# End benches scattered light modelling & substraction in Advanced Virgo

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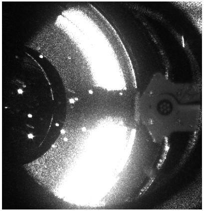
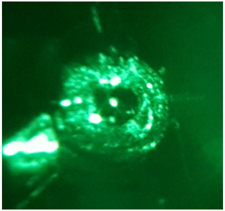
on behalf of the Virgo Collaboration

LAPP/IN2P3 - Annecy

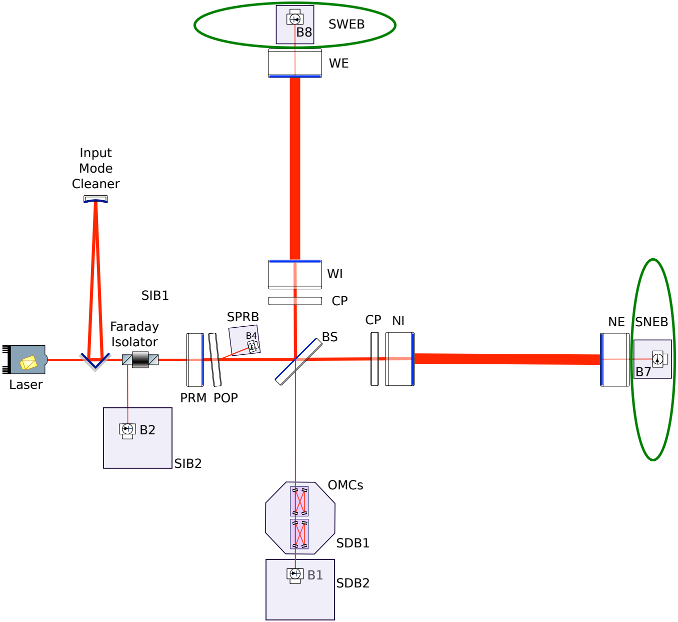




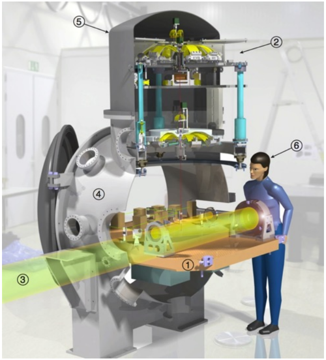
# Outline

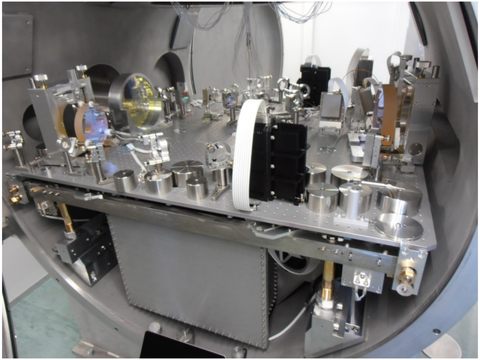
- Scattered light coupling model – 4 different paths
- Using scattered light to measure intereferometer optical parameters
- Subtraction of scattered light noise from O3 Advanced Virgo h(t) data
- Checking h(t) calibration accuracy with scattered light

# Advanced Virgo optical layout - end benches



# Scattered light from suspended end benches

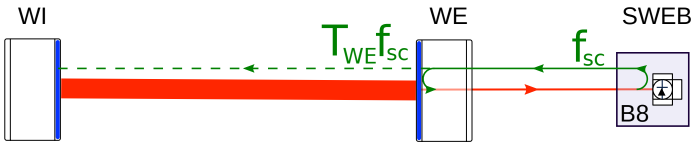


- Receiving beam transmitted by end mirrors
- 7 m behind end mirrors, suspended in separate vacuum chamber
- Tracking mirror position by pushing on the bench suspension point

