Improving LIGO’s Performance with the OSEM Estimator

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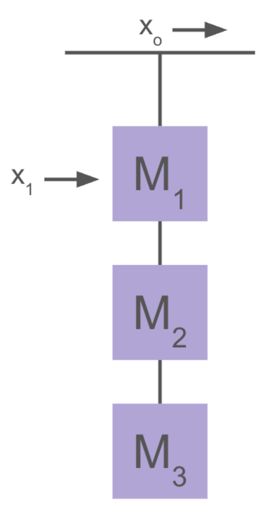
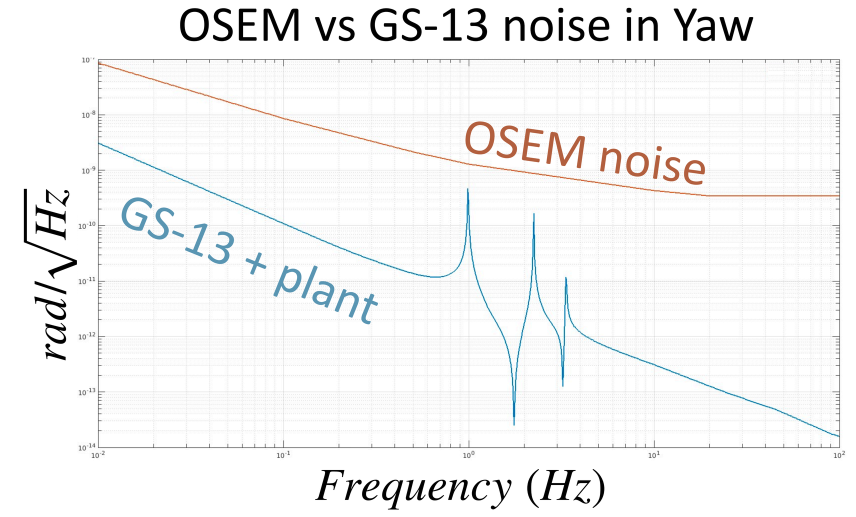
Introduction

LIGO detects gravitational waves, tiny spacetime ripples that shift its mirrors by just 1/1000 the diameter of a proton. To measure this, the mirrors are stabilized with passive and active isolation. Optical sensor electromagnetic motors (OSEMs) provide active control but add noise above 1 Hz, limiting sensitivity. Our project seeks to implement an OSEM Estimator on Signal Recycling Mirror 3 (SR3) in yaw and pitch to reduce this noise, with future deployment on LIGO’s main test masses. SR3 is well-suited for tests since it has a lower-noise witness sensor.



The OSEM measures the gap between the suspension point and the mass M1: gap = x_o - x_1

OSEM vs GS-13 noise in Yaw

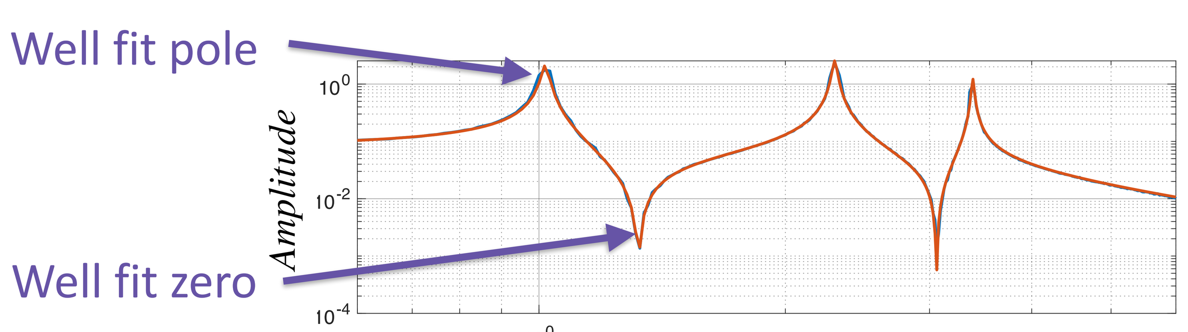


Motion of the suspension is the blue trace, which is, at the least, a factor of 5 below OSEM noise, making it difficult to get accurate measurements

