The Statue of Liberty, New York, USA

Leon Chao, BS MS

Mechanical Engineer at NIST

He received his BS MS degrees from the University of Maryland, USA in Mechanical Engineering. In 2013, he began his career in mass metrology and precision design at the National Institute of Standards and Technology in 2013. He aided in the design, construction, and characterization of the NIST-4 Kibble balance which contributed to the global redefinition of the International System of Units in 2019, specifically redefining the unit of mass, the kilogram, in terms of a fixed value of the Planck constant. Since then, Leon has been the project lead for modernizing Kibble-based technology optimized for calibrations laboratories for both direct realization of gram-level masses and small torque traceable to the revised SI. Recently, he spearheaded a collaboration between NIST and Snap-On Industrial for commercialization of the Kibble-based torque standard.

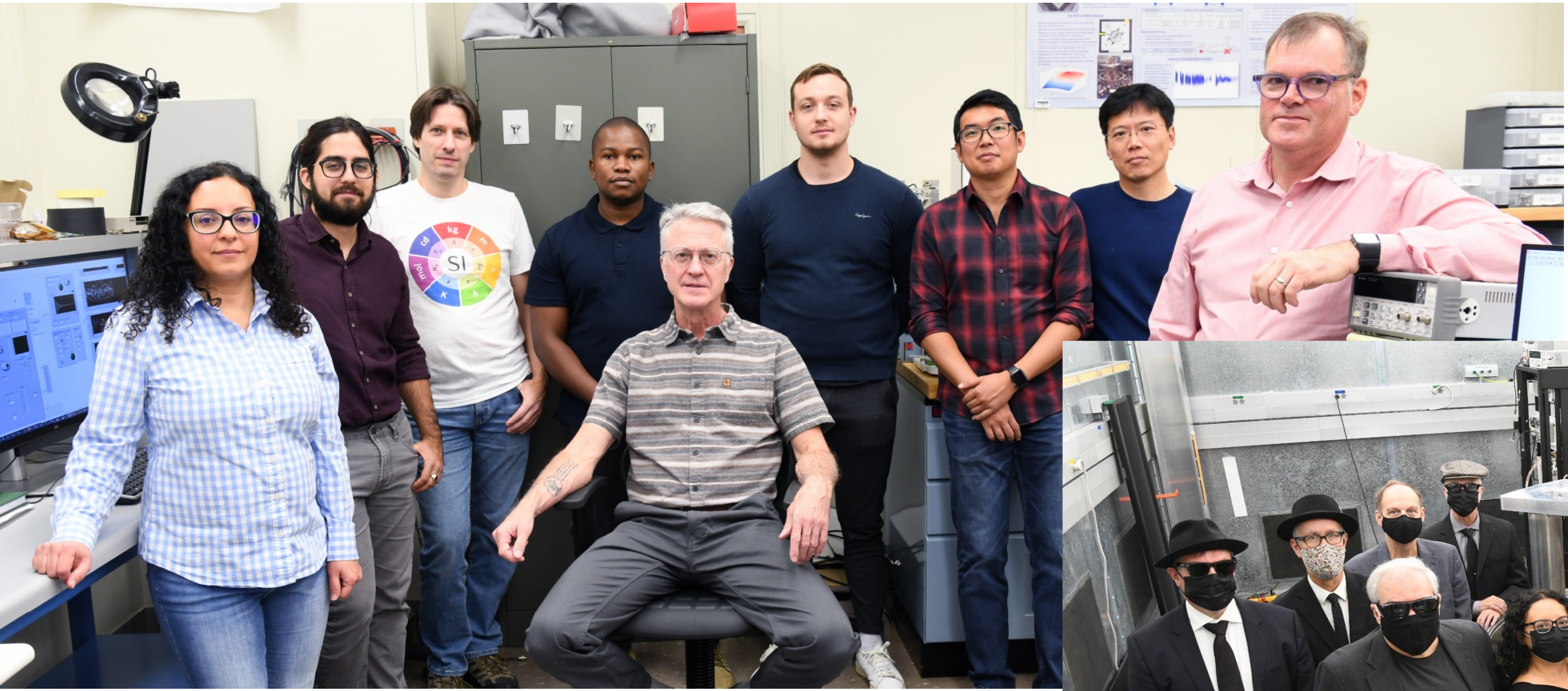
METROLOGY SYMPOSIUM
DIGITALIZATION AND AUTOMATION IN MASS METROLOGY
Third Edition: Future and New Solutions

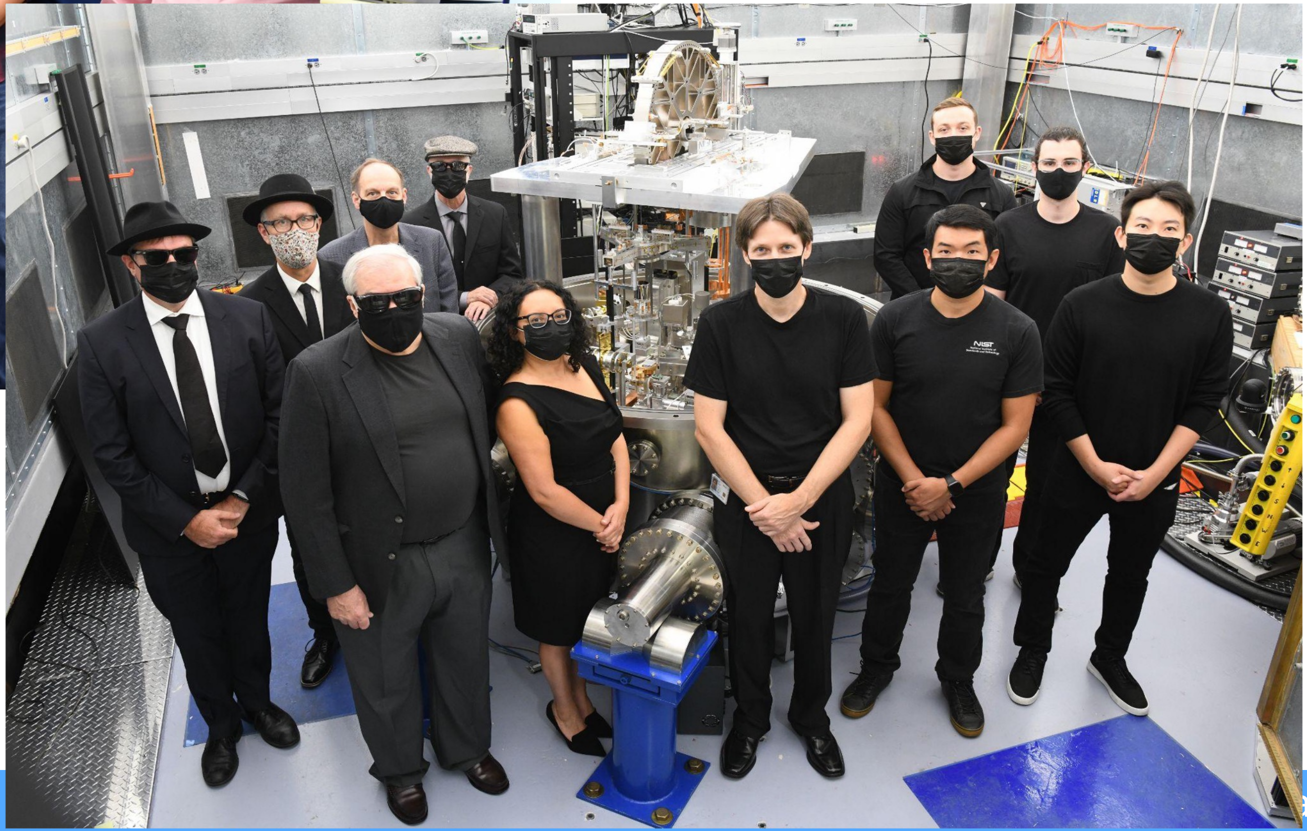
RADWAG
ČESKÝ METROLOGICKÝ INSTITUT

Modernizing Mass and Torque Metrology with Tabletop Kibble Technology at NIST

Leon Chao, Kumar Arumugam, Zane Comden, John Draganov, Stephan Schlamminger, David Newell

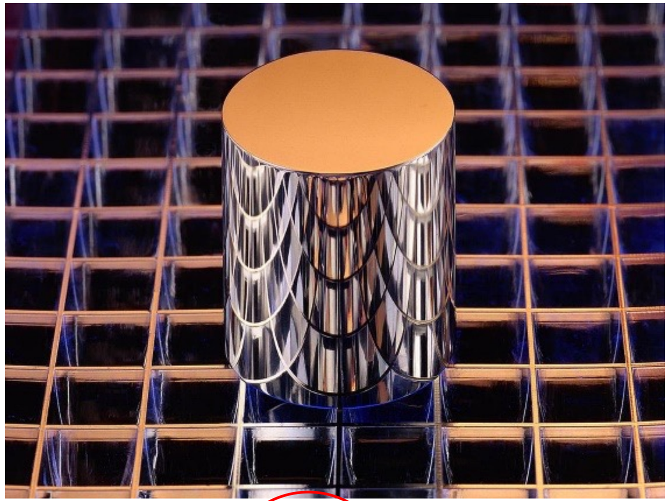
Our Team at NIST



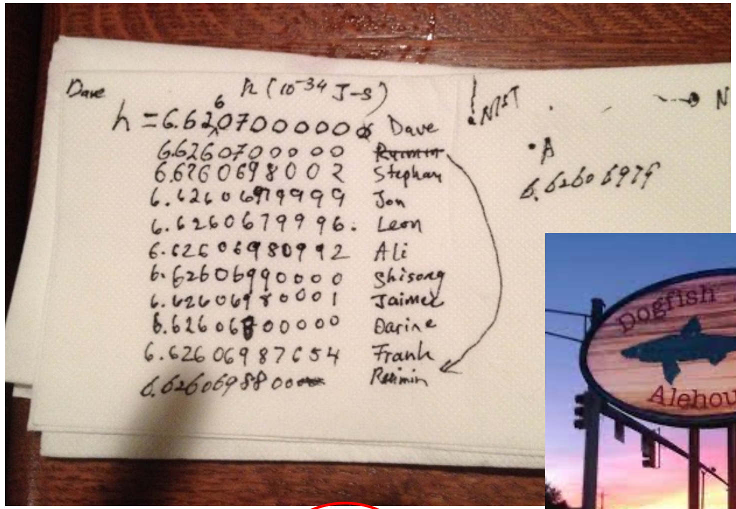


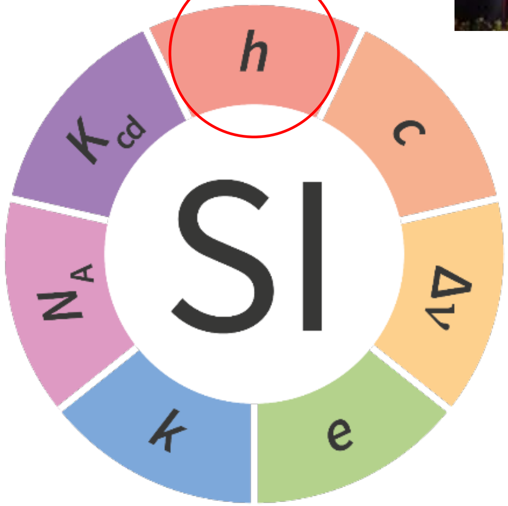
and

3 Metrology Addicts + 3 Chickens



2019

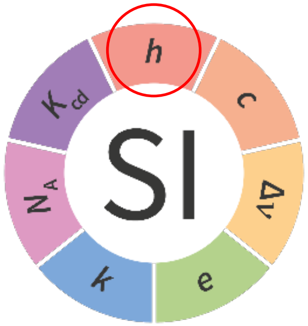




IPK no more

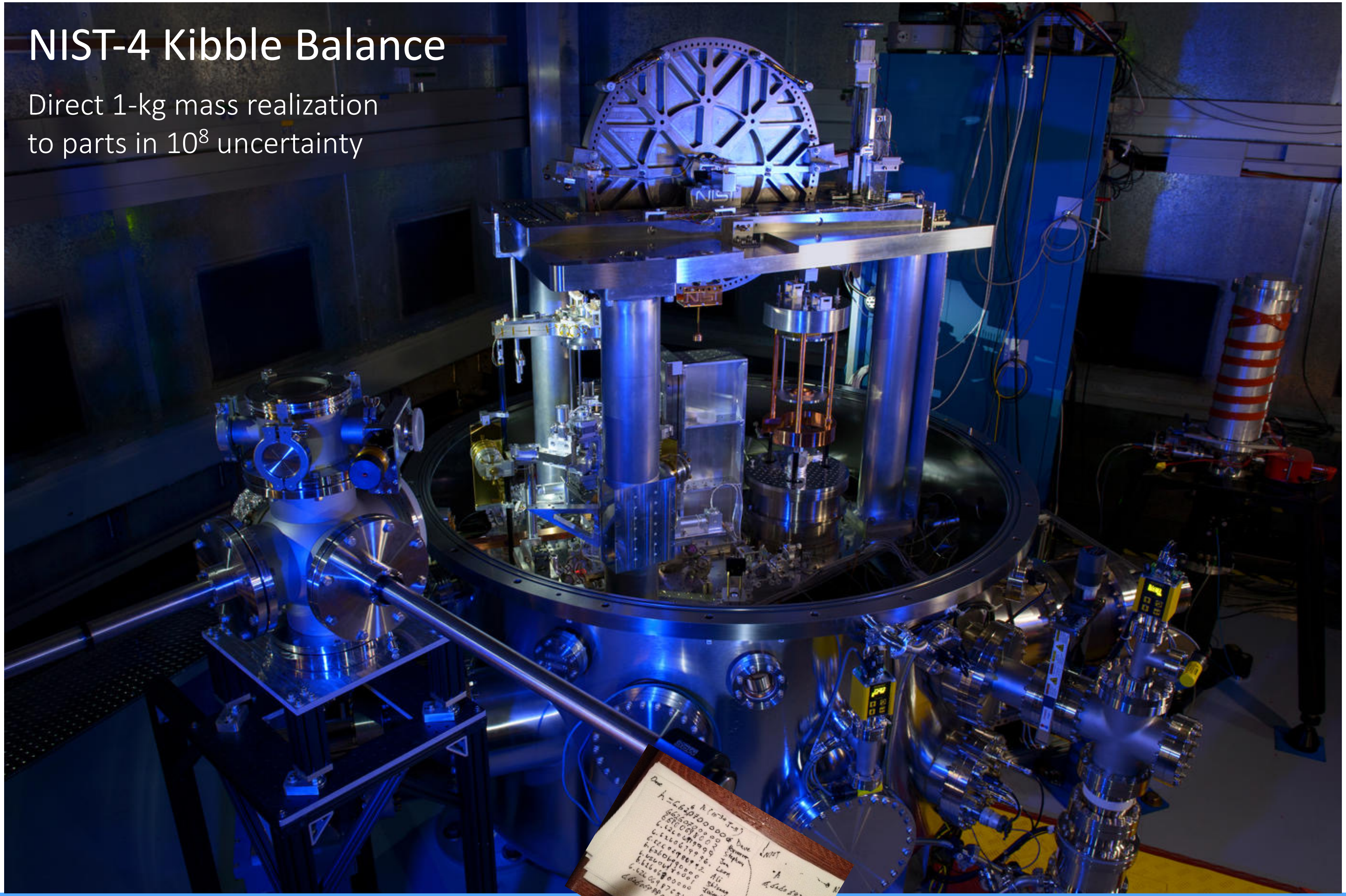
Before 2019:

