Minimizing Sensor Error to Improve LIGO Seismic Isolation

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In LIGO, seismic isolation tables help create the high precision environment required for gravitational wave detection. One limitation of these isolation systems is the coupling between vertical motion and tilt of the seismic isolation table between 100 mHz and 2 Hz. Experiments applying a vertical drive to the isolation table confirm that discrepancies in vertical sensor readout appear as table tilt. We minimized the difference in sensor signals using multi-objective optimization and observed a 50x reduction in the predicted vertical to rotational coupling for the driven data in the frequency range of interest. Assuming the optimal parameters apply to sensors on an undriven table, we estimate the tilt readout noise to within a factor of 2 relative to the genuine table tilt readout signal. This demonstrates the viability of sensor calibration optimization as an alternative to new sensor installation for mitigating tilt noise in LIGO sensor signals.

Motivation

- The laser interferometer gravitational-wave observatory (LIGO) detects high energy interstellar events by observing the emitted gravitational waves.
- Interferometer components sit on isolation tables with vertical and horizontal sensors.
- Between 0.1 - 2Hz, seismic noise dominates vertical sensor readings.
- → **Miscalibrations in sensor parameters cause discrepancies in sensor readout when under identical inputs.**
- Vertical motion measurement discrepancies couple into table tilt, which couple into translational table motion causing performance loss in the detector.
- → Minimizing discrepancies between sensor readout minimizes accidental tilt generation and horizontal coupling, thus improving detector performance.

Genetic algorithm

The multi-objective genetic algorithm can be summarized in the following steps:

1. Define a quasi-random sampled population N, parameter space P, and constraint vectors L, U such any $p \in P$ satisfies $L \leq p \leq U$.
2. Recursively generate offspring from parent populations via **crossovers** and mutations
3. Evaluate the fitness of the offspring and the parents for the **multi-objective function**. Trim the total population by minimizing the fitness objectives and choosing the best performers.

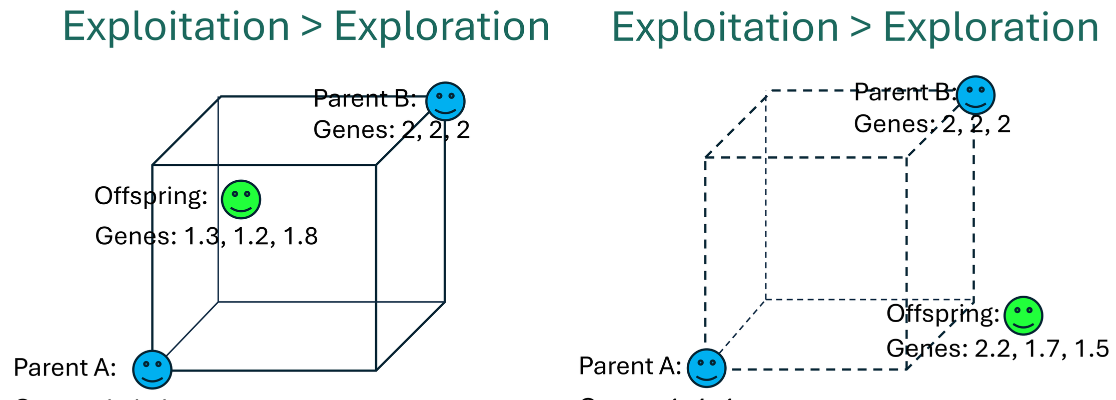
Intermediate crossover:

Let K be a vector with length N (dimension of parameter space), and each entry in K be a random float chosen uniformly between 0 and 1.

The offspring's parameters $C \in R^n$ satisfy:
$C = parent_1 + K * weights * (parent_2 - parent_1)$,
where $weights$ is a n-vector of weights.

