Displacement fiducials for gravitational-wave detectors with sub-percent accuracy using laser power sensors calibrated at NIST

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Gravitational-wave detectors require accurate and precise calibration to maximize scientific benefit. As the sensitivity of these interferometers improve, calibration accuracy better than 1% is needed to optimally extract astrophysical source information. Continuous, differential-length fiducials at the 10^{-18} m level are currently generated via radiation pressure by systems known as *Photon Calibrators*. Recent improvements in methods for transferring laser power sensor calibration from NIST to a reference transfer standard located at the Laser Interferometer Gravitational-wave Observatory (LIGO) Hanford site, then to transfer standards for each detector, and finally to the power sensors of the photon calibrator systems, has enabled differential length calibration at the sub-percent level.

PHOTON CALIBRATORS

Photon Calibrators [1] (Pcals) use auxiliary, power-modulated lasers to induce periodic modulation of the positions of suspended (up to 40 kg) mirrors via radiation pressure. The forces applied to the mirrors, and thus the modulation of the mirror positions, are proportional to the laser power reflecting from the mirror. The accuracy of the calibration fiducials is therefore directly dependent on the accuracy of the reflected laser power measured outside the vacuum envelope and the estimate of the optical losses in propagating from the mirror to the laser power sensor.

CALIBRATION OF PCAL POWER SENSORS

Following a scheme conceived in 2007 in consultation with J. Hadler at NIST, the first step in calibrating the interferometer's power sensors is to calibrate a reference transfer standard that is referred to as the Gold Standard (GS). It consists of a Labsphere 4-inch-diameter integrating sphere with an interior Spectralon shell and an unbiased InGaAs photodetector with an integrated transimpedance amplifier. The GS is sent to NIST annually for calibration.

The next step is to transfer the GS calibration to Working Standards (WS) of similar design, one for each observatory, as shown schematically in Figure 1. This is achieved by measuring the WS to GS responsivity ratios in a laboratory setup at the LIGO Hanford Observatory (LHO). Referencing all of the WSs to a single GS reduces uncertainty in the relative calibration of the detectors in the global gravitational wave (GW) detector network.

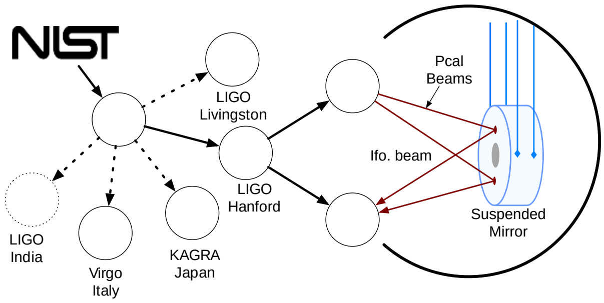

Figure 1 Transfer of laser power calibration from NIST to the GS to a WS maintained at each observatory then to the power sensors located outside the vacuum envelope on the transmitter side (Tx) and the receiver side (Rx). *H* for LIGO Hanford, *L* for LIGO Livingston, *V* for the Virgo observatory in Italy, *K* for the KAGRA observatory in Japan, and *I* for the LIGO India observatory currently under construction in India.

To measure the responsivity ratios, a 1047 nm laser beam is divided on a beamsplitter. One detector is placed in the transmitted beam and one in the reflected beam and sensor outputs are recorded simultaneously. The positions of the two detectors are then swapped using automated pneumatic sliders and additional time series are recorded. The square root of the product of the ratio of the first set time series with that of the second set yields the responsivity ratio, eliminating laser power variations and slow changes in the beamsplitter ratio.

The third step is measurement of the responsivity ratio of the power sensor measuring the light reflected from the interferometer mirror and the WS. This is achieved by placing the WS in one of the two Pcal beams in both the transmitter and receiver modules and recording a set of time series for each beam. These measurements yield the ratio of the laser powers in the two Pcal beams, the optical efficiency for each beam, and the power sensor to WS responsivity ratios. The measured optical efficiencies, together with in-chamber efficiency measurements made when the vacuum envelope was vented, enable correcting the power sensor calibration to infer the power reflecting from the suspended mirror.

The variation in the responsivity of the power sensors with temperature is measured to be 0.02 to 0.10 % per K. Temperature differences between the NIST laboratory, the Pcal laboratory at LHO, and the various interferometer laboratories where the mirrors are suspended, as large as 4 K, are incorporated in the calibration uncertainty estimate.

Nominally, the Pcal beams are diametrically opposed and equally spaced away from the center of the suspended optic and the interferometer beam is centered. However, in practice the Pcal beams can be mis-located by as much as 2 mm and the interferometer beam is intentionally displaced to optimize interferometer sensitivity. The resulting in unintended rotations of the mirror due to Pcal forces being sensed by the interferometer as length variations is an additional source of uncertainty.

The relative uncertainty introduced by the sources described above are listed in Table 1 for the Y-end mirror at LHO. The overall relative uncertainty in the induced displacement of the mirror is 0.46 %. These results are typical for both interferometer end mirrors and for both LHO and the LIGO Livingston Observatory. Results for other detectors in the global GW network are expected to be similar.

Table 1. Summary of the major factors contributing to relative uncertainty mirror displacement induced by the Pcal system for the LHO Y-end mirror.

Parameter	**Rel. Uncertainty (1-σ)**
GS responsivity	0.32 %
WS/GS resp. ratio	0.024 %
Rx/WS resp. ratio	0.016 %
Temperature	0.09 %
Optical efficiency	0.044 %
Unintended Rotation	0.31 %
Displacement	**0.46 %**

RELATIVE AND OVERALL CALIBRATION OF THE GW DETECTOR NETWORK

Referencing the working standards for all of the observatories to the same transfer standard reduces relative calibration uncertainties for the global network. The laser power calibration of the GS carried out by NIST has a 1-σ relative uncertainty of 0.32% (see Table 1). However, in 2009 the EUROMET Comparison [2] reported disagreements between various national metrology institutes as large as 3.5 % for calibration of the same (thermal) power sensors operating at a wavelength and power level close to that used for GW detectors. Pursuant to the EUROMET study and a GW Metrology Workshop hosted by NIST in 2019 [3] some of the discrepancies have been understood and reduced. A bilateral comparison by NIST and PTB in Germany of a LIGO-style power sensor is underway and a broader comparison using one of these sensors is being considered [4].

As shown in Table 1, the dominant sources of uncertainty in the Pcal displacement fiducials are the calibration of the GS and the uncertainty introduced by unintended rotation of the mirror due to calibration forces. A new generation of primary standards under development by NIST [5] may reduce the former and methods to reduce the latter are being investigated.

CONCLUSION/DISCUSSION

Calibration of Pcal power sensors at the various GW observatories using the scheme shown schematically in Figure 1 has enabled generation of differential length fiducials with sub-percent accuracy. Calibrating interferometer output signals over the full frequency range and continuously, over long observing intervals, poses significant additional challenges. Continued development of calibration methods and further improvements in calibration accuracy will be required to ensure that the scientific reward of higher signal-to-noise-ratio GW detections is not limited by calibration uncertainty.

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