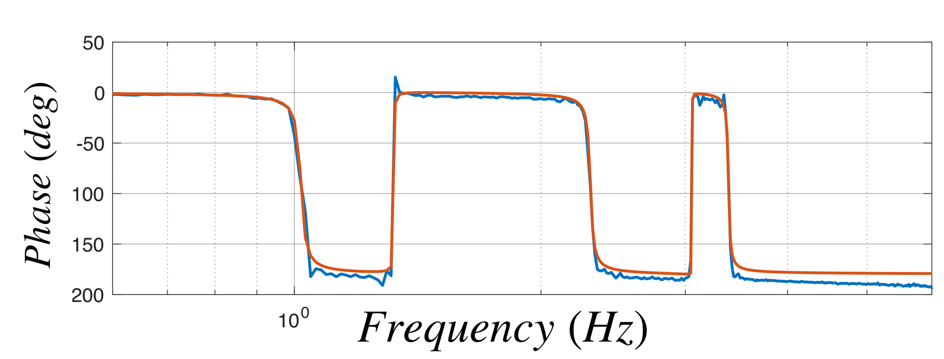
Methods

My time was split into three main parts:

1. **Transfer function fitting:** We selected and implemented the best algorithm for transfer function fitting, which we determined to be Vectfit3. This program requires minimal manual adjustment for an optimal fit.