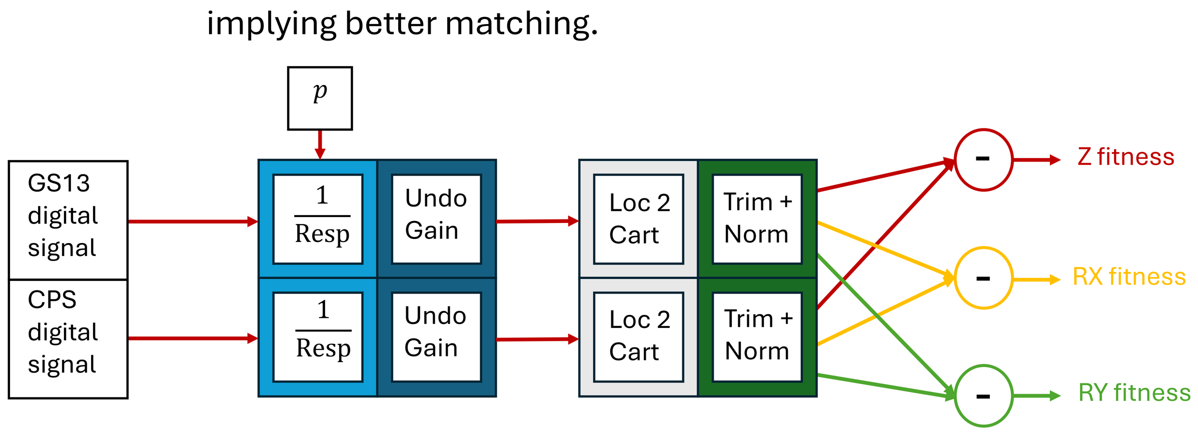
$|weights < 1|$ Exploitation > Exploration

$|weights \geq 1|$ Exploitation > Exploration



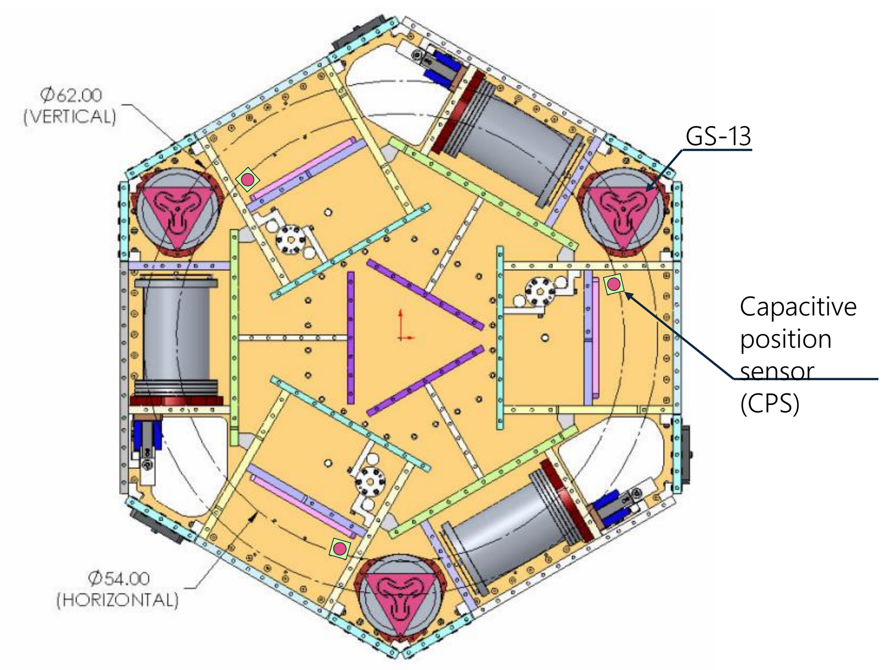
Objective function

- Sensor signals pass through analog filter modules and amplifiers which process them locally.
- → **To recover genuine table motion, local signals must be projected into the basis of the table (cartesian).**
- The difference between the sensor signals in each degree of freedom is the fitness value, with a smaller fitness value implying better matching.

