

Noise budget in Virgo

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- What is a noise budget?
- Noise budget in control loops
- Example of non-linear up-conversion: scattered light
- Two examples of electronic noises
 - ▶ Demodulation noise
 - ▶ Resistor flicker noise

What is a noise budget

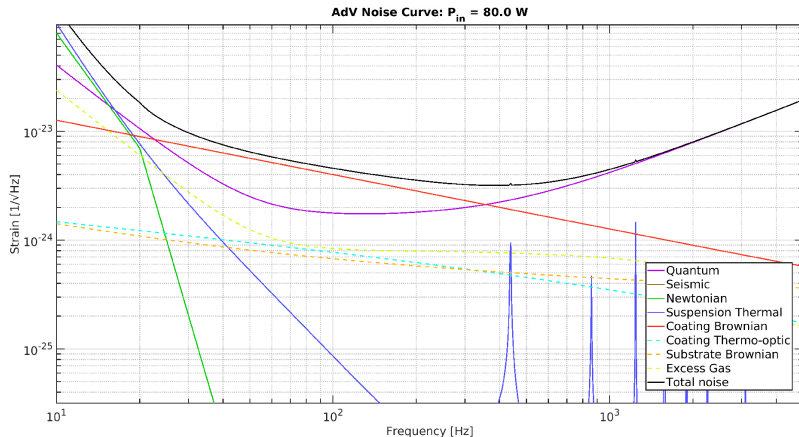
- Sum of instrumental noise sources contributing to the overall detector noise
- Product of two components
 - ▶ A physical process creating a noise
 - ▶ A coupling from the noise source to the detector output
- Simple analogy
 - ▶ Noisy road traffic outside your home
 - ▶ Two complementary paths to reduce noise inside
 - Close windows to reduce the coupling
 - Reduce speed limit on the road to reduce noise source

- Usually consider linear coupling

$$\text{noise contribution to strain} = TF_{\text{coupling function}} \times S_{\text{noise level}}$$

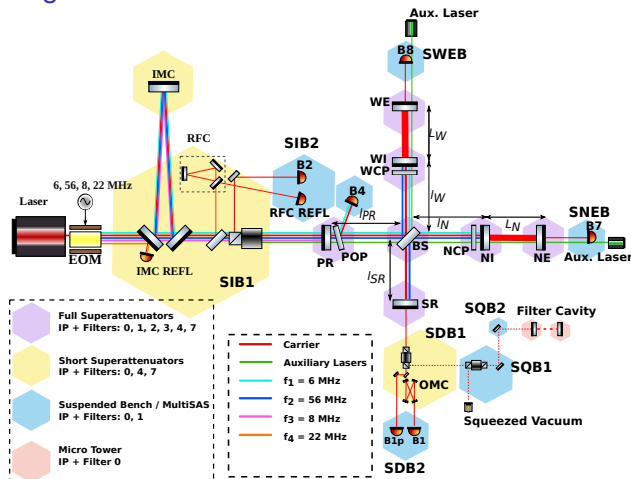
- Coupling function $TF_{\text{coupling function}}$
 - ▶ modeled - calculated response of a pendulum
 - ▶ modeled with several free parameters continuously measured
 - ▶ broadband measurement performed from time to time - assumes coupling constant
- Noise level $S_{\text{noise level}}$
 - ▶ modeled - quantum shot noise
 - ▶ measured offline once - electronic noise at output of card
 - ▶ measured online with auxiliary channels
- Noise sources independent $\Rightarrow$ add in quadrature all the noise contributions
- Non-linear couplings are sometimes also included in noise budget

Theoretical noise budget



- Theoretical noise budget used for detector designs
- Fundamental noises only - not dependent on details of detector implementation
- Theoretical calculation informed by material measurements
- Coating thermal noise
 - ▶ Fluctuation-dissipation theorem and measured losses of materials
 - ▶ Also measured directly on deposited full stack coatings

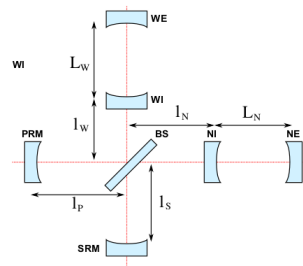
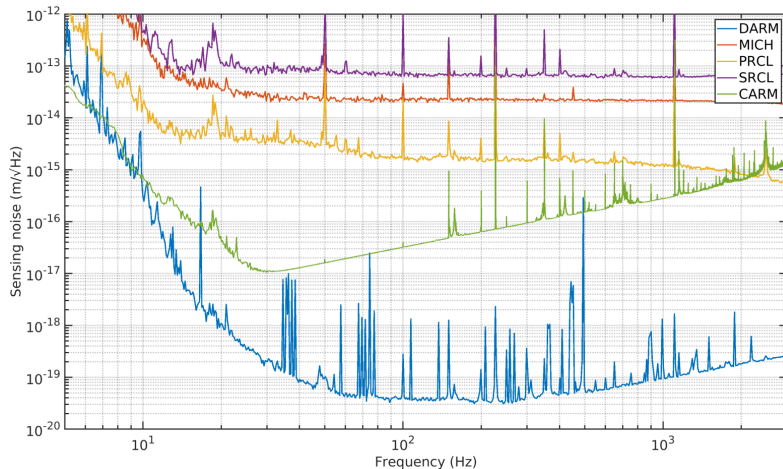
Experimental noise budget



• Several classes of noises in addition to fundamental noises

- ▶ Control noises - noise injected to mirrors to maintain them on resonance
- ▶ Electronic noises - sensing and actuation uses electronics that add noise to the signal
- ▶ Environmental noises - local disturbances that manage to partially bypass mirrors mechanical isolation
- ▶ Up-conversion - non-linear coupling converting large noise at frequency that does not matter to more broadband noise that matters