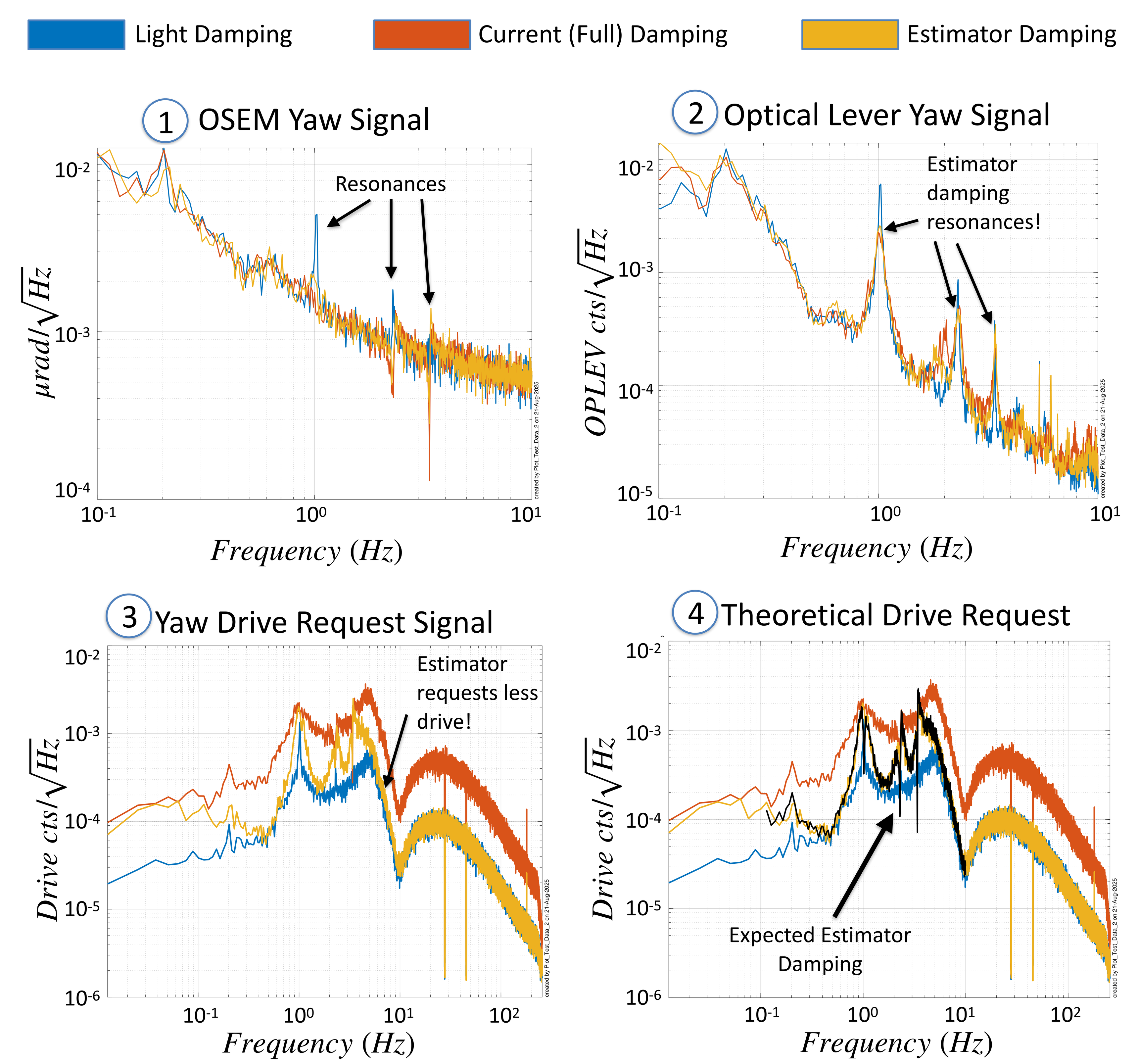


★Strongly weight the fit by 1/zeros



2. **Test analysis:** Analyzed data from tests that operators run on SR3, comparing estimator damping, light damping, and full damping modes.
3. **Result verification:** Calculated theoretical contributions to the estimator drive request to confirm experimental behavior.

