Squeezed Angle Fluctuations: Experiment

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Description	Looking at data from the aLogs, can we explain the squeezed angle fluctuations with an equation?

1. LIGO Alogs

- https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=49026
- https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=80194
- https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=85358

What was seen?

Changes in the alignment of squeezer optics (particularly the ZM5 and ZM6 mirrors) cause substantial shifts in both the demodulation phase of the coherent locking field (CLF) and the actual squeezing angle measured at the **interferometer**.

Moving ZM5 and ZM6 by microradians required a compensating 45-degree shift in the CLF demodulation phase.

More strikingly, alog 85358 shows that 30 microradians of ZM6 yaw produces nearly 4 degrees of squeezing angle change.

Why?

Recall the higher-order mode coupling: misalignments create non-zero amplitudes in TEM_ij modes, and the Gouy phase differences φ_ij between these higher-order modes in the interferometer beam versus the CLF beam cause locking point errors. Static misalignment amplifies the effect of beam jitter (equation 5.54), making this a first-order rather than second-order effect.

Attempted Fixes

People in the alogs tried to manually adjust the CLF demodulation phase to re-optimize squeezing, as seen in **alog 80194** where they needed to shift the phase by 45 degrees after an alignment change. **Alog 85358** describes another approach: using the Output Mode Cleaner (OMC) transmission RF3 signal to control the squeezing angle, which should theoretically reduce higher-order mode contamination? They implemented an "SQZ to IFO ASC" system where the SQZ ASC guardian controls specific alignment degrees of freedom (AS42 B for ZM4 pitch/yaw, AS42 A for ZM6) to minimize squeezing angle drift during interferometer alignment changes. **Alog 49026** shows attempts to characterizing the coupling empirically: measuring squeezing/anti-squeezing versus CLF angle to fit the relationship:

$$\phi_{\mathrm{SQZ}} = 2\cos^{-1}\left(\frac{\cos(\phi)}{\sqrt{\cos^2(\phi)+r^2\sin^2(\phi)}}\right) + \phi_{\mathrm{Ofs}} \quad \text{with} \quad \phi = \frac{\phi_{\mathrm{demod}}+\phi_0}{2} \bmod \pi$$

where r is the ellipse axis ratio related to nonlinear gain. However, none of these fixes address the root cause.

Tests to Try and Characterize This

- Would want to map the couplings in a systemic way- for each degree of freedom- to understand

Understand Coupling

- Could perform a scans of each optic mentioned (ZM4, ZM5, ZM6) in all degrees of freedom (pitch, yaw) while measuring both the required CLF demodulation phase shift and the true squeezing angle

  - **How?** They used a variance-based method in section 5.4.5 of Shiela's thesis to measure the fluctuations.
  - Plot these to identify which optics and which modes dominate the coupling. A given angular misalignment should produce $\Delta\varphi$_demod and $\Delta\theta$_sqz related by factors involving the Gouy phase
    - Could try testing whether 30 µrad of ZM6 yaw consistently produces ~4° of squeezing angle shift
    - If it doesn't I'm not sure how you could ever predict the required compensation

$$\frac{dV}{d\theta} = (V_+ - V_-) = 8\eta_{tot} x \frac{1+x^2}{(1-x^2)^2}$$

  - The variance should be linear in the squeezing angle around θ = 90, where the slope is given by the above equation.
  - This slope increases as x approaches 1, so this measurement will have the best signal to
    noise ratio at high nonlinear gains.
  - By taking a spectrum of the variance time series and calibrating it in terms of squeezing angle fluctuations, we can directly measure a spectrum of squeezing angle fluctuations.
  - This method provides an out of loop sensor for the squeezing angle fluctuations, which can be compared to the spectrum of squeezing angle fluctuations measured by the squeezing angle sensor.
- Somehow monitoring this variance in real time and use this as feedback to continuously correct the CLF demodulation phase?

Understand Misalignment State

- If we knew the spatial mode content of both the squeezer beam and the interferometer beam at the location where they interfere we can determine γ̄_ij^(clf) and γ̄_ij^(ifo) for the dominant higher-order modes

- Equation 5.53 predicts the locking point error, which can verified against measurements.

$$
\begin{aligned}
\Delta\phi &= \frac{\sum_{ij}\gamma_{ij}^{ifo}\gamma_{ij}^{clf}\sin\phi_{ij}}{(1+\sum_{ij}\gamma_{ij}^{ifo}\gamma_{ij}^{clf}\cos\phi_{ij}})\\
&\approx \sum_{ij}\gamma_{ij}^{ifo}\gamma_{ij}^{clf}\sin\phi_{ij}
\end{aligned}
$$

Systems

- **Alignment control (ASC)**: adjusts mirrors (ZM4, ZM5, ZM6, etc.)
- **Squeezing angle control (CLF servo)**: adjusts the demodulation phase to keep squeezing optimized
- Want some situation where “I know alignment moved by X, and I know that causes squeezing angle error Y, I'll pre-compensate by -Y”?