Sensing noise

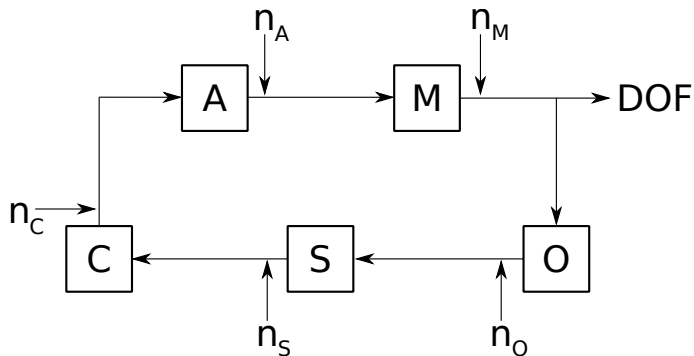


- $DARM = L_N - L_W$
- $MICH = l_N - l_W$
- $PRCL = l_P + \frac{l_N + l_W}{2}$
- $SRCL = l_S + \frac{l_N + l_W}{2}$
- $CARM = \frac{L_N + L_W}{2}$

- Main other degrees of freedom sensing noise
- 3 to 6 orders of magnitude above differential arm length
- also 3 to 6 orders of magnitude above uncontrolled mirror motion

⇒ all motion of mirrors is due to control loops pushing on suspended mirrors

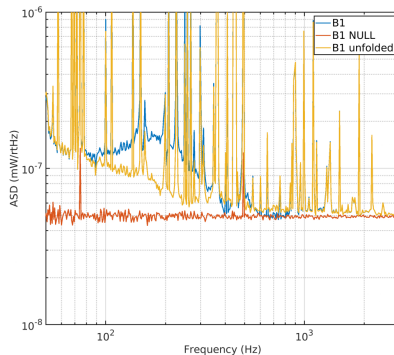
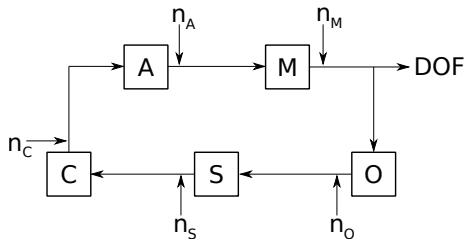
Control loop



$$\text{DOF} = n_M + M \cdot n_A + MA \cdot n_C + MAC \cdot n_S + MACS \cdot n_O + \underbrace{MACSO \cdot \text{DOF}}_L$$

- n_O - noise of optical response (optical field sensitive to other degrees of freedom, scattered light, ...)
- n_S - noise of optical sensor (dark noise, resistors, analog to digital conversion, ...)
- n_C - noise of controller (numerical computation noise, floating number precision, ...)
- n_A - noise of actuator (digital to analog conversion, operating amplifiers, resistors, cross talk, ...)
- n_M - noise of mirror (thermal noise, bonding relaxation, external magnetic fields, ...)
- $L = MACSO$ - open loop transfer function

Control loop

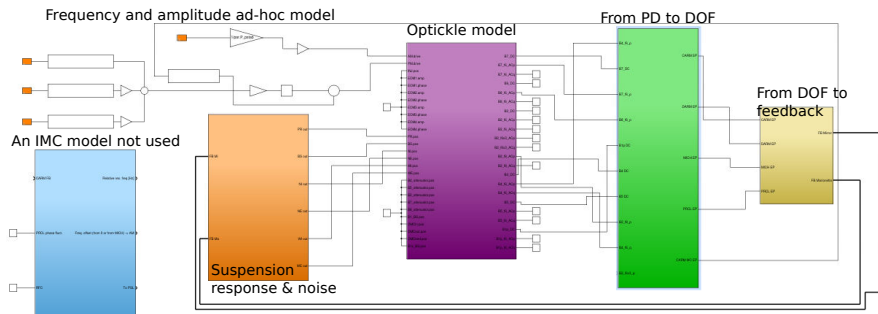


$$DOF = n_M + M \cdot n_A + MA \cdot n_C + MAC \cdot n_S + MACS \cdot n_O + \underbrace{MACSO \cdot DOF}_L$$

$$DOF = \frac{1}{1-L} n_M + \frac{M}{1-L} n_A + \frac{MA}{1-L} n_C + \frac{MAC}{1-L} n_S + \frac{MACS}{1-L} n_O$$

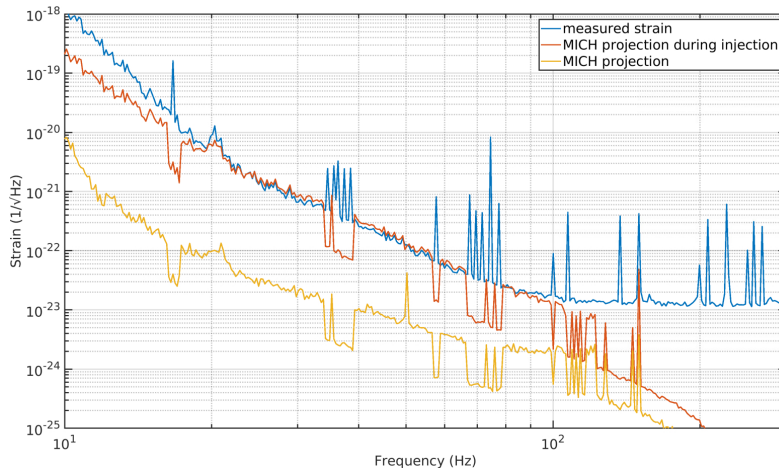
- Control loop shapes noise of degree of freedom, external forces and calibration have $\frac{1}{1-L}$ factor
- High control gain removes only some of the noises: $DOF \xrightarrow{C \rightarrow \infty} -\frac{1}{SO} \cdot n_S - \frac{1}{O} \cdot n_O$
- Replacing numbers by matrices and vectors allows to model multiple coupled degrees of freedom