Results Without the interferometer on lock



Discussion

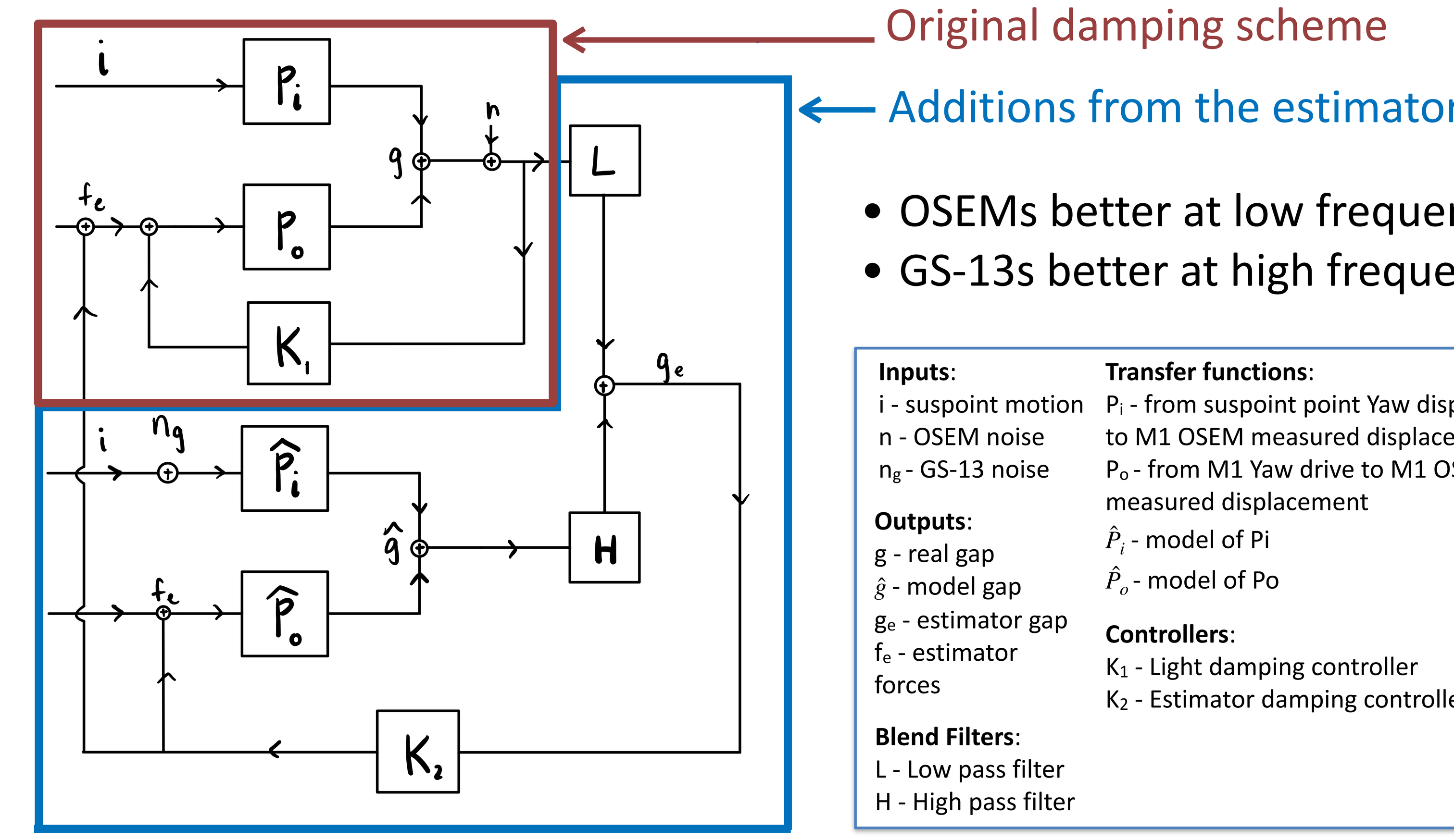
1. While the OSEM signal is dominated by its own noise, the estimator damping is visible in the resonance at 1 Hz.
2. The optical lever is a witness sensor with lower noise than OSEMs, so the yaw motion is more visible. It is more clear the estimator damps the resonances.
3. The estimator damping reduces drive above 5 Hz and by about a factor of five, leading to less overall yaw motion as expected.
4. The estimator damping drive request matches the theoretical expectation with little error, indicating the estimator is working as intended!

Conclusion

We implemented the OSEM estimator on the LIGO Hanford SR3 suspension. Estimator tests show promising reductions in angular noise, motivating further tests on other suspensions and degrees of freedom. We remain hopeful it will continue to perform well as we anticipate further installation.

