$5 \cdot 10^{-6}$
P_{in} impinging power on the viewport	3.6 W
TIS (viewport tilt angle= 4°)	100 ppm

Conclusions

- In this work, the method for the calculation of the scattered light strain noise from viewports has been presented. As shown in the pictures, the viewport scattered light noise is not an issue for the Virgo O4 sensitivity and O5 sensitivity in case of the North arm.
- However, with more sensitive gravitational-wave detectors, the scattered light will be a noise source affecting even more the sensitivity and, therefore requiring more accurate investigation during the commissioning phase. Below, it is reported some guidelines to mitigate it [5]:
  - ✓ stiffening of the optical mounts with the aim to shift the mechanical modes out the detector sensitivity range;
  - ✓ adoption of large beam waist and installation of the optical element as far as possible from the waist location;
  - ✓ optimization of low scattering optics / beam dumps / baffles;
  - ✓ mitigation of the motion of the stray light sources (suspension and motion control);
  - ✓ optimization of anti-reflective coatings;
  - ✓ optical isolation (by using Faraday Isolators to reduce the back-reflected light);
  - ✓ monitoring implementation of displacement of interferometer critical parts.

Reference
1. D. J. Ottaway et al., “Impact of upconverted scattered light on advanced interferometric gravitational wave detectors”, Opt. Express 20, 8329-8336 (2012).
2. T. Accadia et al.,“Noise from scattered light in Virgo's second science run data”, Class. Quantum Grav. **27** 194011 (2010)
3. B. Canuel et al.,“Displacement noise from back scattering and specular reflection of input optics in advanced gravitational wave detectors”, Optica Publishing Group, Vol. 21, Issue 9, pp. 10546-10562 (2013).
4. R. Flaminio. “Status and plans of the Virgo gravitational wave detector”. SPIE Astronomical Telescopes + Instrumentation 2020, Dec 2020, Online, United States. pp.1144511, ff10.1117/12.2565418ff. ffhal-03107929f.
5. I. Fiori et al., “Environmental Noise in Gravitational-Wave Interferometers ”, Handbook of Gravitational Wave Astronomy Springer Singapore (2021).