Virgo Simulink noise budget



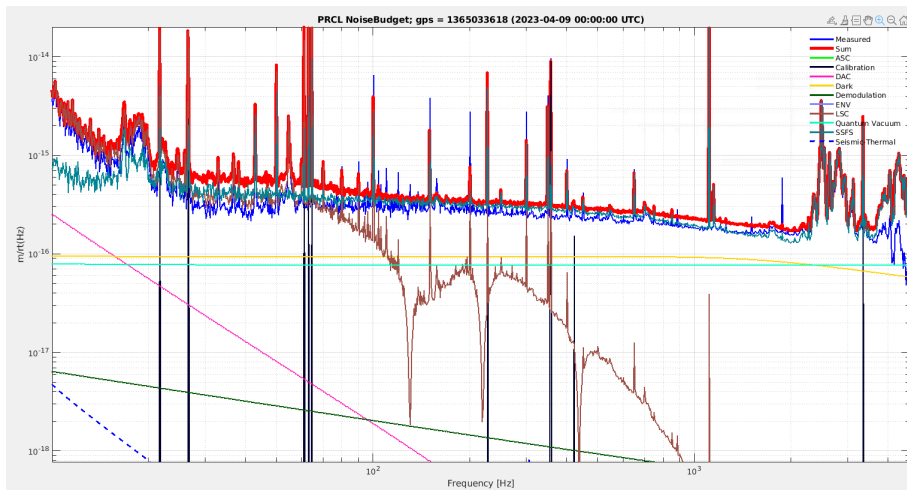
- Main longitudinal control loops implemented in Matlab/simulink
 - ▶ Optical response simulated using plan waves including radiation pressure (Optickle)
 - ▶ Each suspension implemented using two degree state space model (mirror + marionette)
 - ▶ Control filters measured from actual data, transfer function of recorded signals at input and output of filters
 - Filter changes happen often, but requires additional data reading
 - ▶ Coupling between degrees of freedom measured experimentally
- Each noise added in physical units in the right place in the diagram; n_M , n_A , n_C , n_S , n_0
- Alignment control not implemented as $L \ll 1$ above 10 Hz so loop shape doesn't matter

Coupling between degrees of freedom



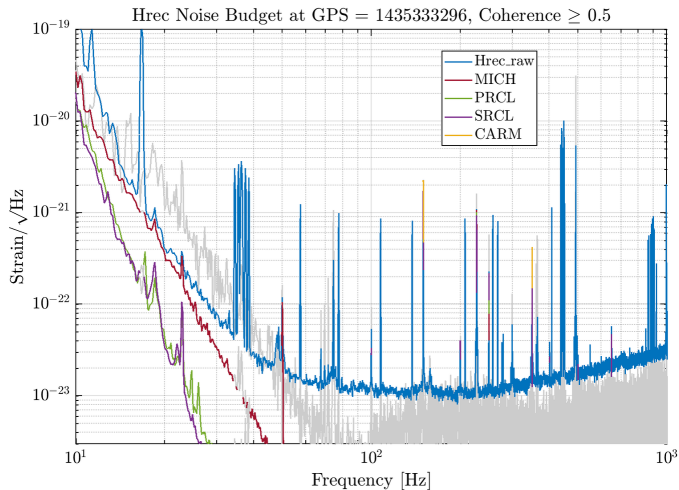
- Coupling between degrees of freedom is small, due to optical defects
 - ▶ Small off-diagonal elements on the O matrix
- Main part of coupling is actively suppressed through feed-forward
 - ▶ Equivalent to adding small off-diagonal elements on the C matrix
- Residual coupling cannot be modeled, relying on measurements
 - ▶ Intentionally adding noise into degree of freedom to measure coupling

Risks of noise double counting



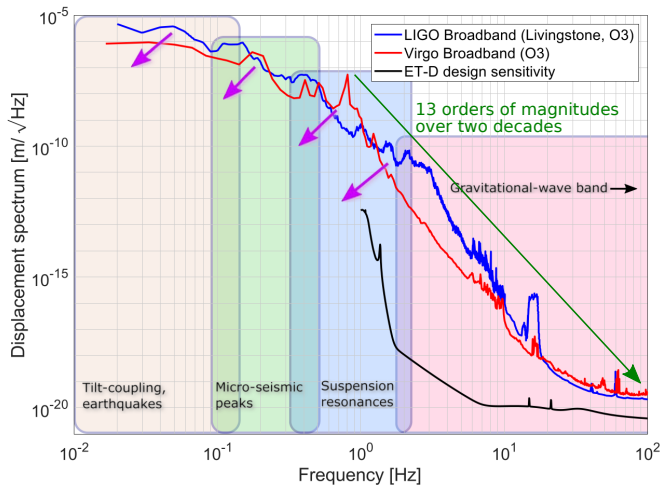
- Can count each individual noise component of the degree of freedom
- Or count the total measured noise which includes are individual components
- Total is complete but hides the noise physical origin
- Total also doesn't fit the loop model as noise has to be added in single point

Often using the simpler alternative



- Measured noise level of auxiliary degrees of freedom
- Measured coupling to GW strain signal
- Yields accurate noise budget but no detailed understanding
- No need to maintain detailed model