$m \rightarrow$



After 2019:

$h \rightarrow$

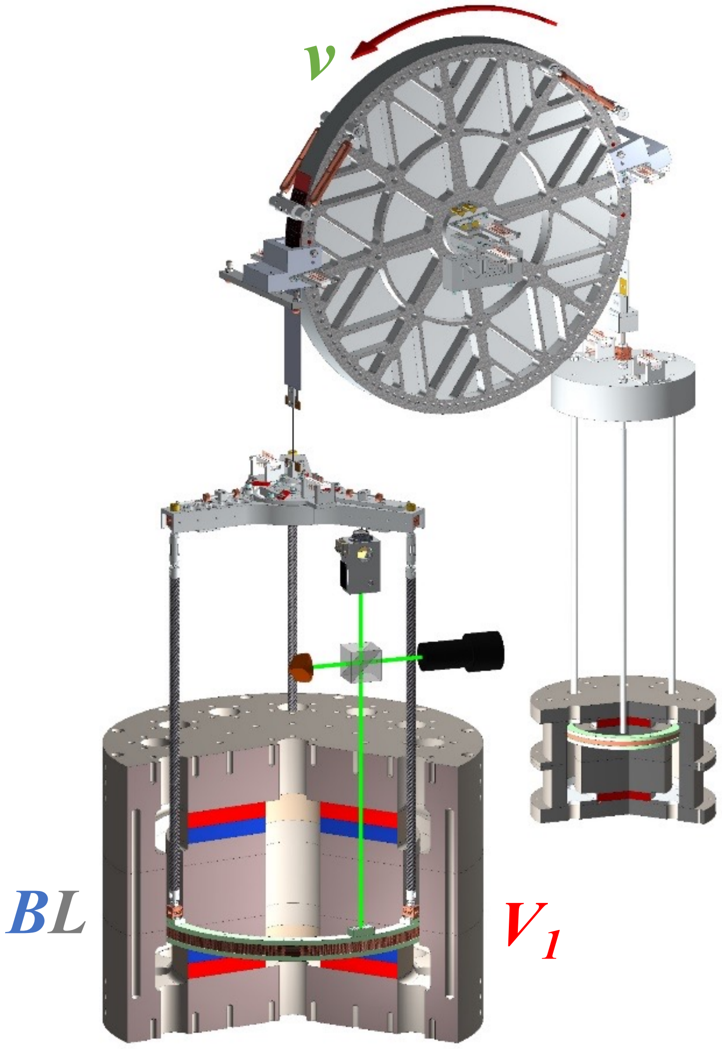


$\rightarrow h$

$\rightarrow m$

Kibble Principle, again

Velocity Mode

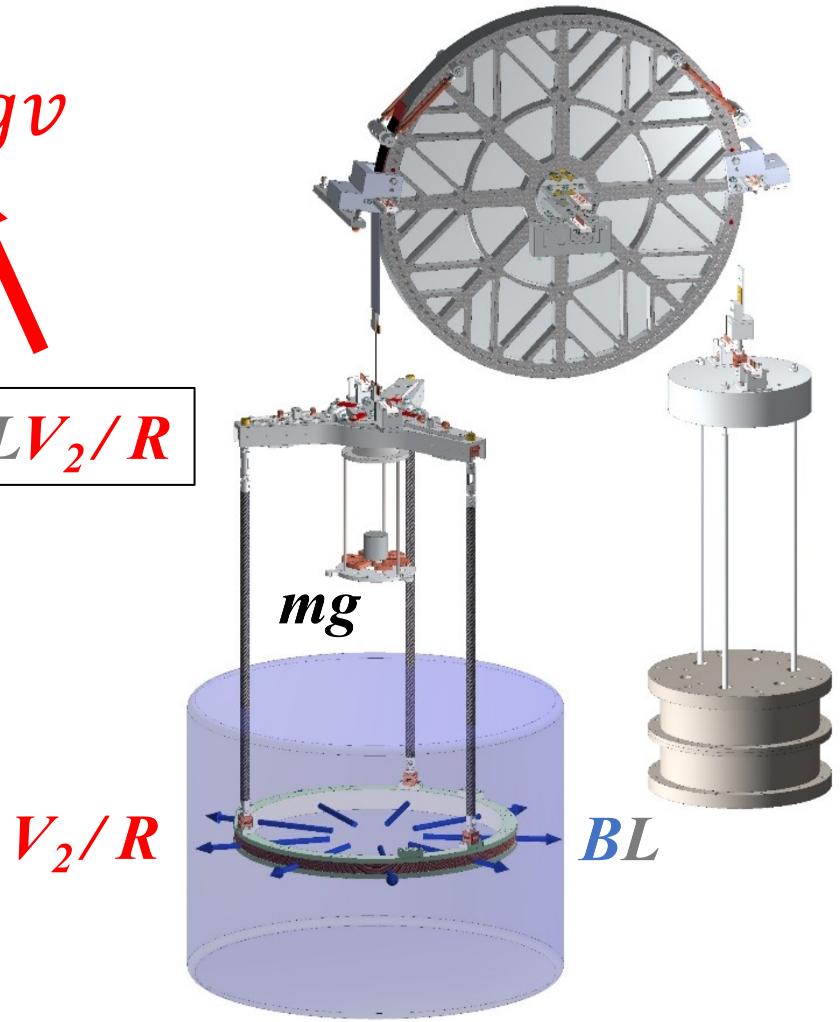


$$m = {}^{V_1 V_2}/_{Rgv}$$

$V_1 = BLv$

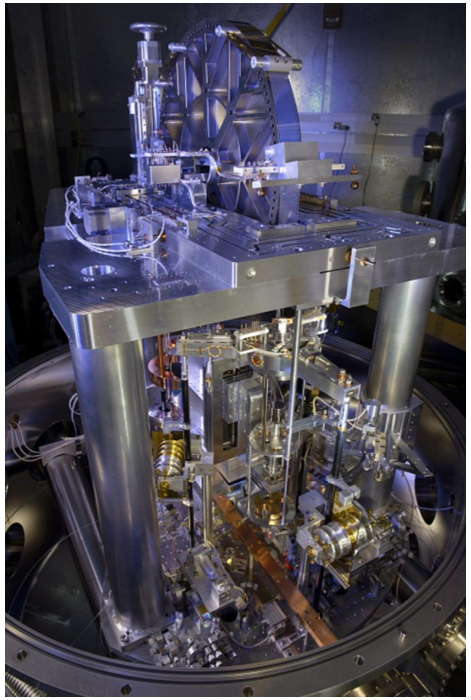
$mg = BLV_2/R$

Force Mode

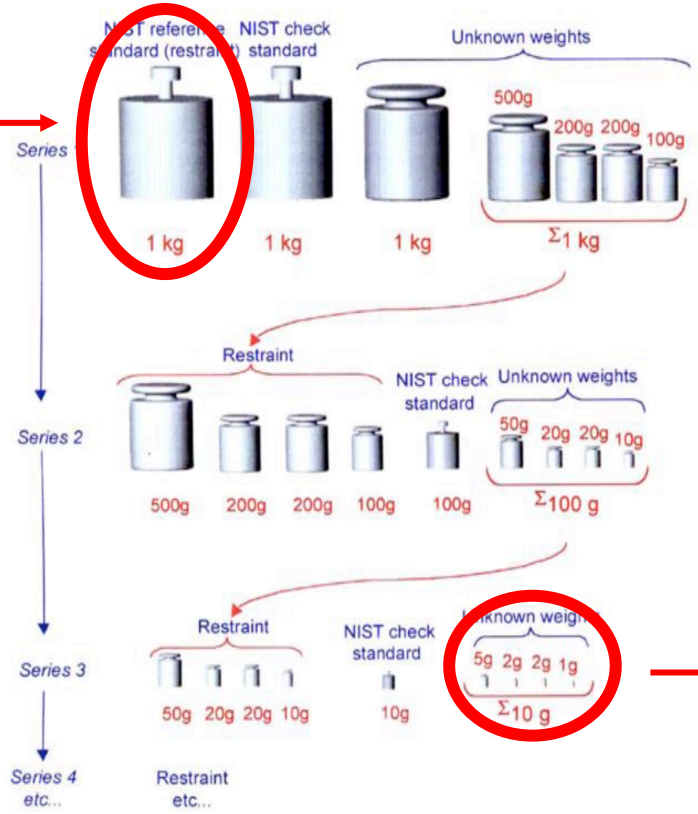


Present State of US Mass Dissemination

NIST



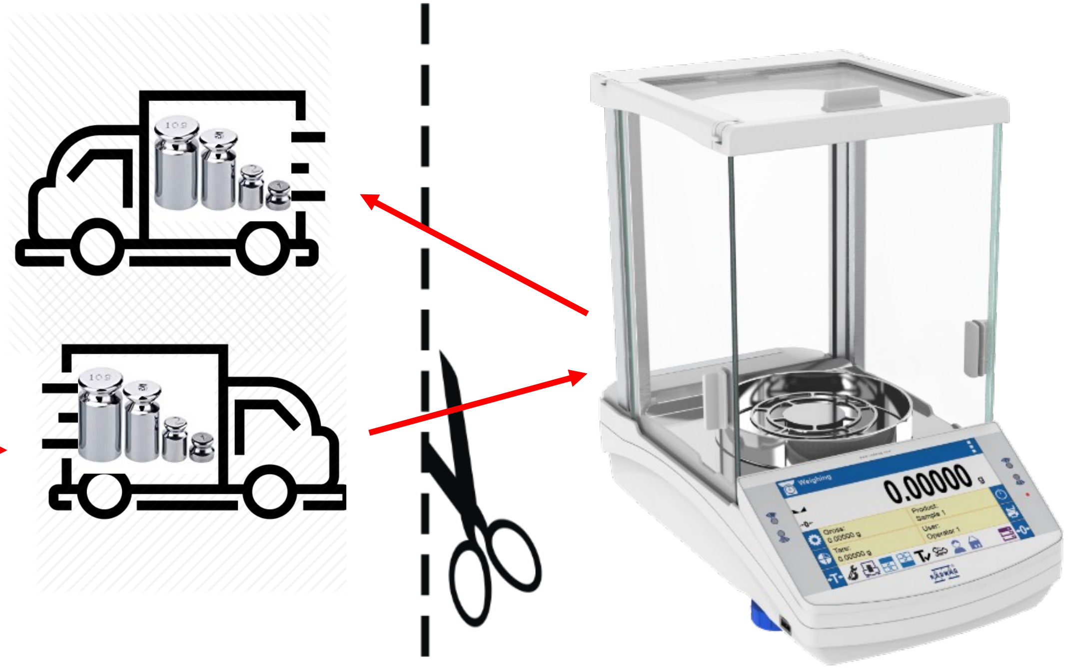
1 kg realization
Uncertainties ~ 10^{-8}



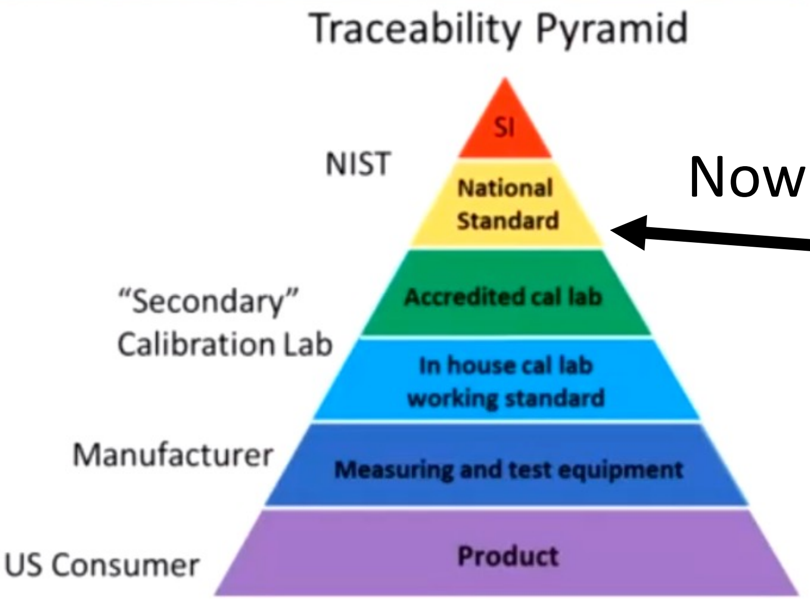
Subdivision from 1 kg to 1 g

- ~1 week to complete
- 44 weighings
- 1200 individual measurements
- Uncertainties now on the order of 10^{-6}