⇒ No scattered light noise above 10 Hz in normal conditions

# Scattered light noise coupling fully reconstructed




- Scatter phase

$$\phi_{sc} = 4\pi \frac{x_{SWEB} - x_{WE}}{\lambda}$$

- Photodiode on bench sees amplitude modulation: $\cos\phi_{sc}$

$$P_{B8} = \alpha T_{WE} |E_0|^2 \left(1 + 2\sqrt{f_{sc}} \cos\phi_{sc}\right),$$

- Other quadrature of scatter phase can be reconstructed

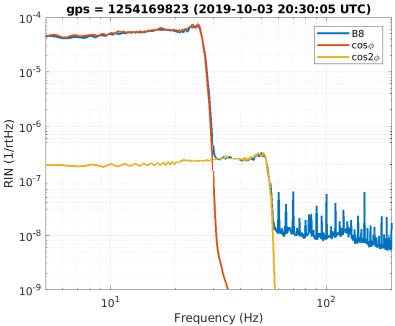
$$\cos\phi_{sc}(t) = \int_{-\infty}^{\infty} \hat{\phi}_{sc}(\omega) e^{i\omega t} d\omega$$

$$\sin\phi_{sc}(t) = i\,\mathrm{sign}\left[\frac{d\phi_{sc}(t)}{dt}\right] \int_0^{\infty} \left[\hat{\phi}_{sc}(-\omega)e^{-i\omega t} - \hat{\phi}_{sc}(\omega)e^{i\omega t}\right] d\omega.$$

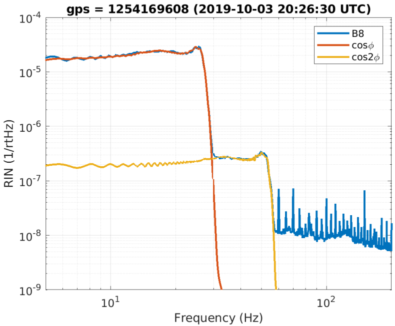
- Only requires adding direction of motion information from position sensors

# Scattered light measured with large SNR

QPD shutter open
$f_{sc} = 4 \times 10^{-8}$

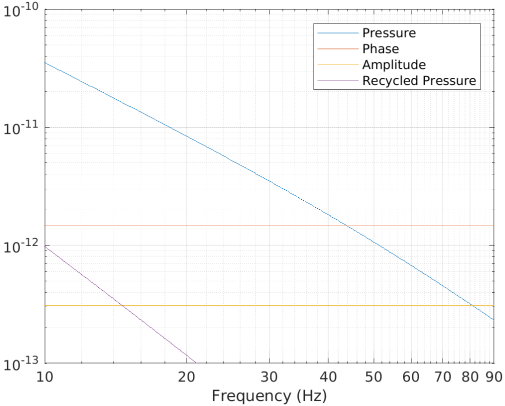



QPD shutter closed
$f_{sc} = 6 \times 10^{-9}$



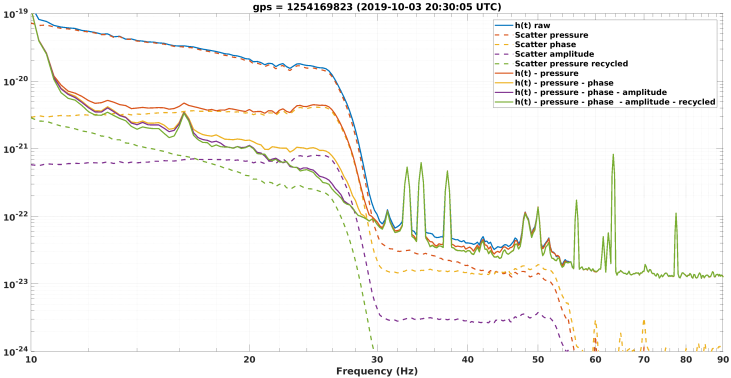

- Intentional 24 um bench motion at 0.1 Hz, single 3 minutes measurement
- Photodiode sensing noise >3 orders of magnitude below scattered light signal
- Dominated by light scattered by quadrant photodiode
- Shelf of scattered light from single and two round-trips can be seen