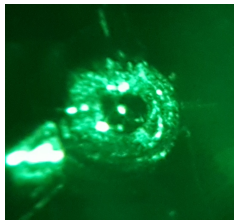
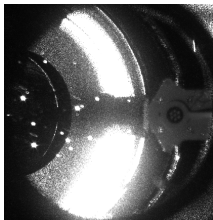
Upconversion



- Excellent seismic isolation creates a high dynamic signal
- 13 orders of magnitude between motion below 1 Hz and sensitivity at 100 Hz
- 10 orders of magnitude between 1 Hz and 10 Hz

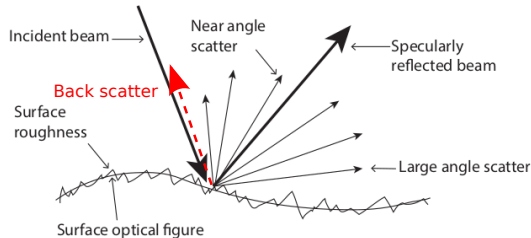
⇒ small non-linearity matters

Scattered light in GW detectors



- A limitation of all interferometric GW detectors ever built
- Sensitive to phase difference between arms of $\sim 10^{-12}$ rad
- ⇒ A stray optical field of 10^{-12} relative amplitude can spoil the sensitivity
- ⇒ A stray optical power of $100 \text{ kW} \times 10^{-24} = 10^{-19} \text{ W}$
- ⇒ One photon per second with 1064 nm wavelength

Relation between f_{sc} , BRDF and TIS



- Total integrated scatter (TIS) is the integral of bidirectional reflectance distribution function (BRDF)

$$\text{TIS} = \int_{\theta} \text{BRDF}(\theta) 2\pi \cos \theta \sin \theta d\theta$$

- f_{sc} - fraction of impinging light that back-scatters and interferes with main beam
BRDF related to f_{sc} through beam divergence solid angle

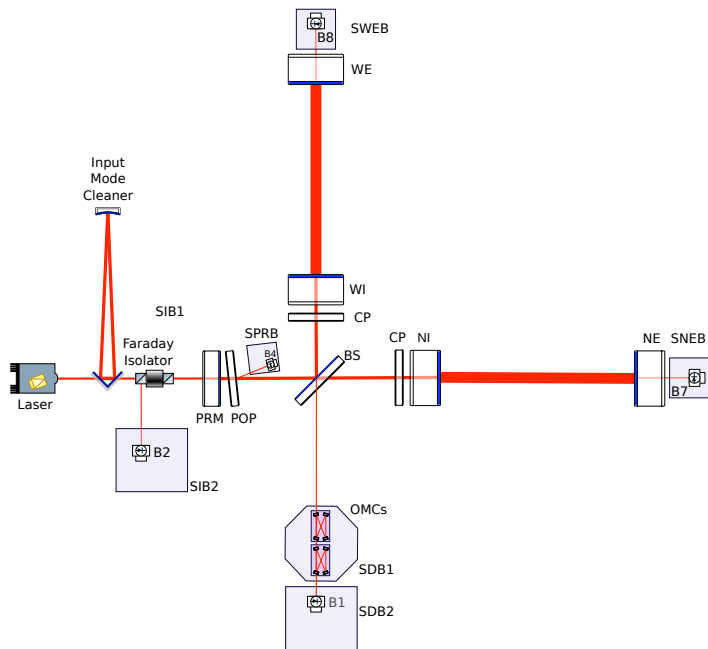
$$f_{sc} = \text{BRDF}(\text{AOI}) \pi \left(\frac{\lambda}{\pi w_0} \right)^2$$

w_0 beam waist

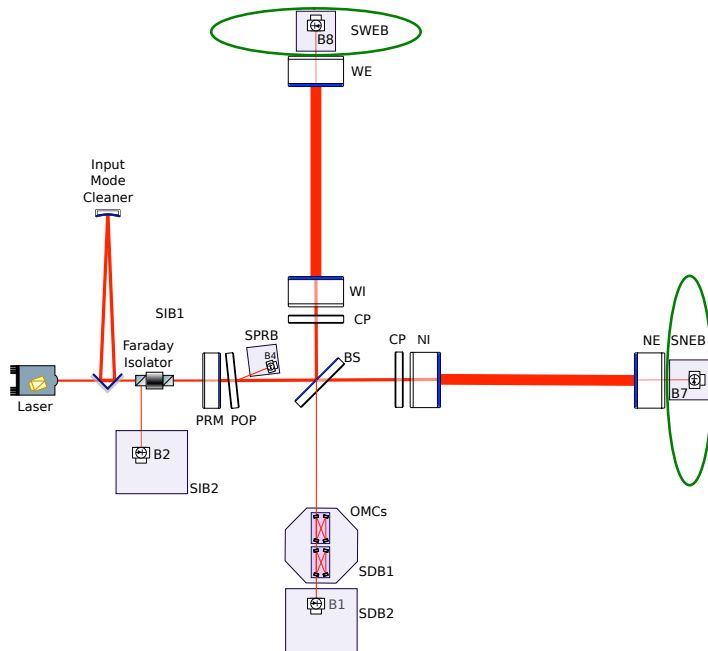
- Perfect reflective diffuser $\text{BRDF} = \frac{1}{\pi} \simeq 0.3$, typical beam $w_0 = 320 \mu\text{m}$