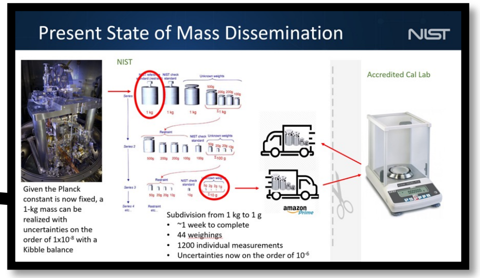
Accredited Cal Lab

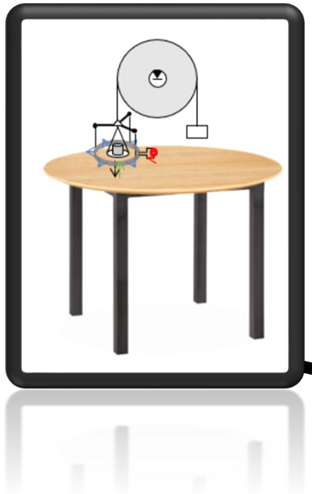


The Big Picture

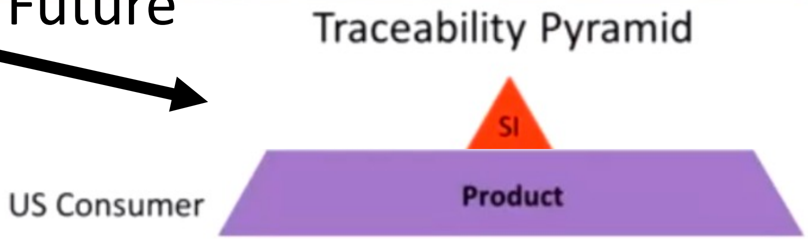


Now





Future



"Destruction in the face of progress is not only possible, but an efficient way to get rid of excess."

What's next? Let's get this technology into the hands of industry.

Shrink and simplify

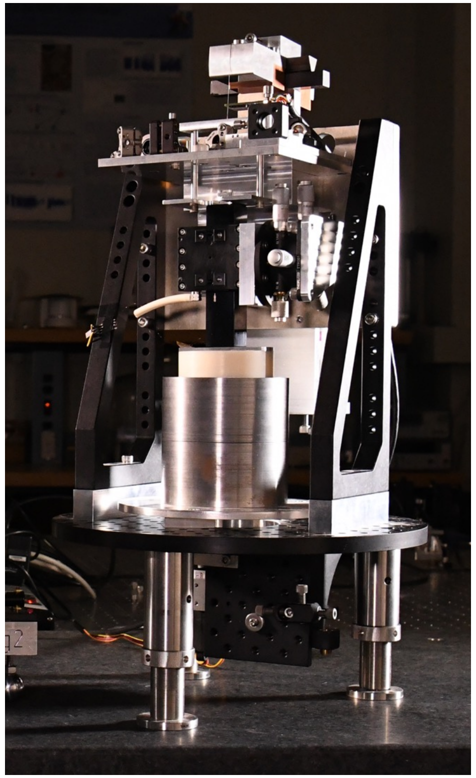


Table 4. Comparison of E_2 mass versus KIBB-g1 mass realization relative uncertainties.

	5 g mass	1 g mass
$\Delta m_{E2}/m_{E2} \times 10^6$	2	5
$\Delta m/m \times 10^6$	1.8	6.3

PAPER • OPEN ACCESS

The performance of the KIBB-g1 tabletop Kibble balance at NIST

Leon Chao[1], Frank Seifert[1], Darine Haddad[1], Jon Pratt[1], David Newell[1] and Stephan Schlamminger[1]

Published 14 May 2020 • Not subject to copyright in the USA. Contribution of NIST
Metrologia, Volume 57, Number 3

TABLE I
KIBB-G1 UNCERTAINTY BUDGET. ALL UNCERTAINTIES ARE $\times 10^{-6}$

Source	5 g measurement Item	5 g measurement Subtotal	1 g measurement Item	1 g measurement Subtotal
Laser Stability/Accuracy	0.0		0.0	
Deadpath Error	0.0		0.0	
Optics Thermal Drift	0.0		0.0	
Electronics Error	0.1		0.1	
Interferometer Readout		**0.1**		**0.1**
Abbe Error	0.0		0.0	
Off Axis Motions	0.0		0.0	
Cosine Error	0.1		0.1	
Alignment		**0.1**		**0.1**
Timing Jitter	0.0		0.0	
Wavelength Compensation	0.2		0.2	
Velocity		**0.2**		**0.2**
Field Gradient	0.0		0.0	
Material Thermal Expansion	0.4		0.4	
Coil Z Position		**0.4**		**0.4**
Statistical		**0.7**		**2.8**
BL Interpolation	0.2		0.2	
Individual BL Profile	0.7		0.7	
Profile Fitting		**0.7**		**0.7**
Resistor	0.1		0.1	
DVM (Force Mode)	0.4		0.4	
DVM (Velocity Mode)	0.4		0.4	
Electrical		**0.8**		**0.8**
Magnetic Susc. of Mass	0.0		0.0	
Balance Sensitivity	0.0		0.0	
Buoyancy	0.1		0.1	
Balance Mechanics	0.2		1.0	
Gravity	0.3		0.3	
Magnet Nonlinearity	0.4		0.4	
Air Bearing Pressure	1.1		5.4	
Forces on mass		**1.2**		**5.5**
Total		**1.8**		**6.3**

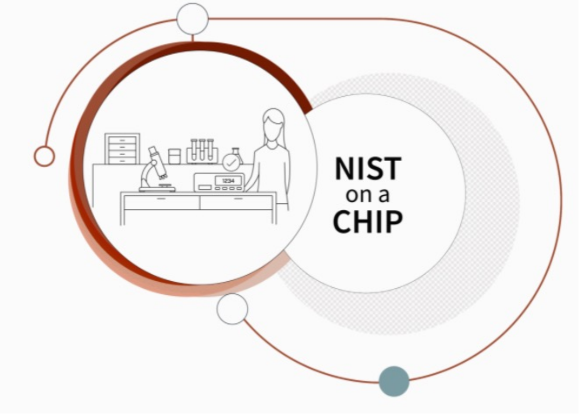
2020 Dept. of Defense Interest for 2 Systems

- Army Request: 3 year funding for R&D of the next generation tabletop Kibble balance with a focus on design for commercialization at ASTM Class 3 (OIML Class F) uncertainties [500 mg – 20 g]

- Air Force Request: 3 year funding for the R&D of an absolute Kibble torque standard