# 4 different coupling paths




- Derived analytically and confirmed with Optickle simulation
- Modulating phase of light in arms: $\sin\phi_{\mathrm{sc}}(t)$
- Modulating amplitude of light in arms: $\cos\phi_{\mathrm{sc}}(t)$
  - Coupled due to radiation pressure
  - Coupled due to contrast defect
  - Recycled in PR cavity and coupled due to radiation pressure

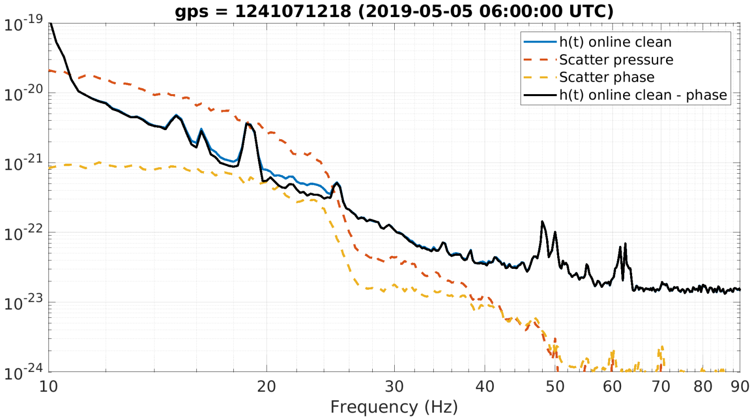
# Powerful interferometer characterization tool




- Intentional 24 um bench motion at 0.1 Hz, single 3 minutes measurement
- Fitting parameters can remove scattered light by up to factor 40
- Measure precisely several interferometer parameters

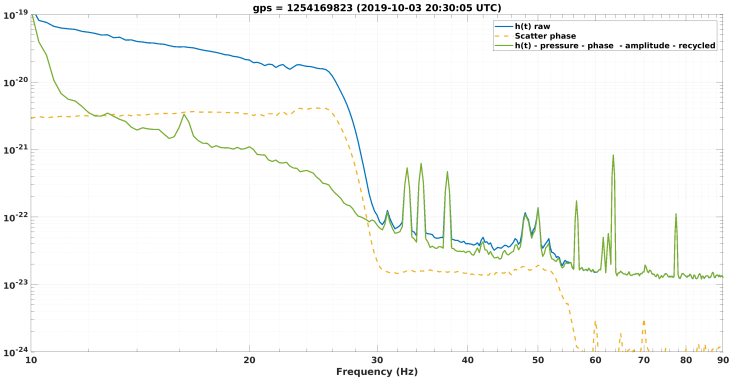
| | $T_{WE}$ (ppm) | arm power $\lvert E_0\rvert^2$ (kW) | contrast defect ($\mu$W) | power asymmetry (%) |
|---|---|---|---|---|
| SWEB injection | $4.34 \pm 0.04$ | $92.1 \pm 0.7$ | $95 \pm 8$ | $1.41 \pm 0.06$ |
| expected | $4.3 \pm 0.1$ | $90 \pm 5$ | $120 \pm 20$ | $\sim 1$ |

# Subtracting scattered light noise from O3 data




- SWEB suspension under-performing during O3
- In bad weather scattered light arches up to 50 Hz visible in h(t)
- Online subtraction was able to remove radiation pressure coupling path
  - Using linear coupling of $P_{\mathrm{B8}}$ auxiliary channel, removes $\cos\phi_{\mathrm{sc}}(t)$ component
- Adding reconstruction of $\sin\phi_{\mathrm{sc}}(t)$ allows to further reduce scattered light noise

# A check of calibration accuracy




- Transmission of end mirrors measured after coating with 2% precision

$$h_{\text{sc, phase}} = \frac{1}{L} T_{\text{WE}} \sqrt{f_{\text{sc}}} \frac{\lambda}{4\pi} \sin \phi_{\text{sc}} = \frac{1}{L} T_{\text{WE}} \frac{\lambda}{4\pi} \frac{\delta \tilde{P}_{\text{B8}}}{2 P_{\text{B8}}}$$