$$\Rightarrow f_{sc} \simeq 10^{-6}$$

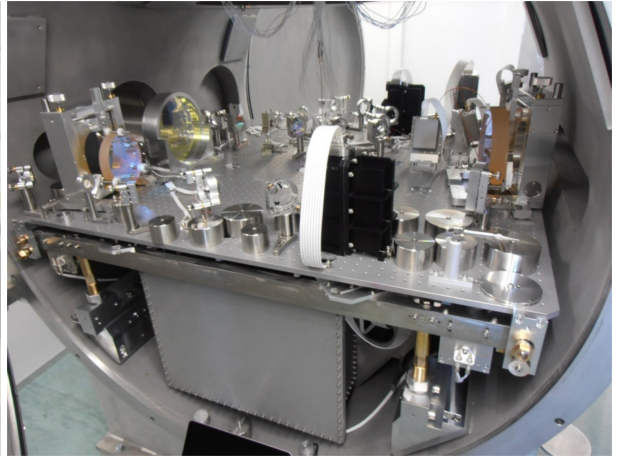
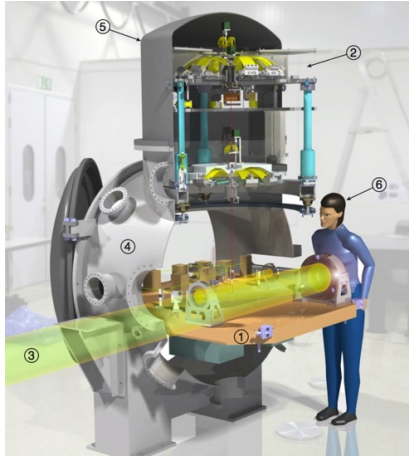
Advanced Virgo optical layout



Advanced Virgo optical layout



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
- ▶ But scattered light when high waves on the sea of Tuscany

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

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

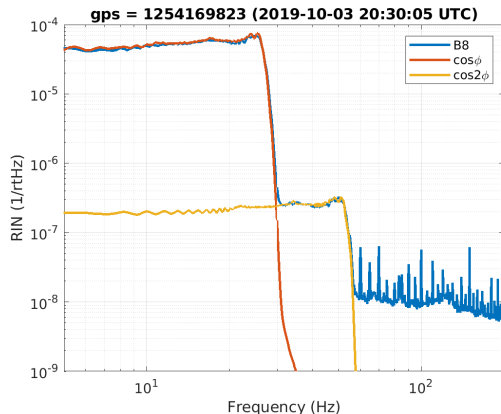
$$\sin \phi_{sc}(t) = i \operatorname{sign} \left[\frac{d\phi_{sc}(t)}{dt} \right] \int_0^{\infty} [\hat{\phi}_{sc}(-\omega) e^{-i\omega t} - \hat{\phi}_{sc}(\omega) e^{i\omega t}] d\omega.$$

- Requires adding information on direction of motion from position sensors

Scattered light measured with large SNR

quadrant shutter open

$$f_{\text{SC}} = 4 \times 10^{-8}$$



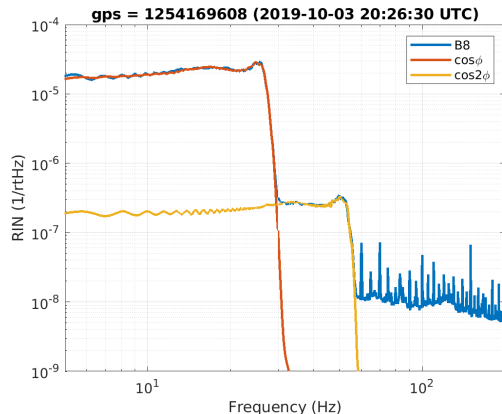
- Intentional 24 μm bench motion at 0.1 Hz
- Shelf of scattered light from single and two round-trips can be seen

$$f(t) = \frac{2\dot{x}_{\text{SWEB}}}{\lambda}$$

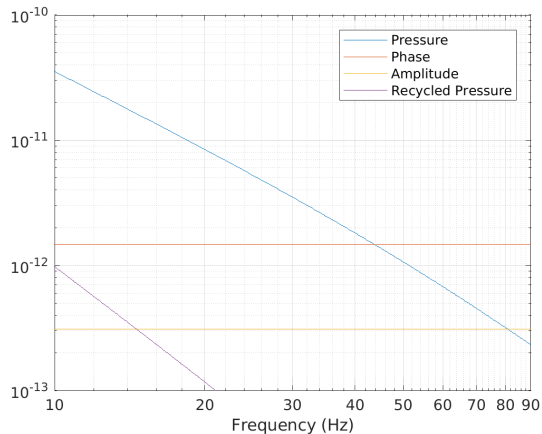
- Direct back-scatter dominated by light scattered by quadrant photodiode
- Two round trip back-scatter independent of quadrant photodiode