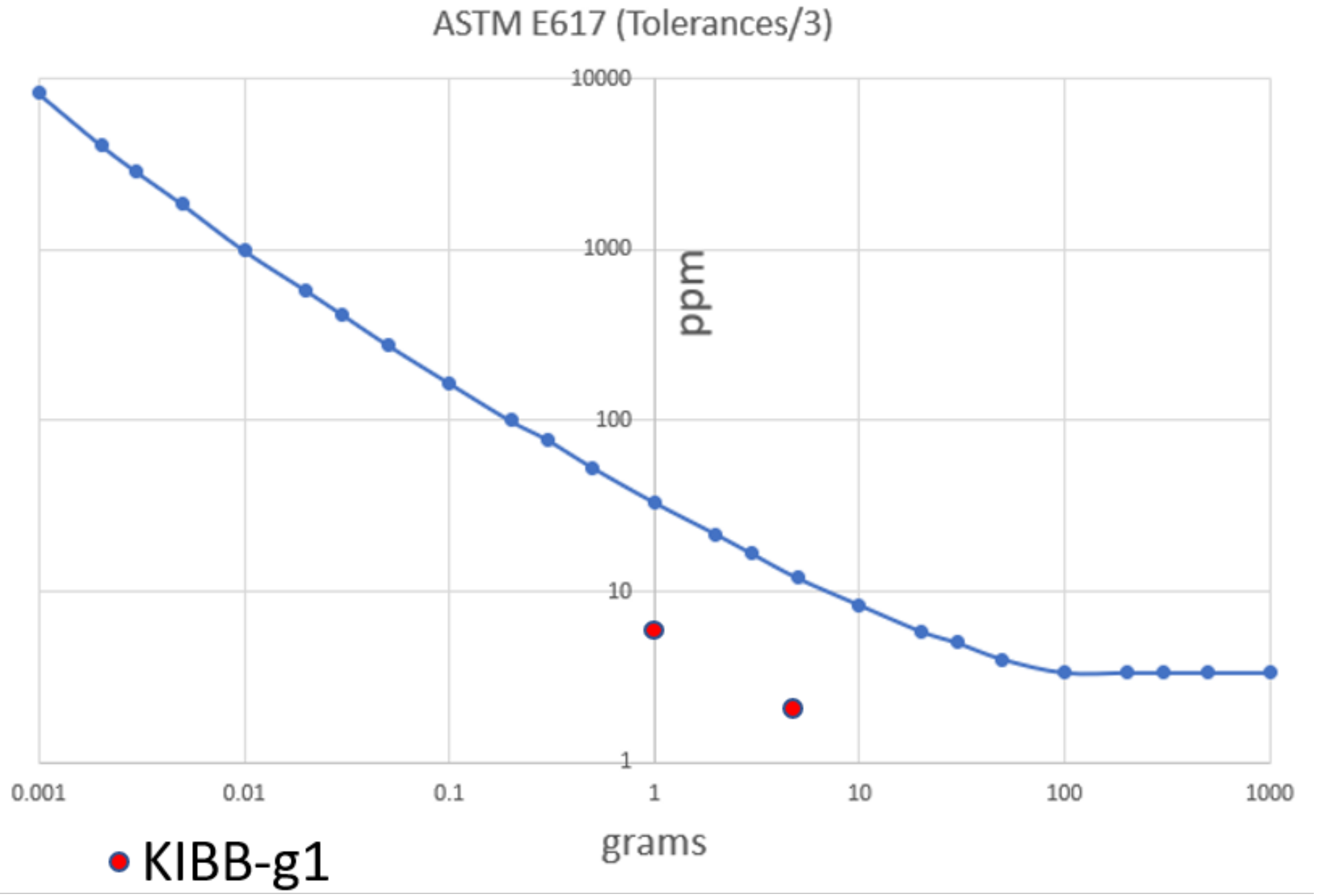
AIR FORCE METROLOGY

USATA
U.S. ARMY TMDE ACTIVITY
METROLOGY AND CALIBRATION



NIST PREME

US Army Primary Mass Lab Requirements



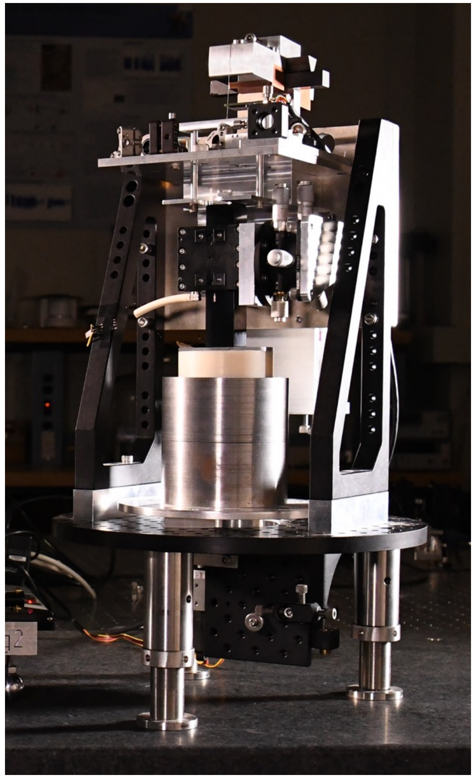


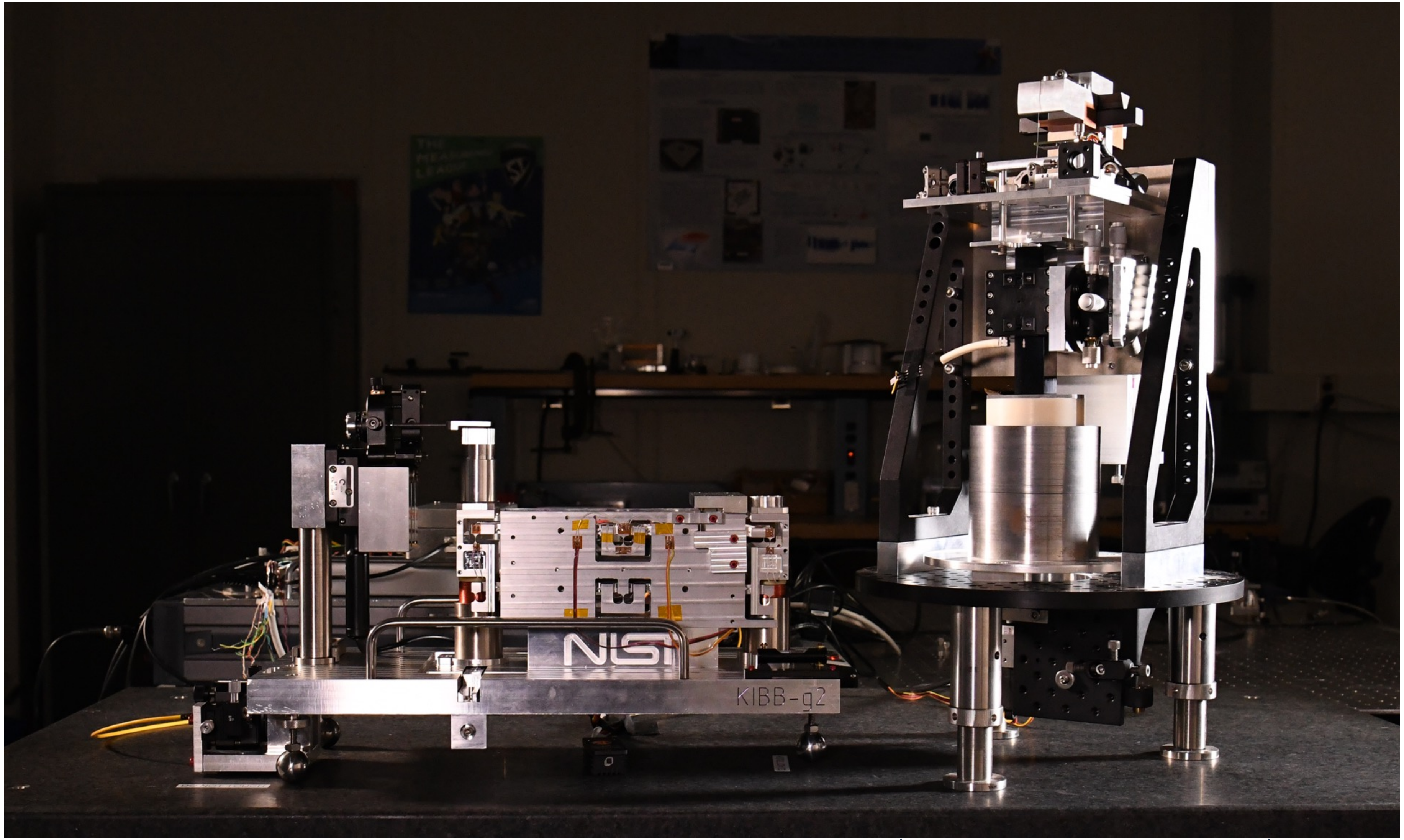
Table 4. Comparison of E_2 mass versus KIBB-g1 mass realization relative uncertainties.

	5 g mass	1 g mass
$\Delta m_{E2}/m_{E2} \times 10^6$	2	5
$\Delta m/m \times 10^6$	1.8	6.3

KIBB-g2 vs KIBB-g1

Goal: Construct a second generation (KIBB-g2) tabletop Kibble balance for directly realizing [500 mg – 20 g] masses with OIML Class F accuracies

U S A T A
U.S. ARMY TMDE ACTIVITY
METROLOGY AND CALIBRATION

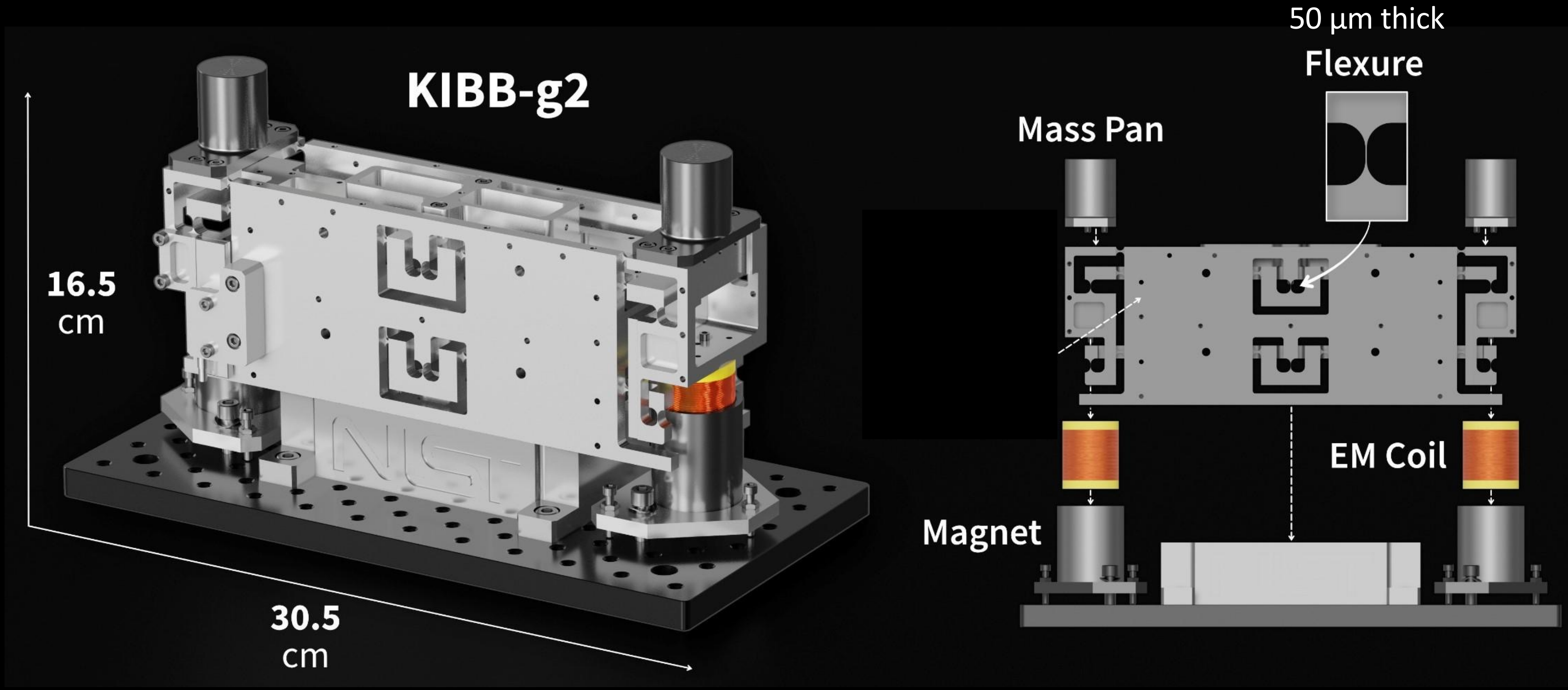


600 mm

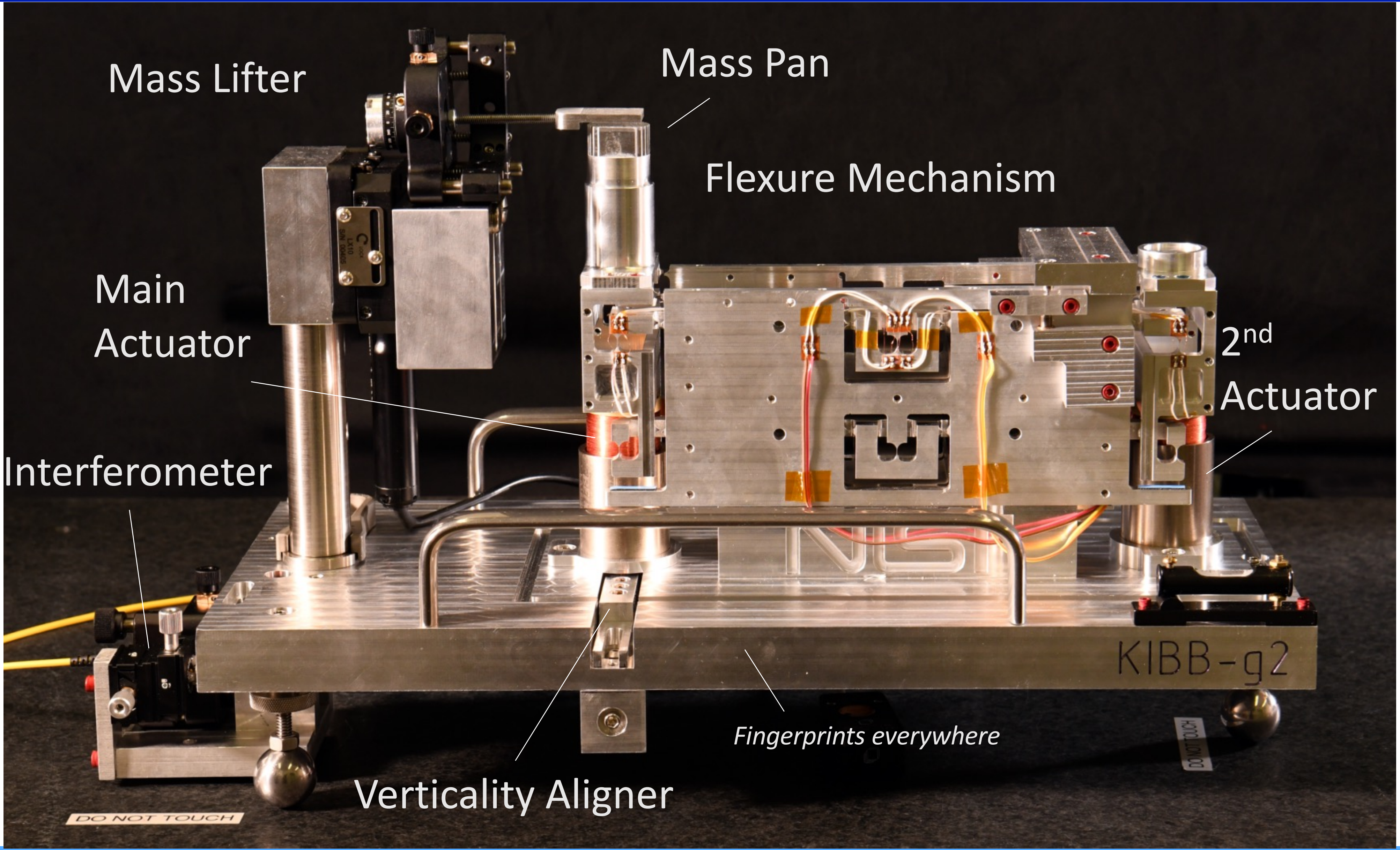
300 mm

KIBB-g2 CAD

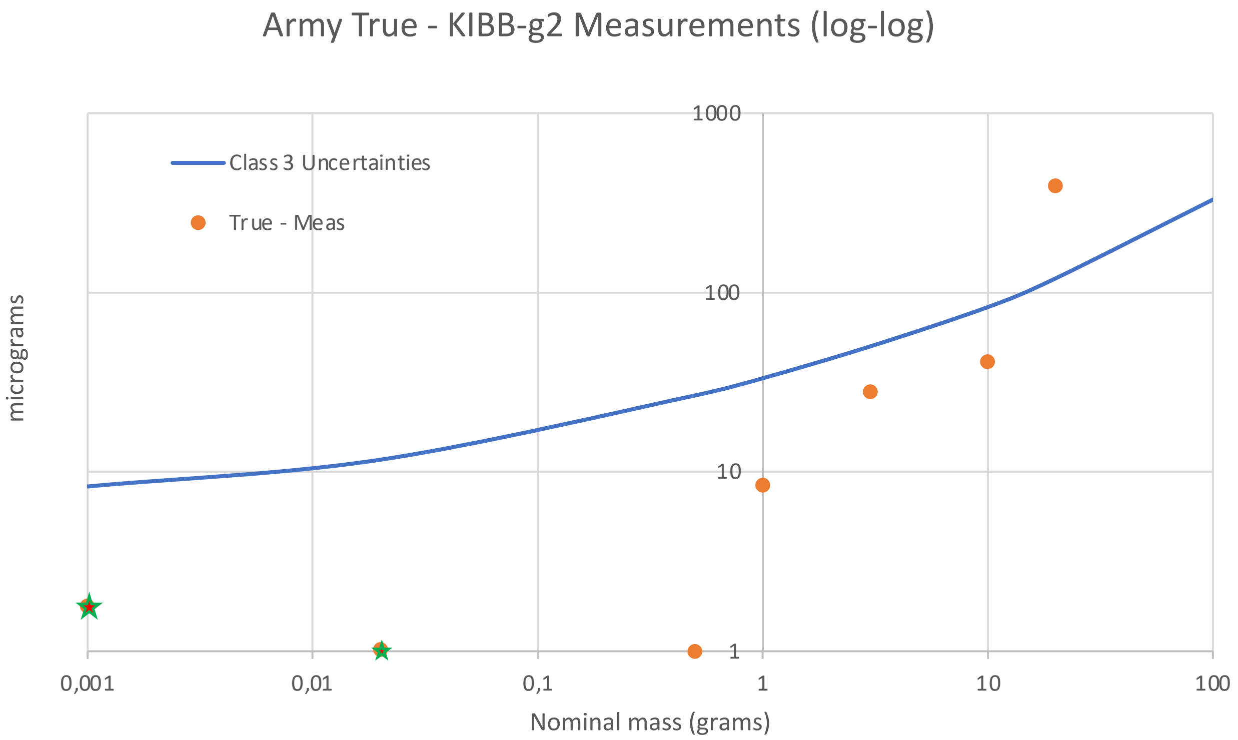
Roberval mechanism



KIBB-g2


Mass Lifter
Mass Pan
Flexure Mechanism
Main Actuator
2nd Actuator
Interferometer
Verticality Aligner
Fingerprints everywhere
KIBB-g2
DO NOT TOUCH