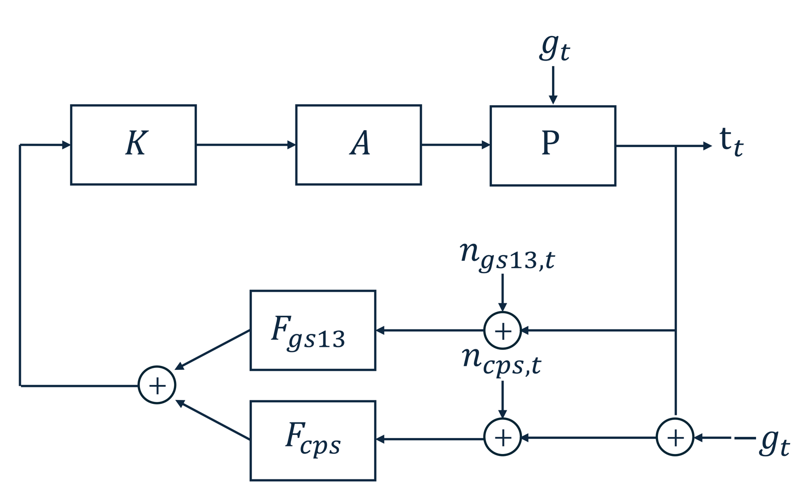


Sensor miscalibration

- The GS-13 measures the table velocity while the CPS measures the relative motion between the ground and the table.
- → **Sensors are not in the same location on the table. Sensor signals must be projected into the same basis for signal processing.**
- Miscalibrations in sensor transfer functions cause sensors to observe different vertical motions of the table.
- Vertical discrepancies are processed as table rotations, which the actuators attempt to minimize by apply a "counter tilt".
- **Tilt horizontal coupling: rotation of the table will couple into translational motion, degrading isolation performance.**

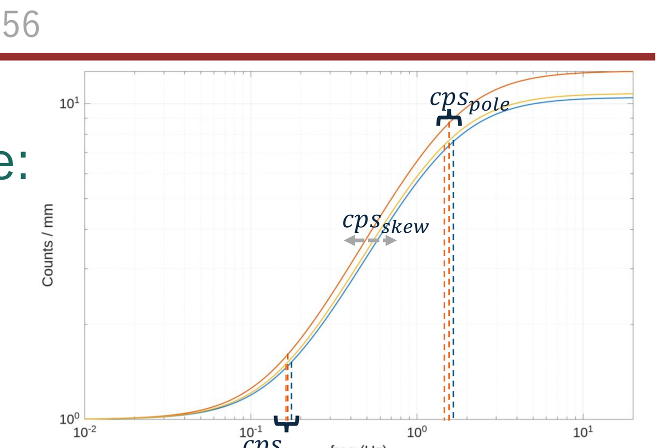


Top view of HAM table with seismometer locations
LIGO-G070156

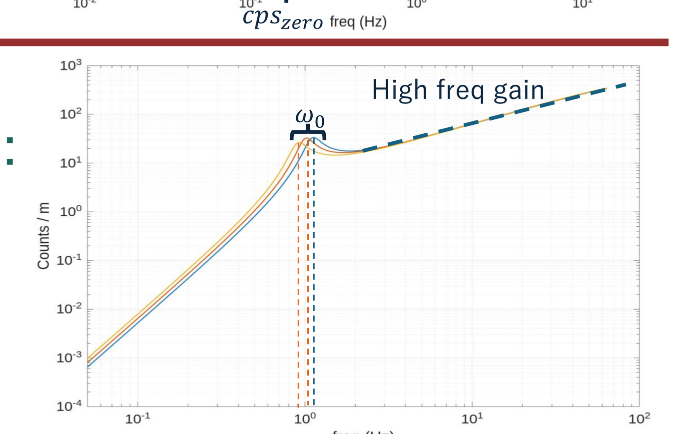


Simplified tilt control loop with actuator block.
LIGO-T080119

CPS response:



GS-13 response:

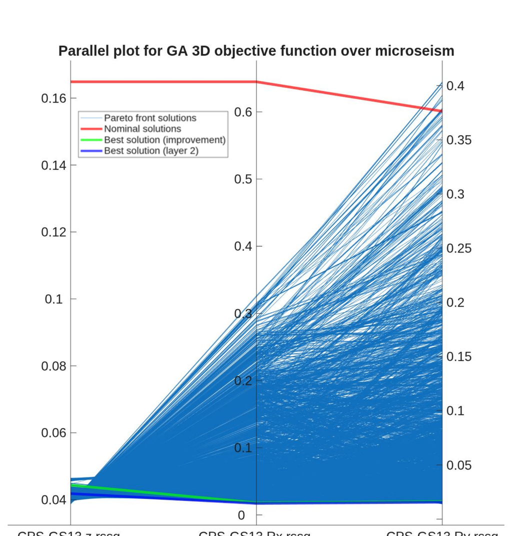


Testing on LIGO data streams

A vertical Schroeder phase drive was applied to seismic isolation table. Since the high gain isolation loops were disconnected, we expect the vertical sensor signals at the drive frequencies to be identical above the noise floor.