quadrant shutter closed

$$f_{\text{SC}} = 6 \times 10^{-9}$$

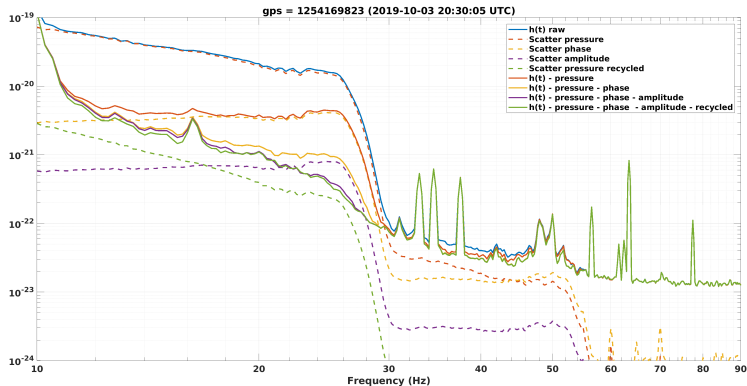


4 different coupling paths



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

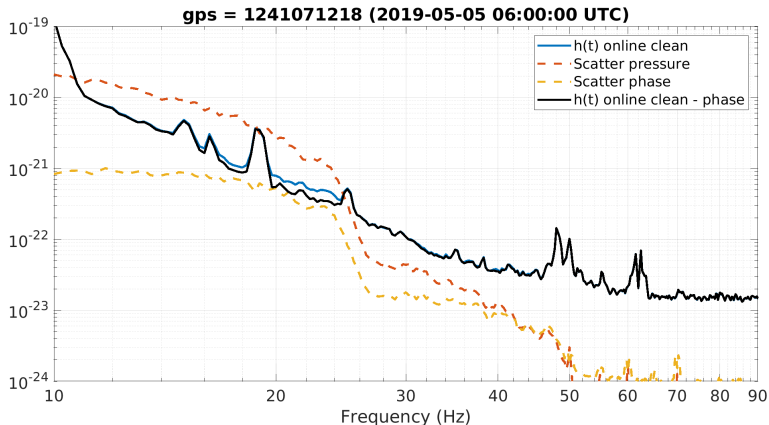
Powerful interferometer characterization tool



- Intentional 24 μm 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

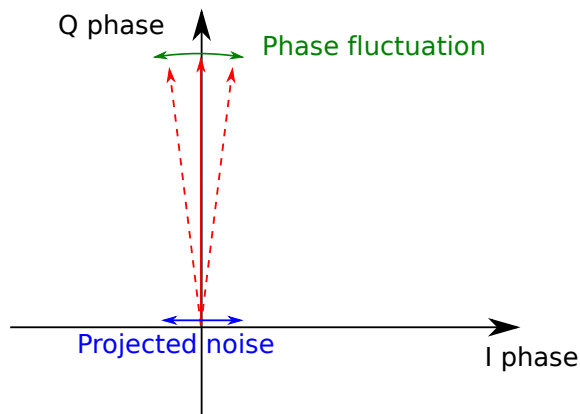
	T_{WE} (ppm)	arm power $ E_0 ^2$ (kW)	contrast defect (μW)	power asymmetry (%)
SWEB injection	4.34 ± 0.04	92.1 ± 0.7	95 ± 8	1.41 ± 0.06
expected	4.3 ± 0.1	90 ± 5	120 ± 20	~ 1

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_{B8} auxiliary channel, removes $\cos \phi_{sc}(t)$ component
- Adding reconstruction of $\sin \phi_{sc}(t)$ allows to further reduce scattered light noise
- Resolved for O4 by upgrading accelerometers in bench suspension

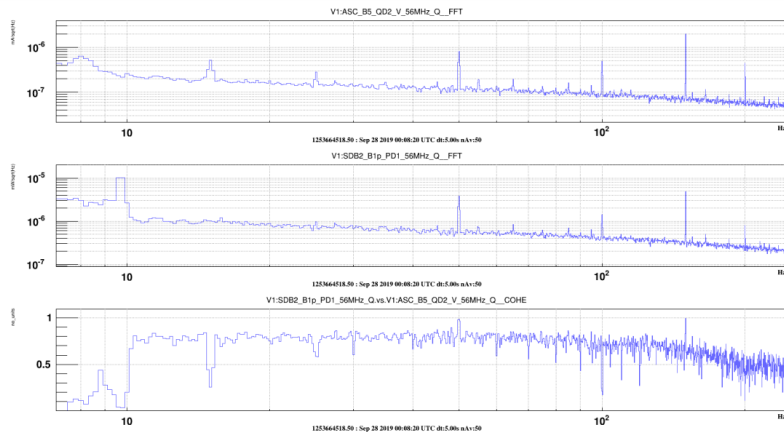
Demodulation phase noise



- Radio-frequency demodulated signals have two quadratures (sine and cosine wave)
- One quadrature used in control, but other quadrature may be large (poorly controlled degree of freedom, intentional offset,...)
- Demodulation phase noise mixes the two quadratures
- In Advanced Virgo RF demodulation is done digitally (very flexible)
- Demodulation phase noise due to timing noise on 400 MHz ADC