Blind Measurement Results



Nominal	KIBB-g2 (mg)	Army True (mg)	Difference (mg)	Difference (ppm)	Class 3 Allowance (mg)	Class 3 Allowance (ppm)	Meas. Date
20 g	20000.4054	20000.0090	-0.3964	-19.8	0.1200	6.0	4/7/2024
10 g	10000.0092	9999.9680	-0.0412	-4.1	0.0830	8.3	3/27/2024
3 g	2999.9857	2999.9576	-0.0281	-9.4	0.0501	16.7	4/6/2024
1 g	999.9794	999.9879	0.0085	8.5	0.0333	33.3	3/30/2024
500 mg	499.9446	499.9456	0.0010	2.0	0.0267	53.3	4/6/2024
20 mg ★	19.9993	20.0003	0.0010	51.4	0.0117	583.0	3/25/2024
*1 mg ** ★	*0.9982*	*E1 unknown*	*0.0018*	*1800.0*	*0.0083*	*8333.0*	*3/29/2024*

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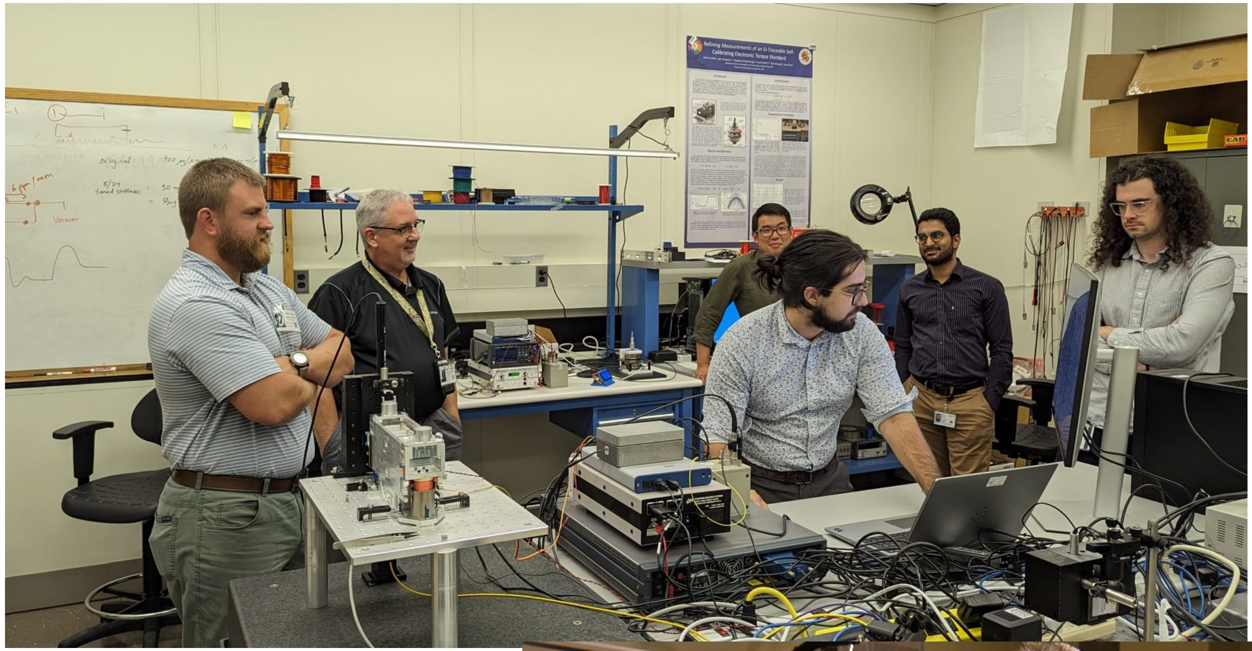
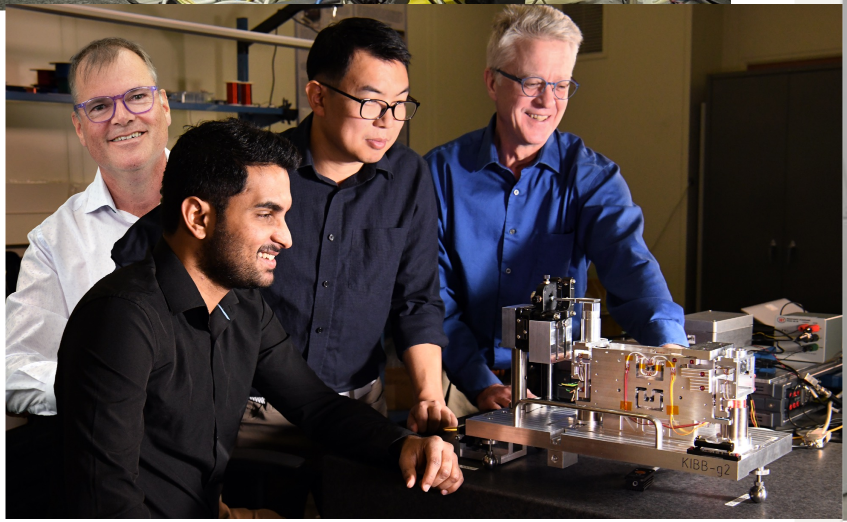
Delivery to Redstone (April 10, 2024)



6 months ago



2 weeks ago

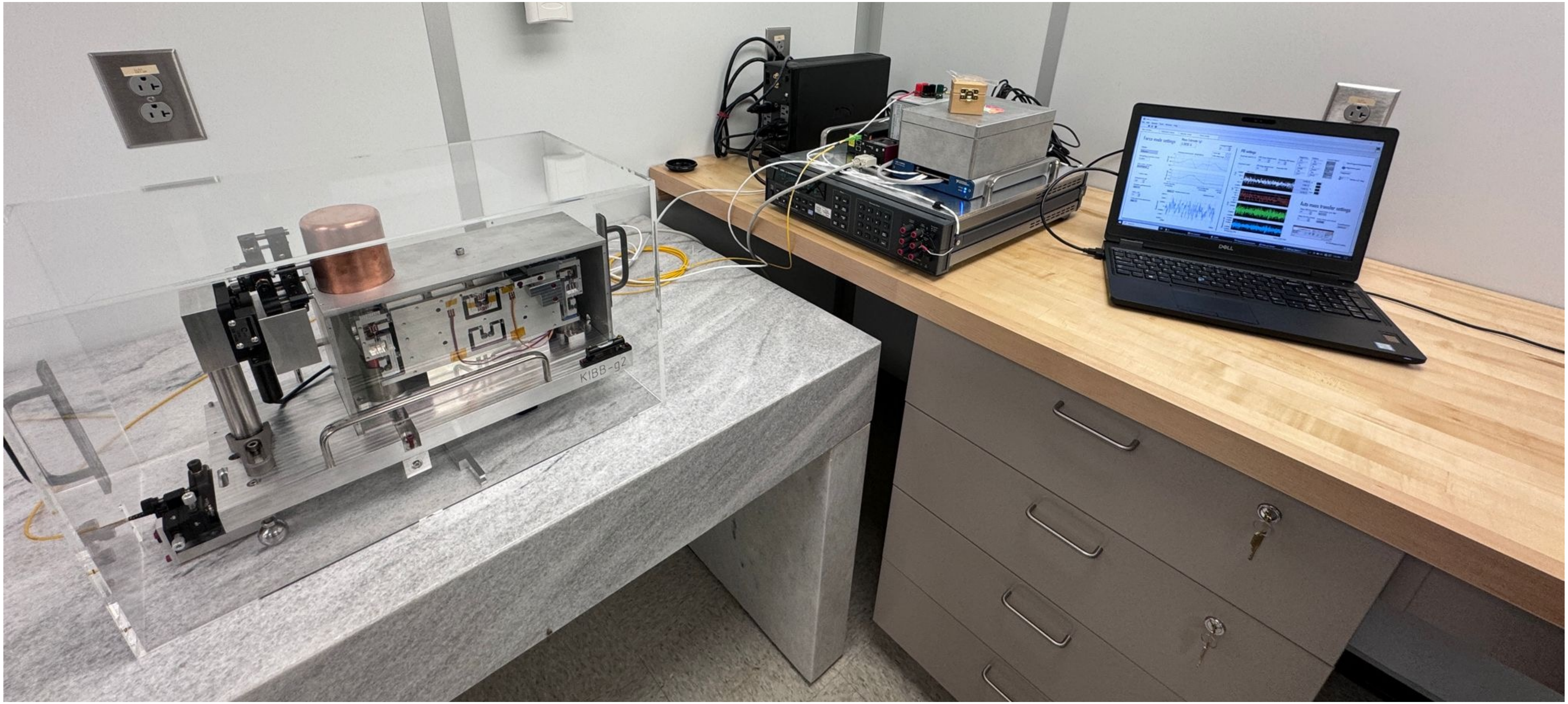
Stephan Schlamminger • 1st
Physicist at NIST
1d • Edited •

in 6 days ago

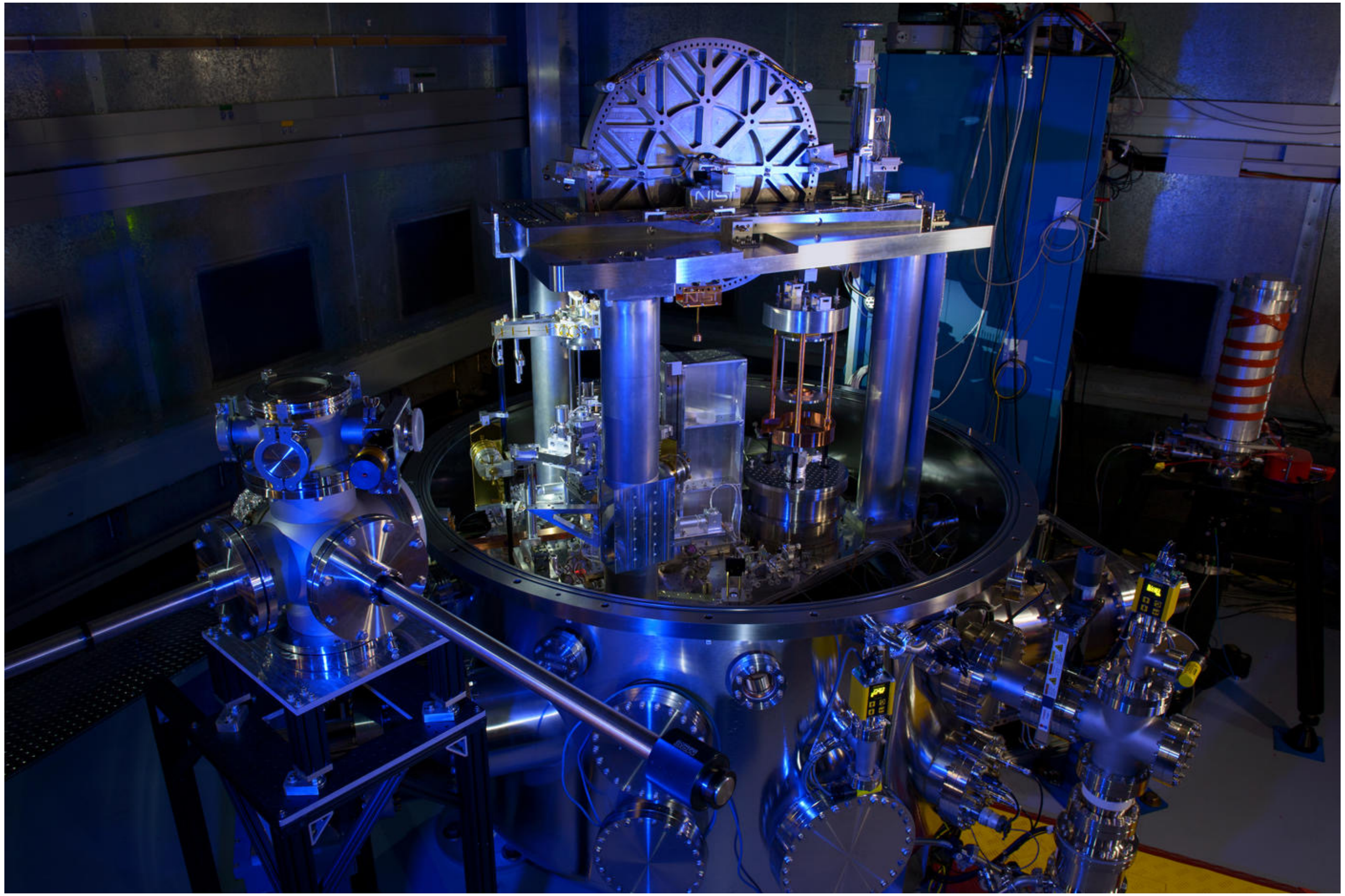
We proposed it, we got funded, we built it, and yesterday, we delivered it. The first professional grade Kibble balance, KIBB-g2, is in the wild at the US Army Primary Standards Laboratory. KIBB-g2 can measure masses ranging from 20 mg to 20 g with uncertainties at or below the level required for weights according to ASTM class 3.
This project was a wild ride, and much credit belongs to Leon Chao and Kumar Arumugam (both in the picture), who spent countless hours in its final stretches. It was so satisfying seeing it working in the mass lab.

