GW (Gravitational Wave) Metrology Workshop
15 March 2019, NIST Boulder, Colorado
Co-hosted with LIGO Hanford Observatory

1. **Gravitational Wave (GW) Event Ranging (absolute accuracy of optical power calibration)** IF the calibration factor for optical power employed for any GW detector is *not accurate* (for example, if LIGO's Gold Standard's answer has an incorrect offset (bias) of 4%), then estimates of the distance to individual GW events are wrong (by 4%).
2. **Estimation of the Hubble Constant (absolute accuracy of optical power calibration)** IF we use an ensemble of several GW detections based on optical power that is *precise but not accurate* (i.e., if National Metrology Institutes (NMIs) agree, but are measuring power incorrectly), then we will get the wrong answer for our consensus estimate of the Hubble Constant. (see endnote)
3. **GW Event Sky Localization v. agreement among GW observatories using independent optical power calibration (for example, what if NMI's providing calibration factors to their respective observatories are disparate?)** IF there is a difference in the optical power calibration among optical power meters employed by GW detectors within the observatory network, then we get the sky-localization wrong.
4. **These three points (above)** are stated assuming we have a global network of 3 to 5 gravitational wave detectors. Accurate measurement of *optical power near 1 watt is timely and critical* for the entire GW community.

The meeting was a great success despite being squeezed into one day by the "Bomb Cyclone" (BC). The GW community, NIST, and other National Metrology Institutes (NMIs) were represented. We had thirty five participants and approximately fifteen unclaimed registrations for the workshop due to the BC. There were six people monitoring the meeting remotely and two speakers presented remotely.

- **Next steps**: Plans for bi- (or tri-) lateral comparisons of LIGO Gold Standard with NIST and PTB are progressing. We expect to start within the next few months.
- **EUROMET and PTB**: The importance and outcome of the EUROMET Comparison, Project No. 156, *Responsivity of detectors for radiant power of* lasers, Supplementary Key Comparison and the Supplementary Comparison Reference Value (SCRV) from the Consultative Committee for Photometry and Radiometry organized by Stefan Kück of PTB (published 2009) was mooted along with the importance of the uncertainty and absolute values of the measurement results from seven NMIs.
- **Incremental improvement**: NIST has reduced uncertainty in the LIGO "Gold Standard" calibration using a primary standard to 0.31% (one-sigma) from 0.44% (one-sigma). (still nearly 3x higher than PTB was at the time of the EUROMET Comparison of 2005-2007).
- **Next Gen**: NIST is implementing new primary standards expected to provide calibration of the LIGO Gold Standard near 0.1 % (k=2) uncertainty.
- **Nuclear Option**: NIST could provide (the 'nuclear option') a primary standard based on the superconducting nanotube radiometer tailored to LIGO's needs near 1 W that might reach the 0.01% uncertainty level. This could reside at LIGO.
- **NIST on a Chip**: It is possible that chip-scale nanotube radiometers could be incorporated into the observatories as absolute standards functioning in real time.
- **Next meeting**: NIST is hosting NEWRAD 2020 and we plan to have a "GW" session during the NEWRAD meeting (global NMIs) in Boulder, June 2020.
- **Training**: There is potential for training and collaboration in optical power metrology with LIGO India and with NPL of India as well as researchers at LIGO.
- **Workshop Program**: The content of the program (following page) summarizes the content of the workshop.

GW (Gravitational Wave) Metrology Workshop
15 March 2019, NIST Boulder, Colorado
Co-hosted with LIGO Hanford Observatory

Slides online: The entire content of the program is being hosted by LIGO and is available publicly available at: https://dcc.ligo.org/cgi-bin//DocDB/DisplayMeeting?conferenceid=1029

8:30	Structure of the CCPR/BIPM, overview of "EUROMET Comparison Project 156" results, goals of this workshop, introduction of participants	John Lehman, (NIST)
8:45	GW Astronomy results to date and prospects, Current and future GW detectors – sensitivity they achieve and how they do it, Astrophysical requirements and benefits of calibration accuracy	Stefan Hild, (Univ. Glasgow)
9:15	The international comparison on laser power 2005 – 2007 & Laser Power Meter calibrations at PTB REMOTE	Stefan Kück (PTB, Germany)
9:50	**Break**	
10:30	Methods for calibrating km-scale interferometers REMOTE	Evan Goetz (Univ. Michigan)
11:00	LIGO Photon Calibrators	Sudarshan Karki (Univ. Oregon)
11:15	Statistical Treatment of Multiple Results of the Same Measurand	Amanda Koepke, (NIST, Boulder)
12:15	**Lunch**	
13:30	LIGO Power Standards and Relative GW Detector Calibration Strategy (S. Karki presenting for Y. Lecoeuche)	Yannick Lecoeuche (LIGO Hanford Observatory)
13:45	GEO600 Calibration Status	Jim Lough (Albert Einstein Institute)
14:00	KAGRA Calibration Status	Darkhan Tuyenbayev (Academia Sinica)
14:15	LIGO Calibration Status	Jeff Kissel (LIGO Hanford Observatory)
14:30	LIGO India Status	Shivaraj Kandhasamy (IUCAA)
14:45	KAGRA Gravitational Calibrator (Gcal)	Yuki Inoue (National Central University, Taiwan)
15:00	LIGO Newtonian Calibrator (Ncal) implementation status	Jeff Kissel for Univ. Wash. Grp.

15:15	**Break**	
15:30	Laser Power meter calibrations at LNE	Jimmy Dubard, (LNE, France)
15:45	Laser Power Meter Calibrations at NIST	Matt Spidell, (NIST, Boulder)
16:00	Toward the Next Generation of Standards for Laser Power Measurements	Michelle Stephens, (NIST, Boulder)
16:15	Discussion of plans for comparative study, other roundtable discussions	All
17:00	Overview and Closing Remarks	Michelle, John, Rick

Endnote for item 1, page 1: An ensemble of GW detections has the potential to substantially contribute (i.e. with potentially very low statistical uncertainty) to the consensus of value for the Hubble constant, currently best estimated from supernovae (SNe) and the cosmic microwave background (CMB). Those estimates are currently, statistically discrepant. If the GW ensemble estimate becomes more precise but not accurate, the GW ensemble's prediction would skew the three-party consensus. If accurate, then the ensemble has the potential to 'break the tie' and refine the collective consensus with greater confidence.