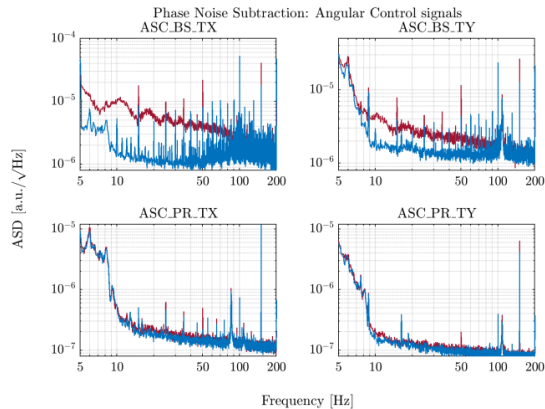
Demodulation phase noise

dataDisplay v10r9p3 : started by mwas on Nov 5 2019 13:50:01 UTC



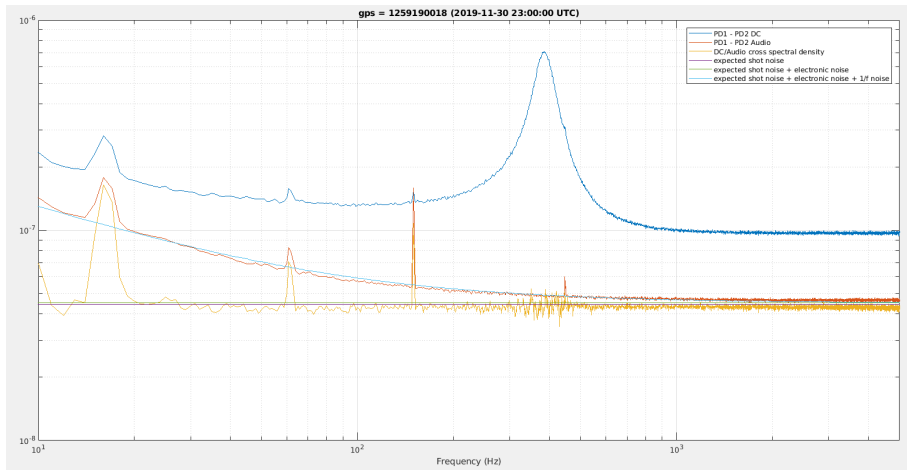
- Noise picked up during timing signal propagation from GPS clock to ADC boards (suspended in vacuum)
- Coherent across all PDs/QPDs located on same optical bench (sharing timing signal)
- A factor 10 above RF source phase noise

Demodulation phase noise mitigation



- Better timing signal (10 MHz clock → 100 MHz clock)
 - Replace copper wire by optical fibers
 - Put both quadrature in loop, thermal tuning of interferometer to reduce need for offsets
- ⇒ Subtract phase noise measured with different PDs, or using 2f signal
- Strategy successfully used also for main longitudinal signals

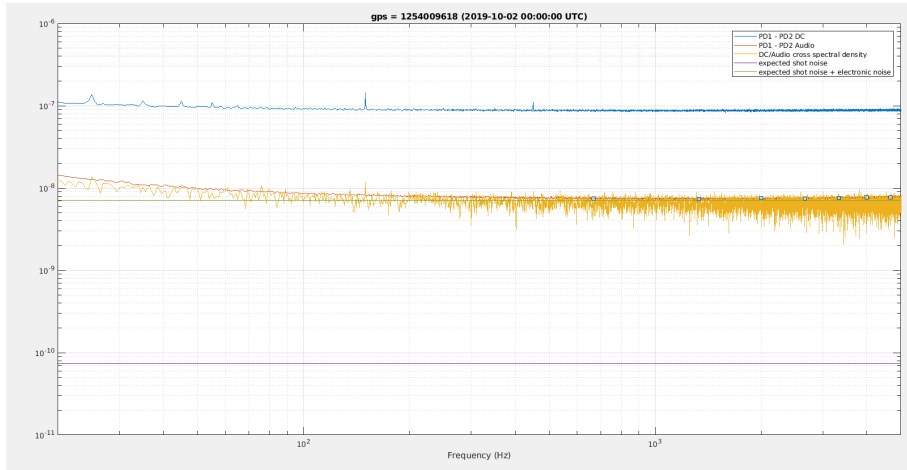
Flicker noise measured in DC PD difference



- Spectrum of difference of two B1 photodiode (red), 2mW per photodiode
- Shows excess at low frequency fitted with flicker noise + quantum shot noise (cyan)
- $5.3 \times 10^{-8} / \sqrt{F/40}$ mW/rtHz

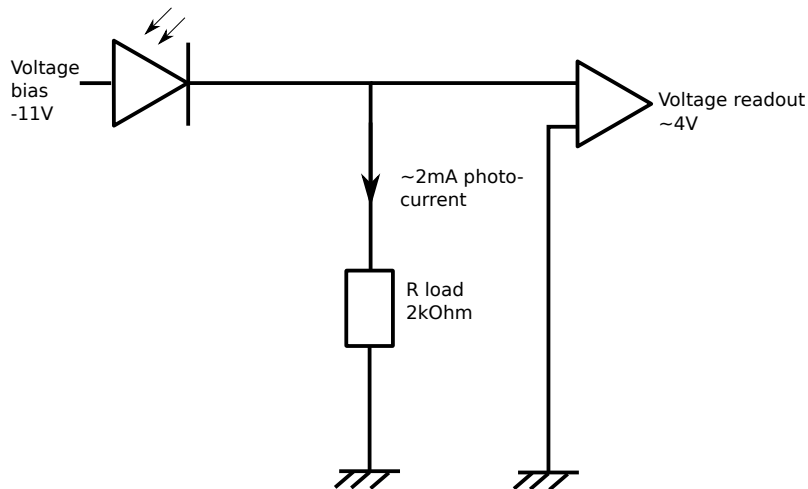
<https://logbook.virgo-gw.eu/virgo/?r=47313>