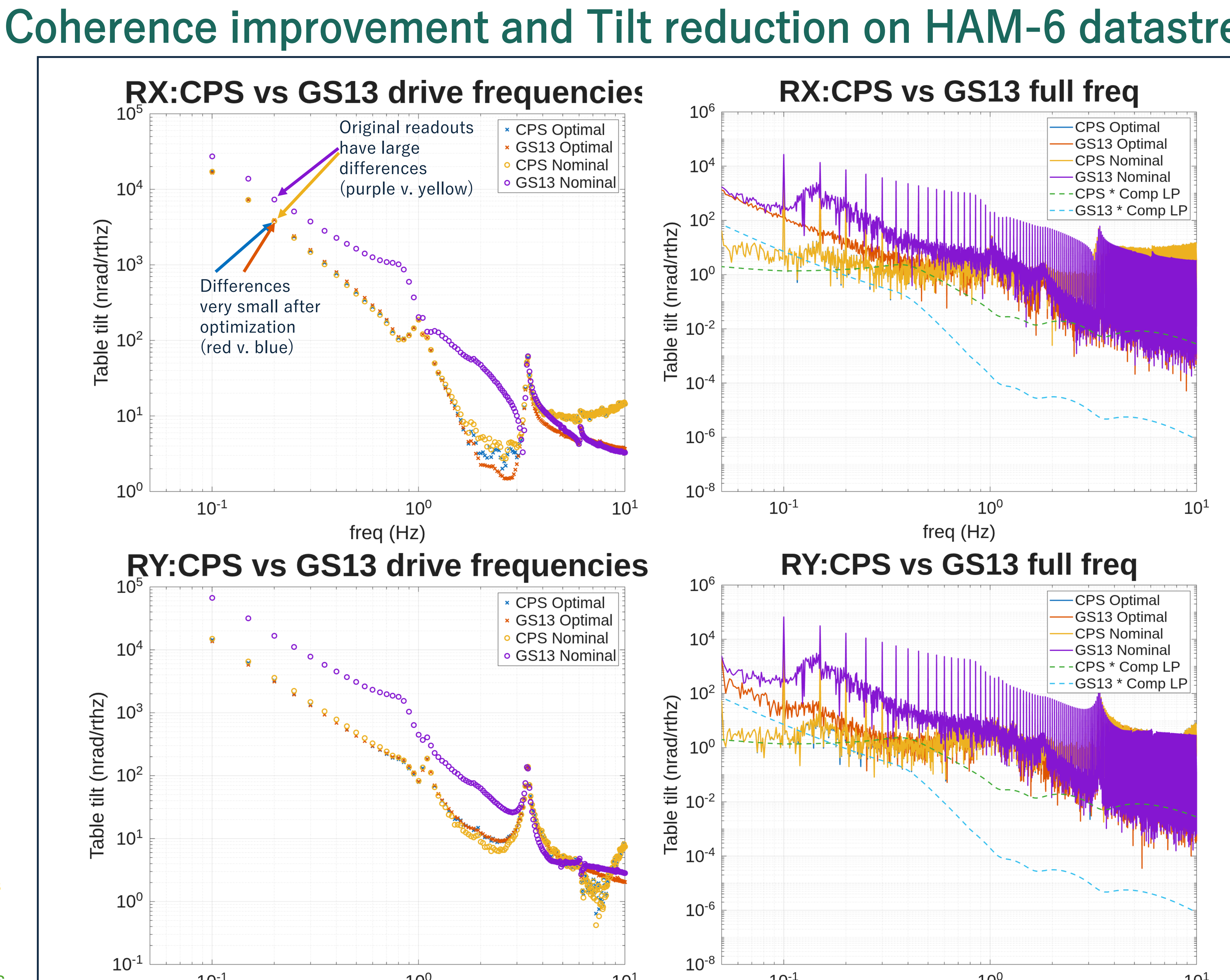
The sensor calibrations found from the drive driven table apply to the undriven table, as the sensors for both measurements are the same.

Minimization of signal differences over the drive frequencies results in sensor calibration parameters which reduce the table tilt over the microseism by a factor of 50.



Visualization of nondominated costs on the pareto front.