- Scattered light is an injection of calibrated light phase shift

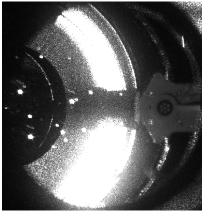
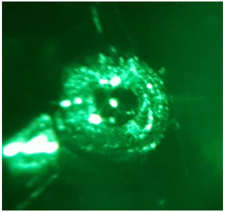
# A check of calibration accuracy

$$\frac{h_{\mathrm{rec}}}{h_{\mathrm{signal}}} = \frac{T_{\mathrm{WE}}}{T_{\mathrm{WE}}^{\mathrm{LMA}}} = \frac{4.34 \pm 0.04 \times 10^{-6}}{4.3 \pm 0.2 \times 10^{-6}} = 1.009 \pm 0.05.$$

$$\frac{h_{\mathrm{rec}}}{h_{\mathrm{signal}}} = \frac{T_{\mathrm{NE}}}{T_{\mathrm{NE}}^{\mathrm{LMA}}} = \frac{4.46 \pm 0.05 \times 10^{-6}}{4.4 \pm 0.1 \times 10^{-6}} = 1.014 \pm 0.025.$$

- Calibration checked with $2 - 5\%$ accuracy
- Limited by mirror transmission metrology
  - 10 times lower error achieved for squeezing filter cavity mirrors
- Higher amplitude motion $\rightarrow$ check h(t) accuracy as a function of frequency
- Completely independent from other calibration methods
- Other methods rely on mirror displacement
  - mirror actuators (magnets or electrostatic)
  - photon pressure (Pcal)
  - gravitational interaction (Ncal)

# Conclusion


- Scattered light is an inherent problem of interferometric GW detectors
- With good sensors and models scattered light noise can be removed from data in some cases
  - Has been done online during O3, but only for the $\cos\phi_{sc}$ component

⇒ Any installed photodiodes should have electronic noise below shot noise in the audio band

⇒ Quadrant photodiode can be a dominating source of scattered light

- Controlled scattered light injection is a tool to characterize the interferometer
- A new method to check the GW strain data calibration with potential $< 0.5\%$ precision

⇒ Requires good metrology of end mirrors transmission before installation
  - aLIGO, aVirgo changing mirrors for O5

https://arxiv.org/abs/2011.03539 – M Wąs et al 2021 Class. Quantum Grav. 38 075020

# 4 different coupling paths

- Photodiode on bench sees amplitude modulation: $\cos\phi_{\mathrm{sc}}$

$$P_{\mathrm{B8}} = \alpha T_{\mathrm{WE}} |E_0|^2 \left(1 + 2\sqrt{f_{\mathrm{sc}}}\cos\phi_{\mathrm{sc}}\right),$$

- Modulating phase of light in arms: $\sin\phi_{\mathrm{sc}}(t)$

$$h_{\mathrm{sc,\ phase}} = \frac{1}{L} T_{\mathrm{WE}} \sqrt{f_{\mathrm{sc}}} \frac{\lambda}{4\pi} \sin\phi_{\mathrm{sc}}$$

- Modulating amplitude of light in arms: $\cos\phi_{\mathrm{sc}}(t)$
  - Coupled due to contrast defect

$$h_{\mathrm{sc,\ amplitude}} = \frac{\epsilon}{\psi} \frac{1}{L} T_{\mathrm{WE}} \sqrt{f_{\mathrm{sc}}} \frac{\lambda}{4\pi} \cos\phi_{\mathrm{sc}}.$$

  - Coupled due to radiation pressure

$$h_{\mathrm{sc,\ pressure}} = \frac{G}{L} \frac{1}{M} \frac{1}{\Omega^2 - (2\pi f)^2} \frac{8|E_0|^2}{c} T_{\mathrm{WE}} \sqrt{f_{\mathrm{sc}}} \cos\phi_{\mathrm{sc}},$$

  - Recycled in PR cavity and coupled due to radiation pressure

$$h_{\mathrm{sc,\ pressure\ recycled}} = \rho\sqrt{T_{\mathrm{WI}}} \frac{G_{\mathrm{combined}}}{2} h_{\mathrm{sc,\ pressure}}$$