More Methods

A block diagram of the OSEM Estimator



- OSEMs better at low frequencies
- GS-13s better at high frequencies

Inputs:
i - suspoint motion
n - OSEM noise
n_g - GS-13 noise

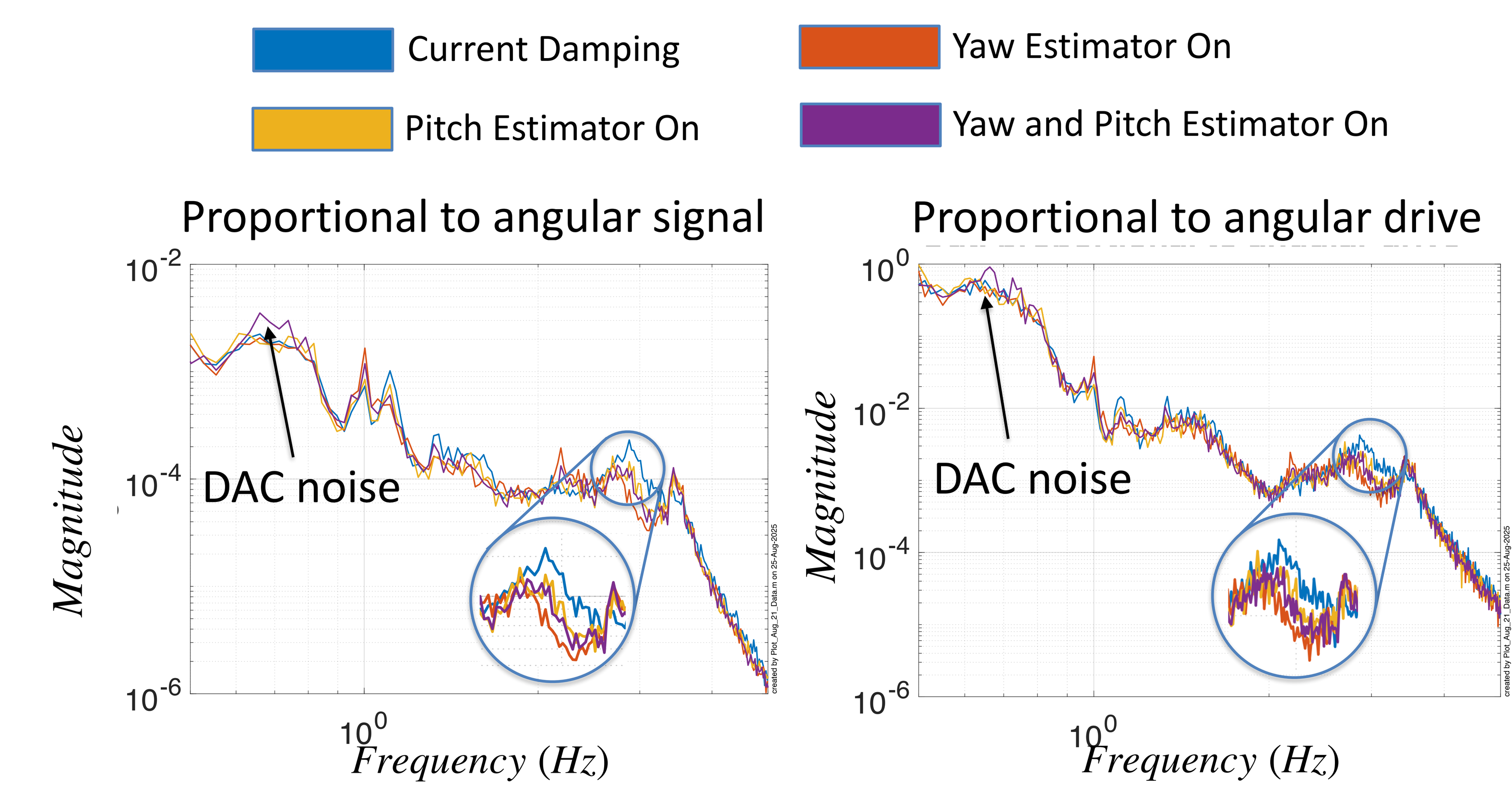
Outputs:
g - real gap
$\hat{g}$ - model gap
g_e - estimator gap
f_e - estimator forces

Blend Filters:
L - Low pass filter
H - High pass filter

Transfer functions:
P_i - from suspoint point Yaw displacement to M1 OSEM measured displacement
P_o - from M1 Yaw drive to M1 OSEM measured displacement
$\hat{P}_i$ - model of Pi
$\hat{P}_o$ - model of Po

Controllers:
K_1 - Light damping controller
K_2 - Estimator damping controller

More Results With the interferometer on lock



The estimator was implemented on only 1 of 6 suspensions in SRC. It’s impact was not expected to be visible, but it is!

https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=86507

References

1. Garver, P., Bonilla, E., & Lantz, B. (2024, November 20). *S1ISI Estimator Design* (LIGO-T2500016-v1). Stanford LIGO Group. LIGO Document Control Center.
2. Bonilla, E., Garver, P., Lantz, B., Engl, A., & Kissel, J. (2024). *OSEM Estimator for PR3 Yaw* (LIGO-G2402303-v1). LIGO Scientific Collaboration / LIGO Laboratory. LIGO Document Control Center.

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