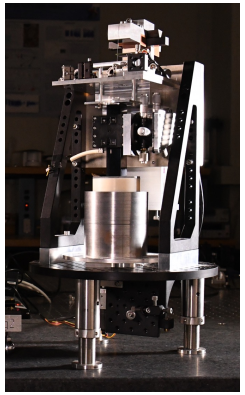
You and 160 others 11 comments • 4 reposts

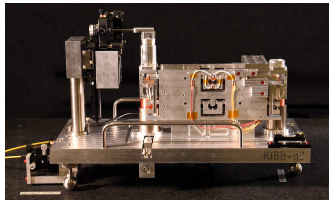
Delivery to Redstone (April 10, 2024)



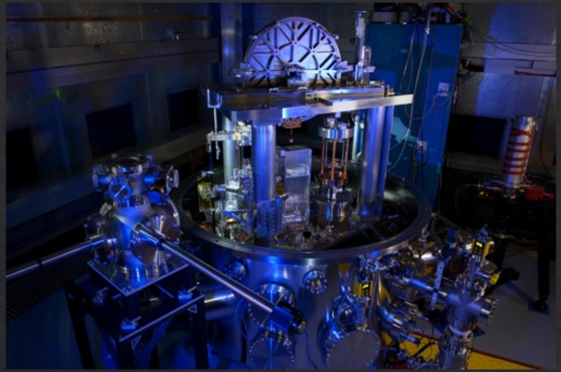
NIST-4 vs KIBB-g1 vs KIBB-g2 to scale





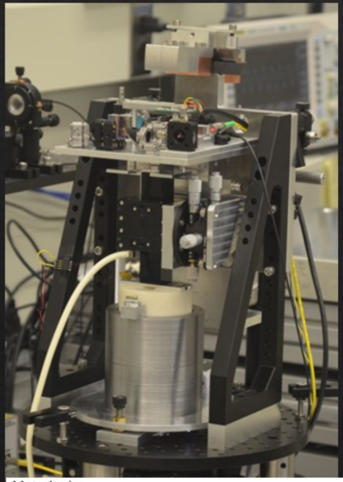


The History of the Tabletop Kibble Balance



2014-2019 NIST-4 Kibble Balance

2017-2019 First Tabletop Kibble Balance



Metrologia

PAPER • OPEN ACCESS

The performance of the KIBB-g1 tabletop Kibble balance at NIST

To cite this article: Leon Chao *et al* 2020 *Metrologia* **57** 035014

2019 Filed Patent (awarded 2021)

US011187571B2

(12) **United States Patent**
Chao et al.

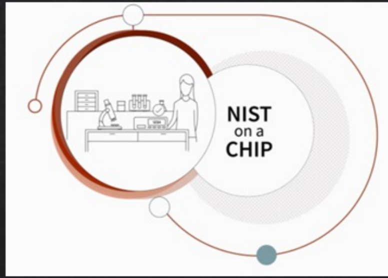
(10) Patent No.: US 11,187,571 B2
(45) Date of Patent: Nov. 30, 2021

(54) ABSOLUTE MASS BALANCE

(71) Applicant: Government of the United States of America, as represented by the Secretary of Commerce, Gaithersburg, MD (US)

(58) Field of Classification Search
CPC G01G 1/18; G01G 1/185; G01G 7/00-7/045; G01G 23/01; G01G 23/10
See application file for complete search history.

(56) References Cited



2019 Inducted into NOAC

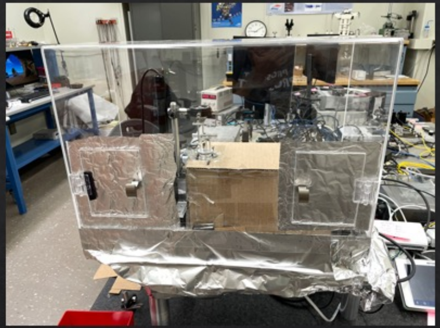
2020 Pitch TTKB at AF

2020 Army Metrology Interest

2021 Army Collaboration

Statement of Work (SOW)
Modernization of Mass Metrology

2021-2023 2nd Gen TTKB



2023 Filed 2nd Patent

US 20230375396A1

(19) **United States**
(12) **Patent Application Publication**
Chao et al.

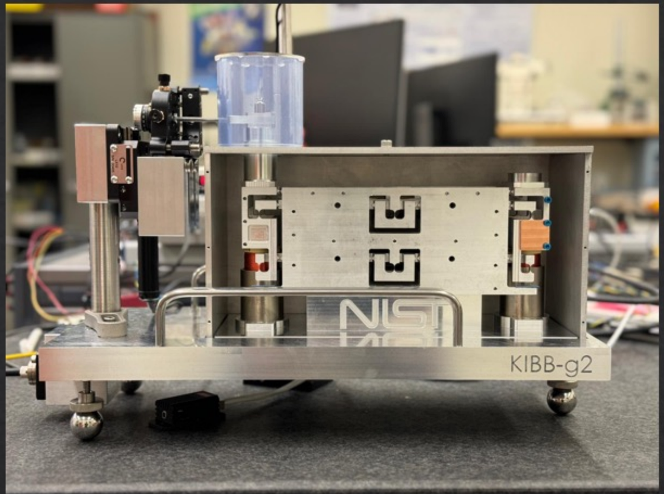
(10) Pub. No.: US 2023/0375396 A1
(43) Pub. Date: Nov. 23, 2023

(54) SECOND GENERATION NIST KIBBLE BALANCE AND DETERMINING ABSOLUTE MASS

G01G 1/29 (2006.01)
G01G 1/24 (2006.01)
(52) U.S. Cl.

2022-2023 NOAC/DOD Demonstrations

2024 Army Deployment in April



2020 Dept. of Defense Interest

- Army USATA SOW on KIBB-g2: 3 year funding for R&D of the next generation tabletop Kibble balance with a focus on design for commercialization at OIML Class F uncertainties [500 mg – 20 g]

- AFMETCAL SOW on torque realization: 3 year funding for the R&D of an absolute torque standard having a dynamic range of 0.1 – 142 ozf-in with 0.1% uncertainty

(0.0007 – 1 N-m)

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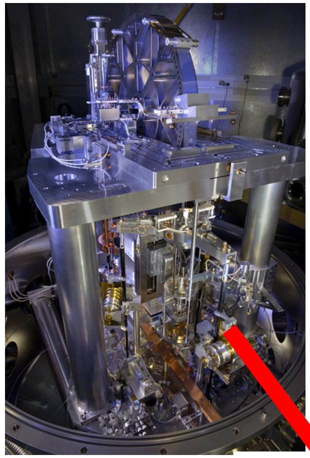
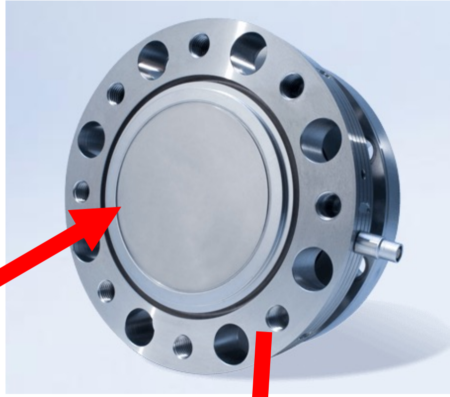
Present State of US Torque Dissemination



NIST mass
0.000001% unc

NIST length
0.00000001% unc

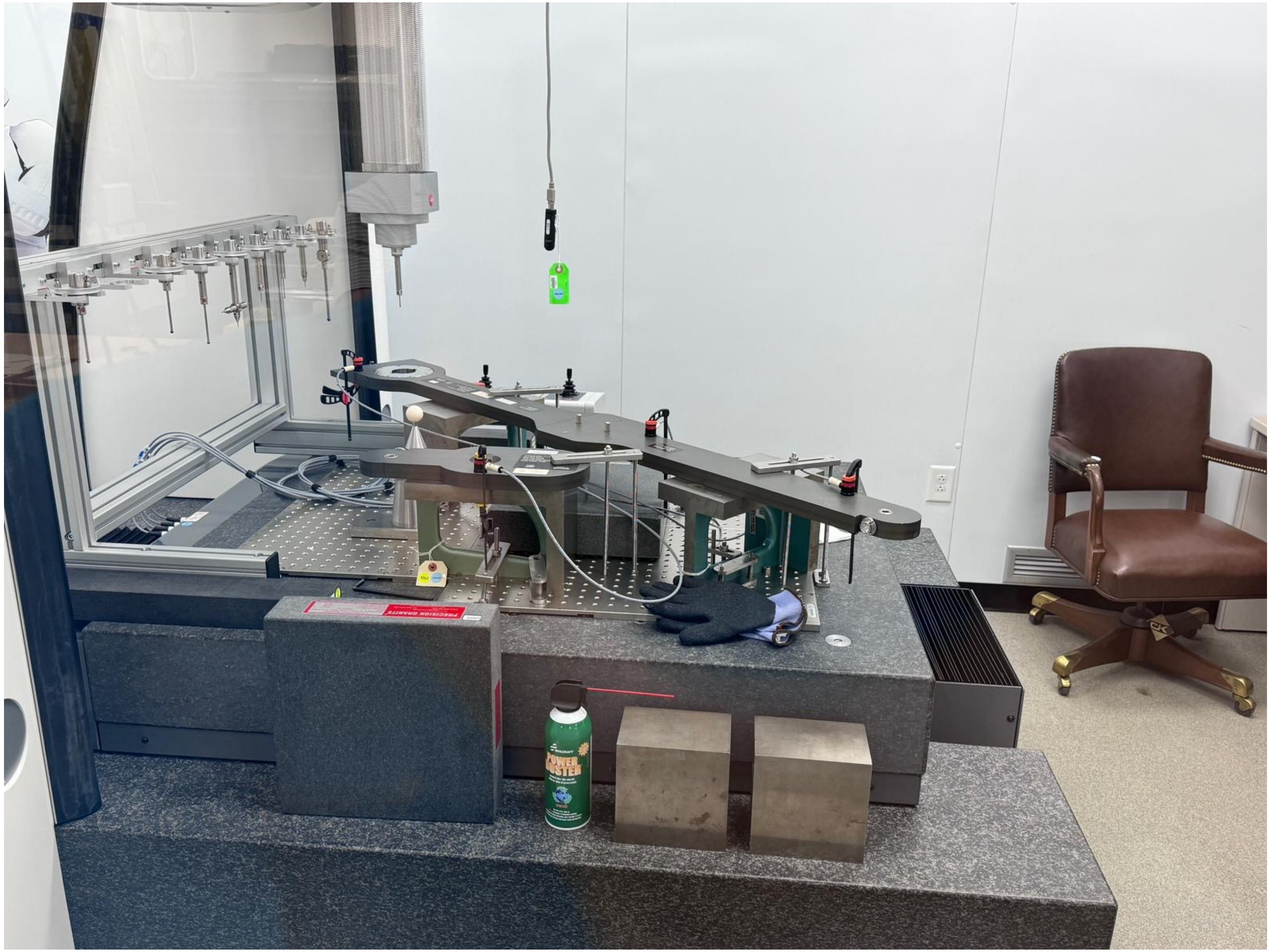
0.002% Uncertainty



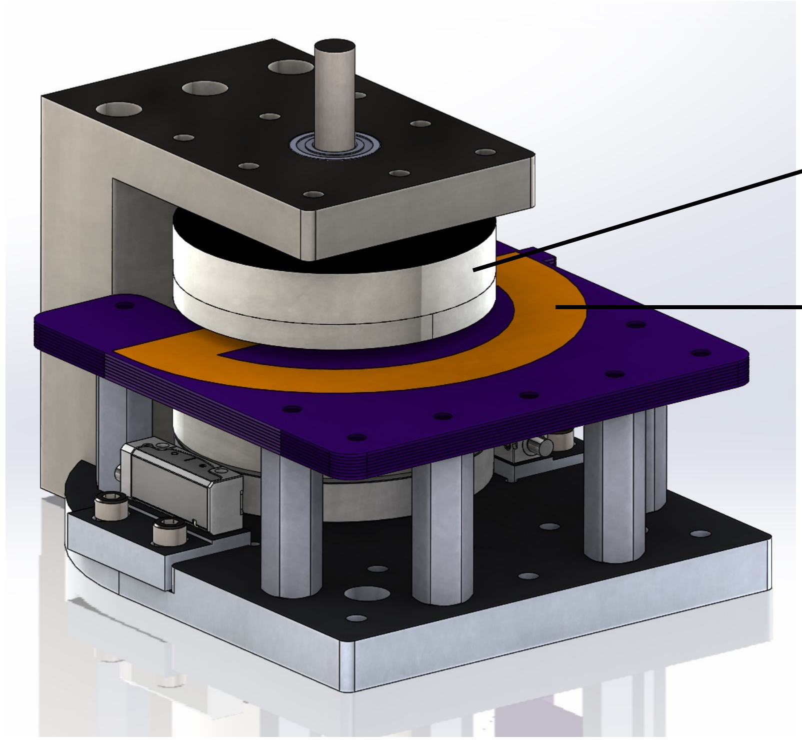
0.25% Uncertainty

2% Uncertainty

How does DOD realize torque?