Noise not present in dark conditions



- Noise not present when only voltage bias enabled but no light

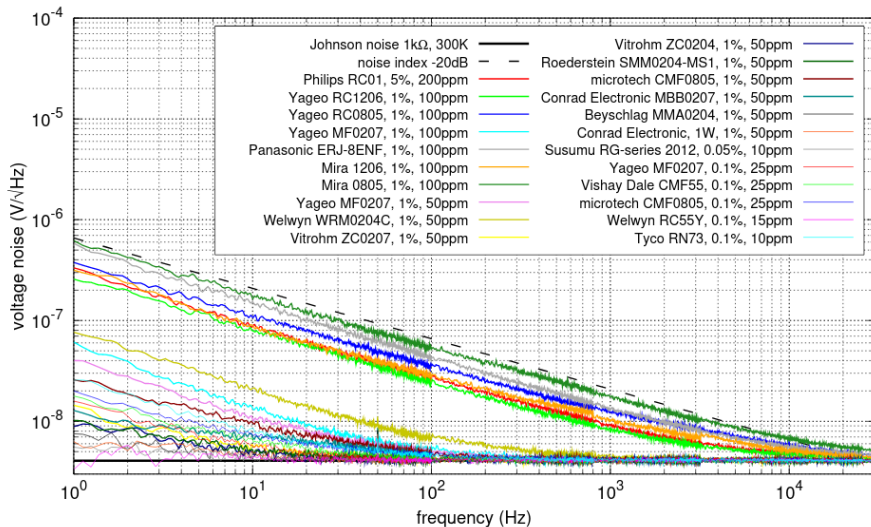
Simplified photodiode schematics



- Potential flicker noise sources

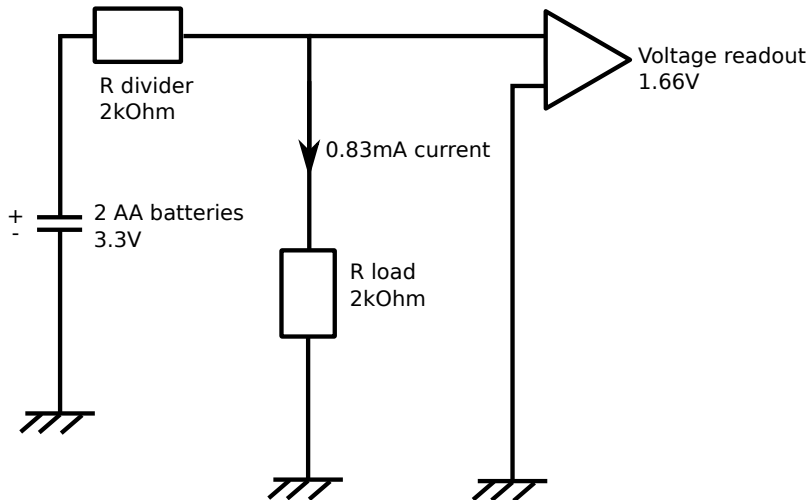
- ▶ Voltage bias
- ▶ Photodiode
- ▶ Load resistor
- ▶ Rest of read-out chain

Resistor flicker noise



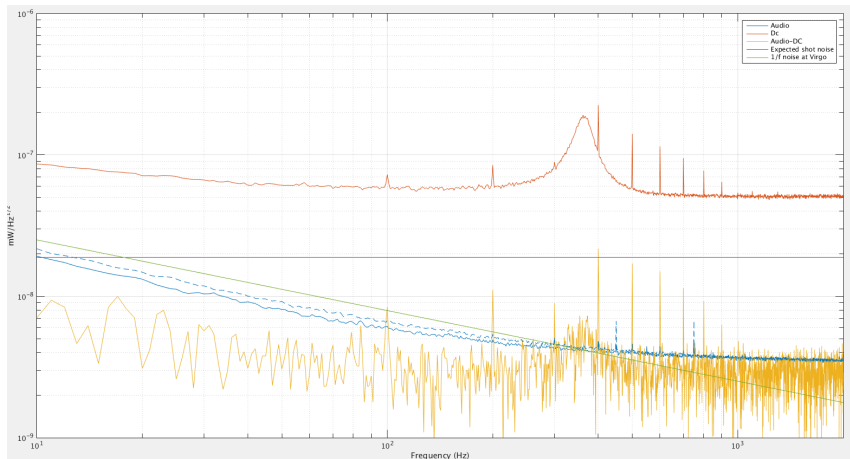
- Example of measured resistor noise depending on technology and manufacturer (LIGO-T0900200)
- Proportional to voltage drop across resistor

Test of load resistor and read-out chain - no PD



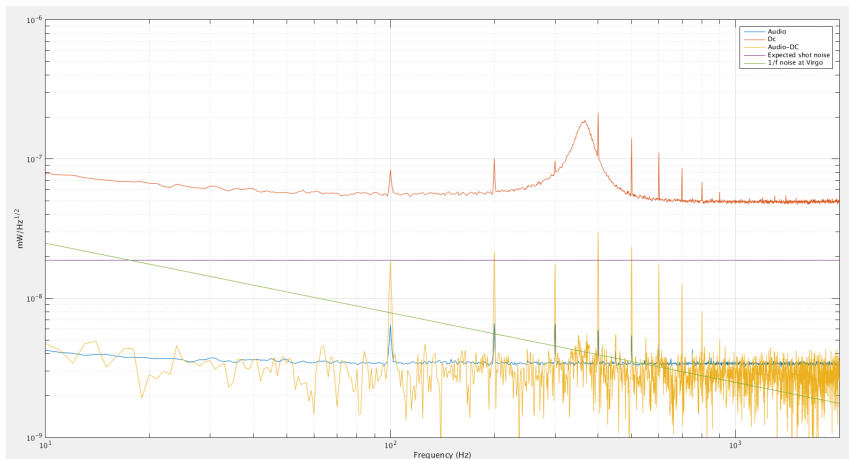
- Measure voltage noise: $\delta V = i \frac{\delta R_{divider} + \delta R_{load}}{R_{divider} + R_{load}}$
- Current provided by battery and voltage divider
- Battery is a voltage source $\Rightarrow$ shot noise is suppressed

Test of load resistor and read-out chain - no PD



- Blue – measured noise for two different identical voltage divider
 - ▶ There is $\sim 10\%$ variability between resistors
- Green – Flicker noise at the site divided by 2
1 PD instead of 2 and voltage divider setup)
- Yellow – DC and Audio spectrum are not coherent

Test of load resistor and read-out chain - thin film resistors



- No flicker noise measured with thin film resistors
- Confirmed after replacing PD electronics at Virgo

Conclusions

- Noise budget is never exhaustive
 - ▶ Model main issues, either expected or encountered in practice
- Successful noise budgets become quickly obsolete
 - ▶ Once a noise is sufficiently understood it can be removed from the instrument
- Noise subtractions are a challenge for noise budget
 - ▶ Main noise removed, but residual noise or replacement noise to model