Coherence improvement and Tilt reduction on HAM-6 datastream

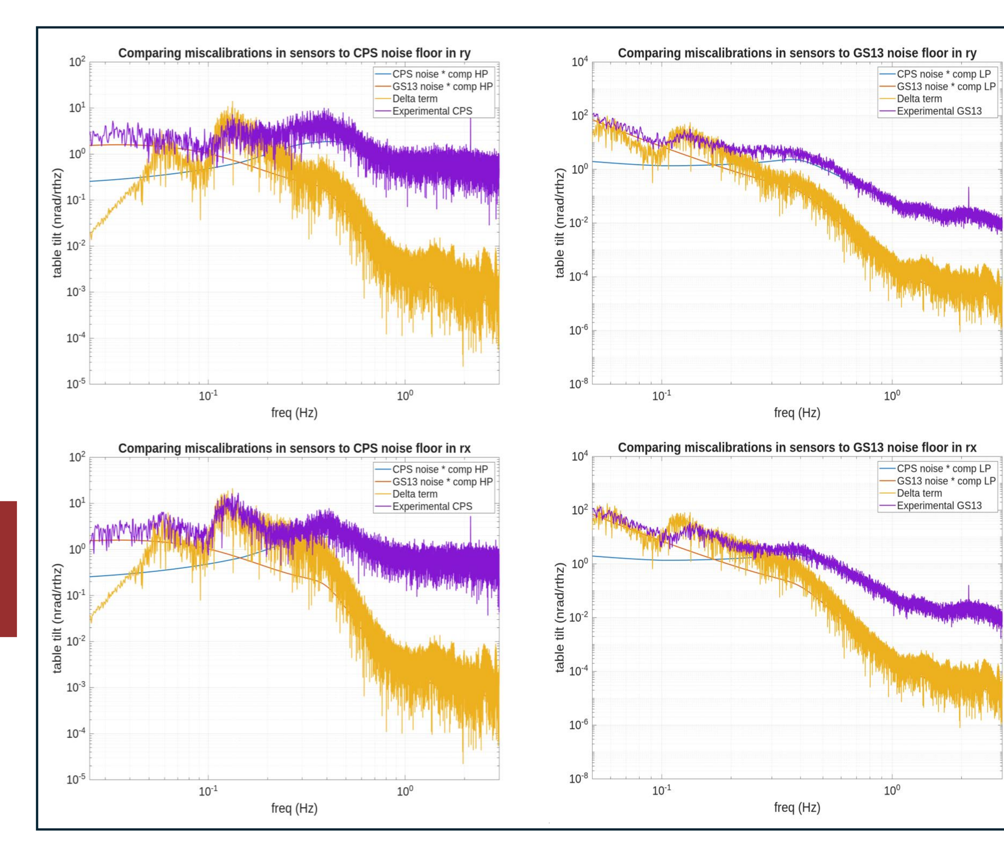


Validation

- We validate the optimization results through comparisons between the experimental non-drive data sets.
- The theoretical CPS readout tilt noise was within a factor of 2 to the experimental CPS tilt signal.
- The theoretical GS13 readout tilt noise matched the measured GS13 tilt noise, suggesting that the tilt noise in the microseism for the GS13 arise mostly from the sensor miscalibrations.
- The theoretical CPS readout tilt noise assumes that the intrinsic electronic noise of each sensor is independent of the ground and table vertical motion:

$$|n_{cps,m}|^2 = F^2\left(|n_{gs13,e}|^2 + |n_{cps,e}|^2 + |(\delta_{cps} + \delta_{gs13})t_z - \delta_{cps} g_z|^2\right)$$

Estimating effect of miscalibration on table motion



Discussion

- Using optimization on the CPS and GS13 calibration filter parameters reduces the tilt caused by vertical motion in the microseism by up to a factor of 50.
- In the experimental non-driven dataset, we saw the tilt noise from miscalibrations in the CPS and GS13 parameters match the noise in the non-driven GS13 data. The CPS data is within a factor of 2 of the experimental.

Next steps

- Package optimization, cost function, and analysis programs into a single executable to be run during maintenance.
- Relax 1-1 sensor parameter to signal assumption in coupling calculation.
- Include additional hyperparameters in the signal processing chain to check if their miscalibrations account for the remaining tilt noise.

Acknowledgements

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