Electronic NIST Torque Realizer (ENTR v1)



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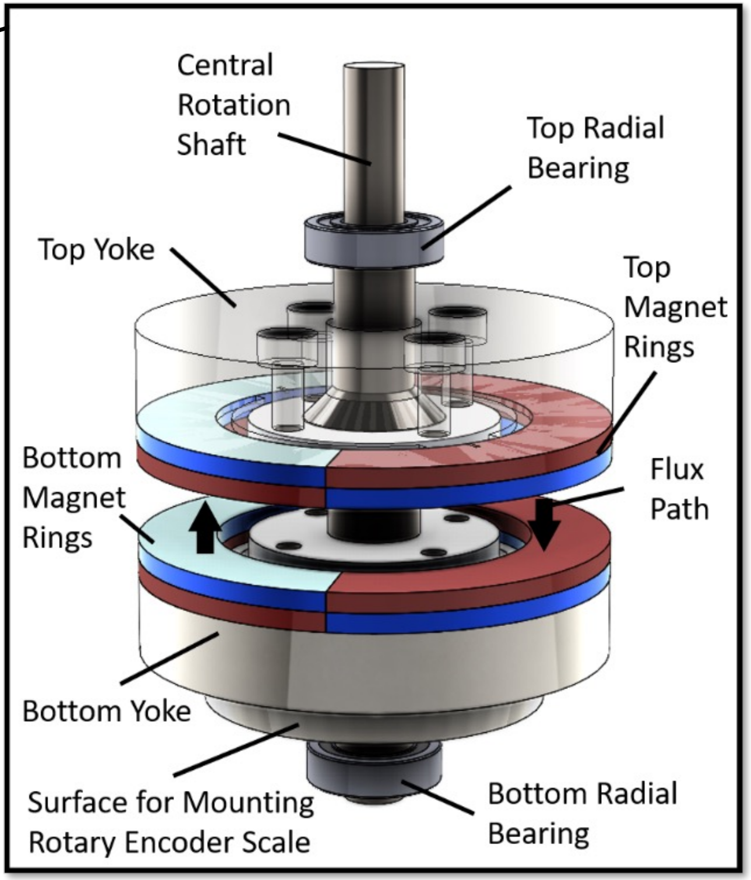


Magnet Assembly

Electronic Torque Realizer (ENTR v1)

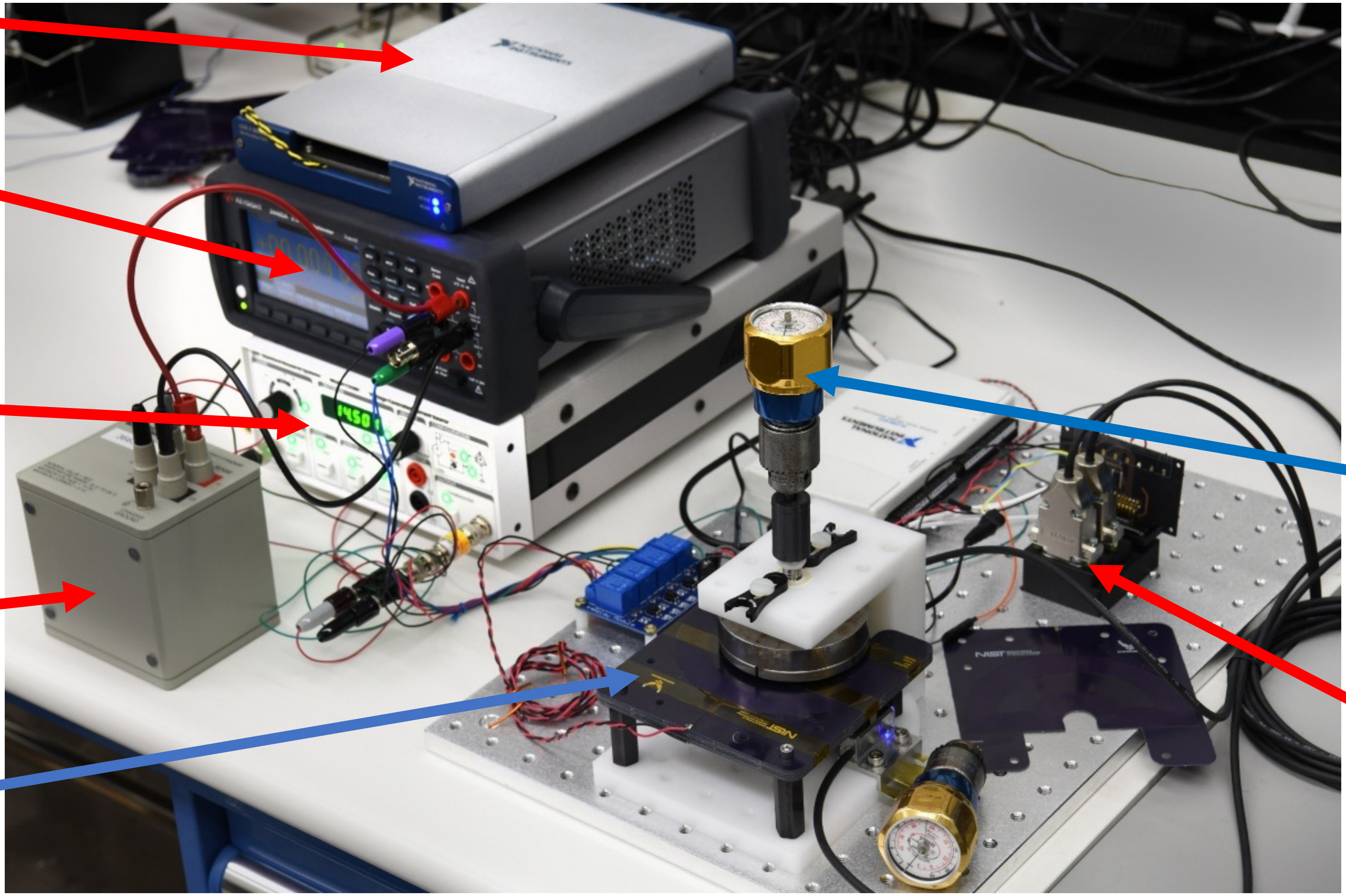
USB DAQ I/O

6.5 Digit Voltmeter

Programmable Current Source

Calibrated Resistor

ENTR



Can produce holding torque up to:

2×10^{-2} N m
(3 ozf-in)

Torque tool under test

Dual read head encoder system

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Third Edition: Future and New Solutions

Results

IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 72, 2023 1005506

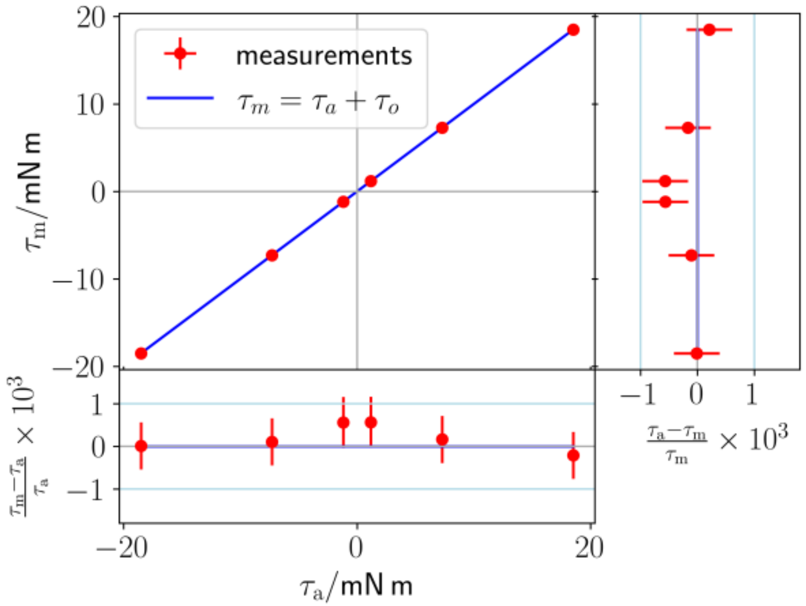
The Design and Performance of an Electronic Torque Standard Directly Traceable to the Revised SI

Zane Comden, John Draganov, Stephan Schlamminger, *Senior Member, IEEE*, Frank Seifert, Charles Waduwarage Perera, David B. Newell, and Leon S. Chao

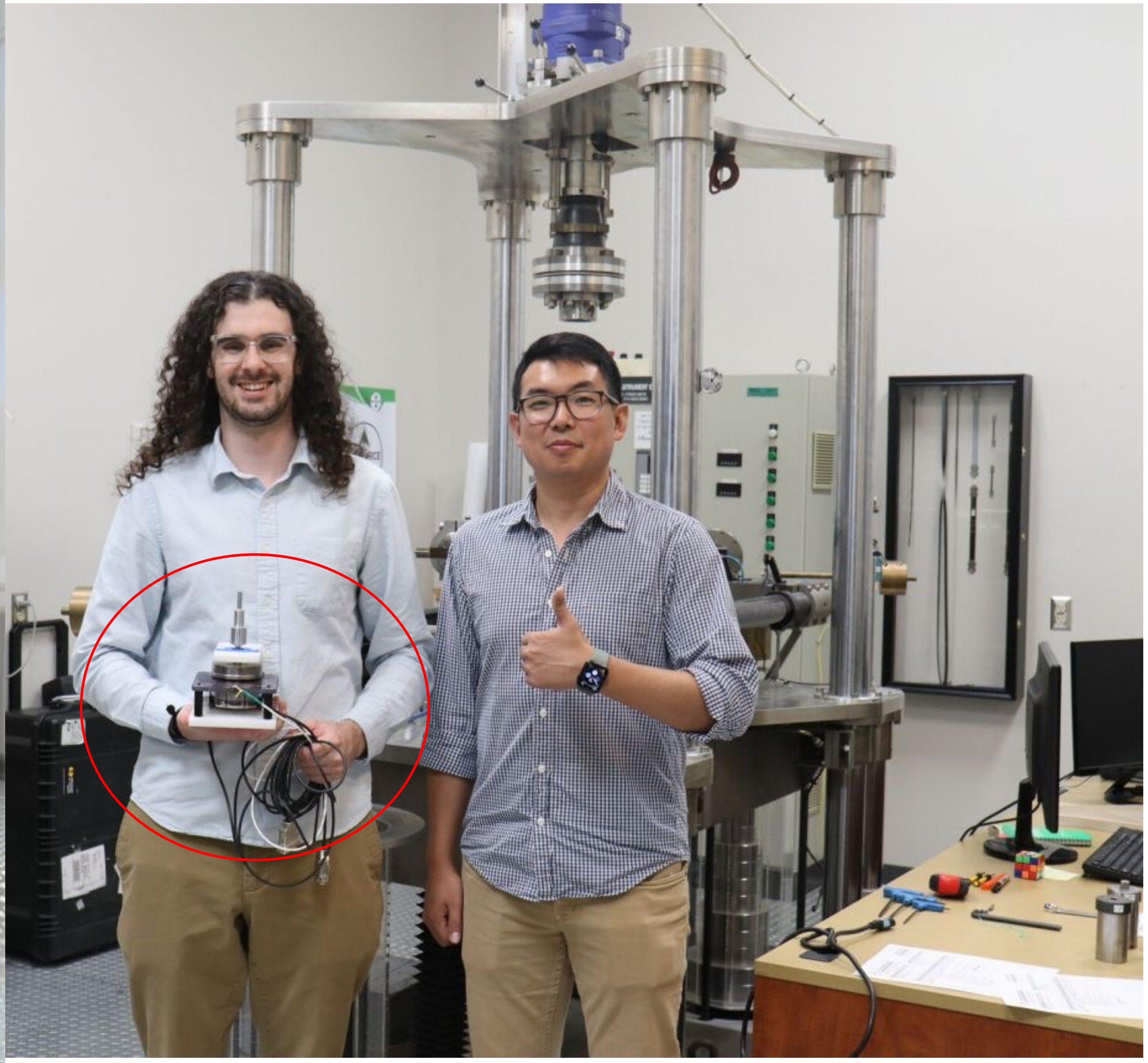
TABLE I

TABLE OF RELATIVE UNCERTAINTIES FOR A 1.18×10^{-3} N m TORQUE VERIFICATION MEASUREMENT. ALL NUMBERS ARE 1 σ UNCERTAINTIES. ENTRIES INDICATED BY <0.01 HAVE RELATIVE UNCERTAINTIES THAT ARE BELOW 10^{-5}

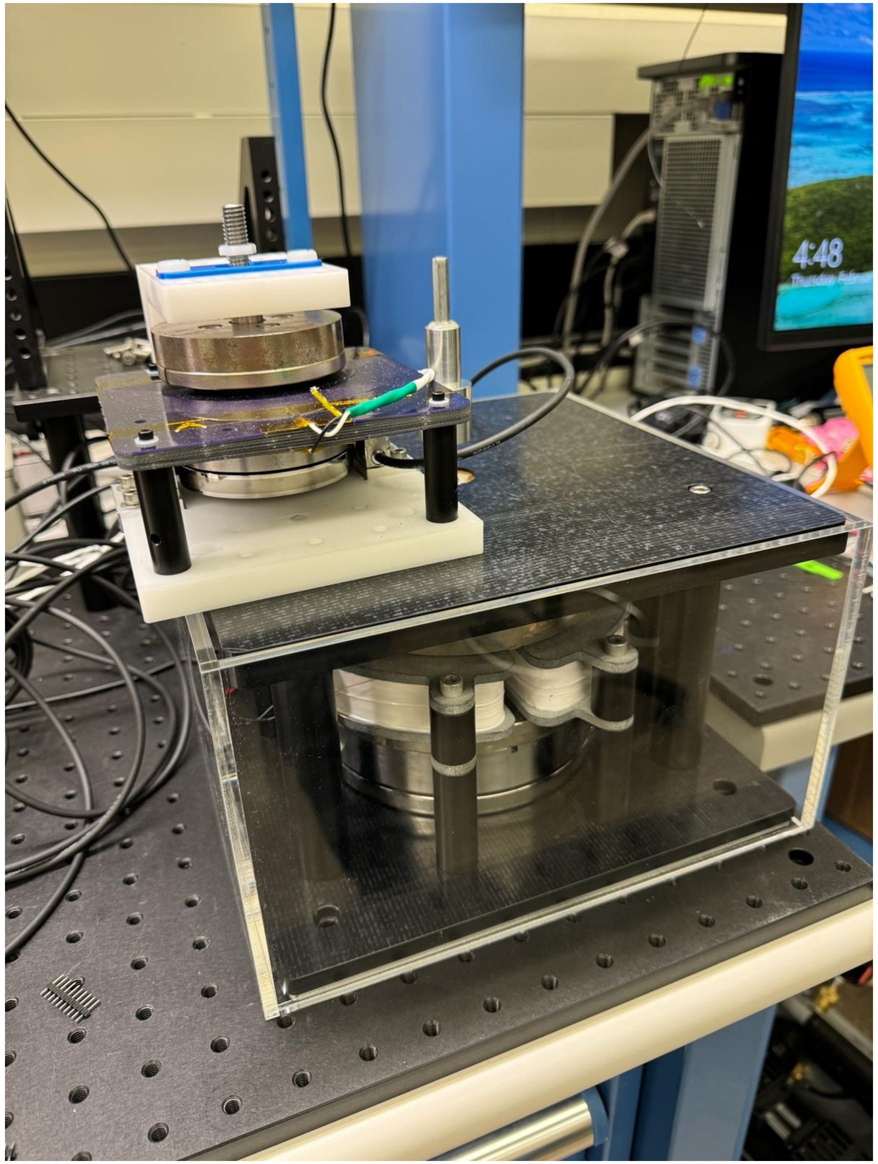
Source	Symbol	rel. unc. $\frac{\tau_a}{1 \times 10^{-3}}$	rel. unc. $\frac{\tau_m}{1 \times 10^{-3}}$
Repeatability	V/R		0.52
Voltage measurement	V		0.24
Profile fitting	$\beta(\phi_o)$		0.12
Encoder	ϕ		0.12
Hardware timing	Δt		0.09
Resistor	R		0.01
DVM sample jitter	δt		<0.01
Mass measurement	m_x	0.40	
Mount hole location	δr_w	0.07	
Diameter of wheel	$2r_w$	0.07	
Radius of fiber	r_f	0.03	
Local acceleration	g	<0.01	
Totals	τ	**0.41**	**0.60**



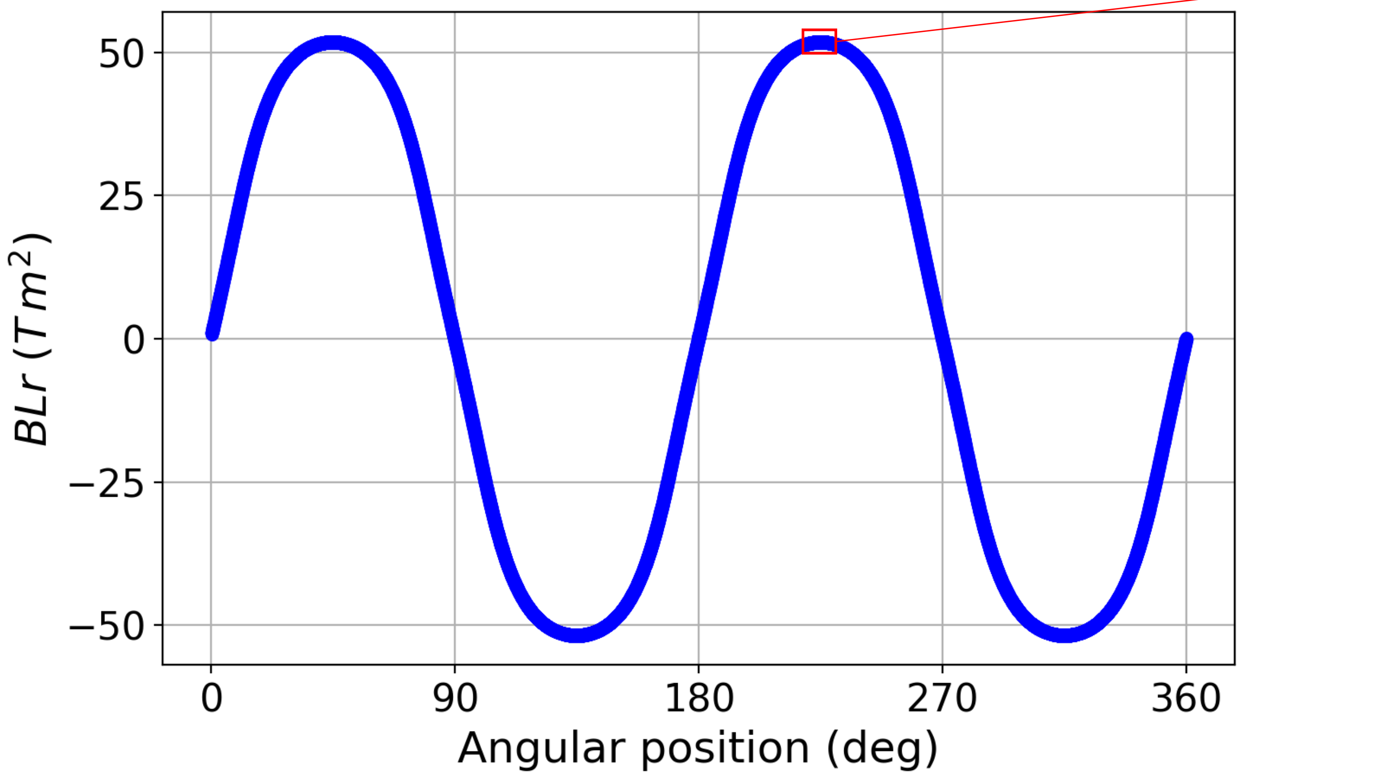
A Paradigm Shift is Coming

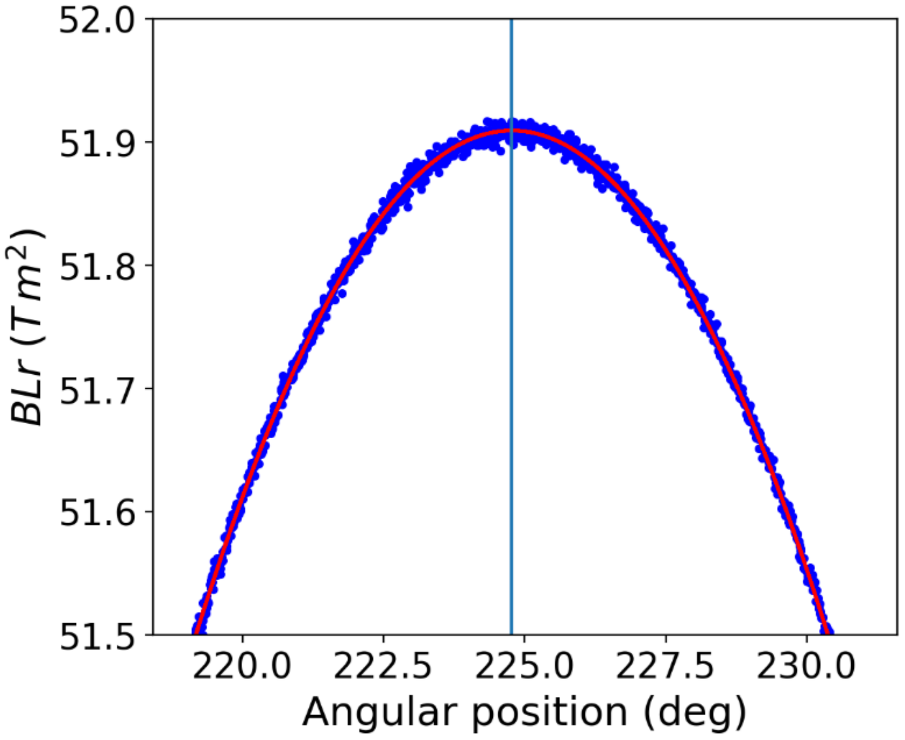


ENTR v1 on top of ENTR v2

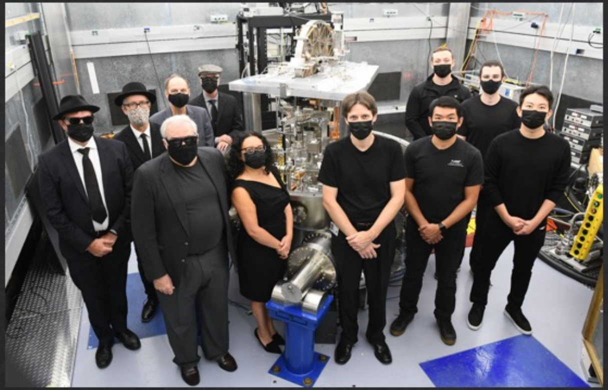


ENTR v2 Preliminary Data



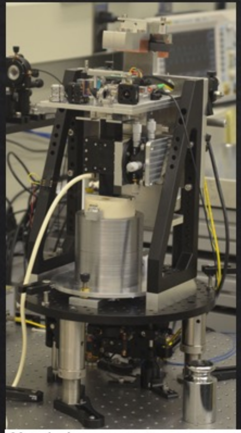


The History of the Electronic NIST Torque Realizer



2014-2019 NIST-4 Kibble Balance

2017-2019 First Tabletop Kibble Balance



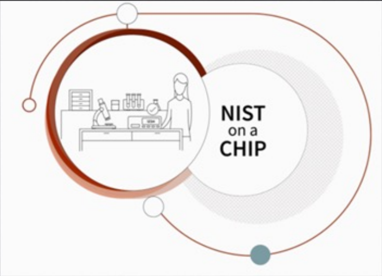
Metrologia

PAPER • OPEN ACCESS

The performance of the KIBB-g1 tabletop Kibble balance at NIST

To cite this article: Leon Chao *et al* 2020 *Metrologia* **57** 035014

2019 Inducted into NOAC



2020 Pitch TTKB at AF

AIR FORCE METROLOGY

The Ah-ha Moment

Wait, you use mass to realize *torque*? Why not directly leverage the *new SI*?!

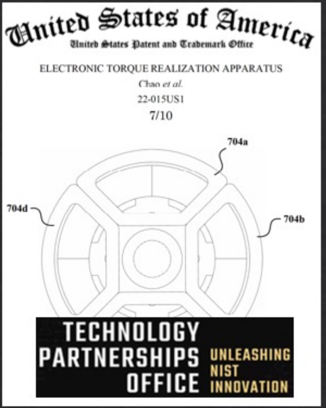
2021-2023 First Tabletop Kibble Torque Standard

ATTACHMENT 1
In Accordance with Support Agreement No. NIST—WNM-20
MIPR# F4FTML

Statement of Work CCG 753
14 September 2020

STATEMENT OF WORK
SI TRACEABLE TORQUE STANDARD (ENTR)
CALIBRATION STANDARD FOR STATIC TORQUE
CCG #753

U.S. AIR FORCE



2022 ENTR Patent

IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, VOL. 72, 2023 1005506

The Design and Performance of an Electronic Torque Standard Directly Traceable to the Revised SI

Zane Comden, John Draganov, Stephan Schlamminger, *Senior Member, IEEE*, Frank Seifert, Charles Waduwarage Perera, David B. Newell, and Leon S. Chao

2023 IEEE Publication

2022-2023 NOAC/DOD Demonstrations

Snap-on

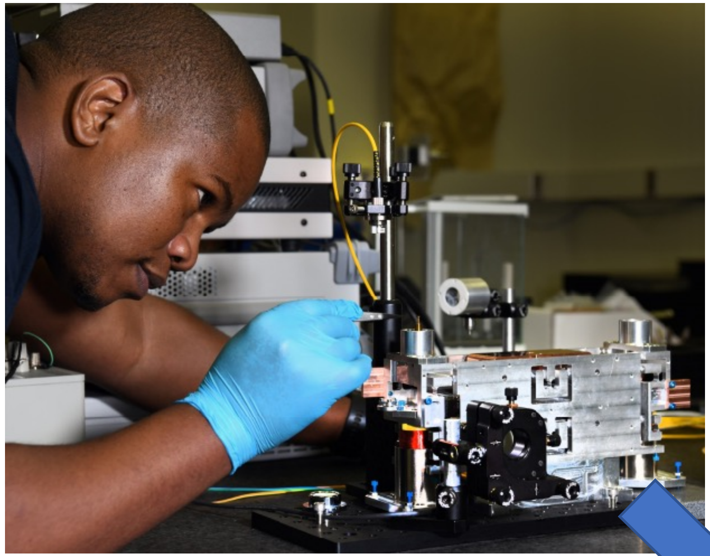
CRADA Identification Number: CN-24-0012
Collaborator: Snap-on Incorporated

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
COOPERATIVE RESEARCH AND DEVELOPMENT AGREEMENT

2024 CRADA Partnership, Snap-On

Ultimate Vision

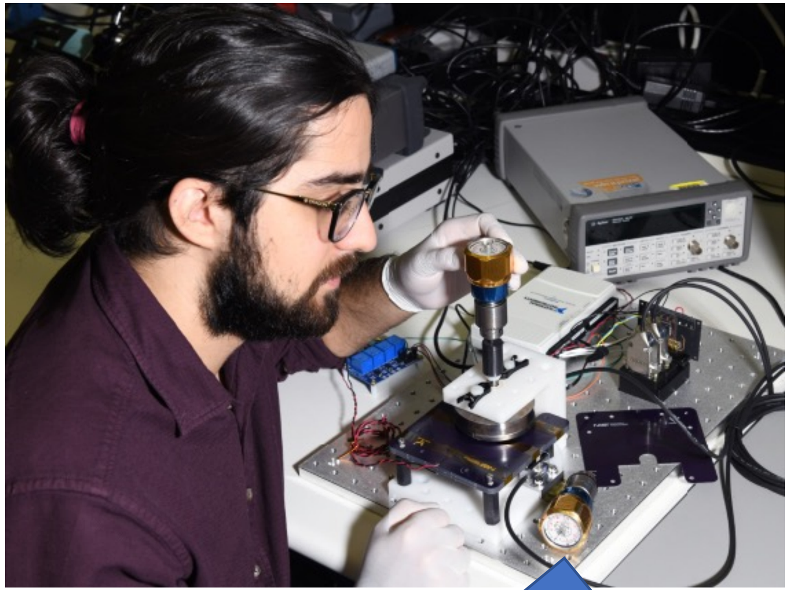
Mass



KIBB-g2

KIBB-g3 ?

Torque



ENTR v1

ENTR v3 ?

METROLOGY SYMPOSIUM
DIGITALIZATION AND AUTOMATION IN MASS METROLOGY
Third Edition: Future and New Solutions

Thank you for your attention

Leon.chao@nist.gov