Status of the BIPM Watt Balance

H. Fang, M. Stock
Present apparatus in the new laboratory

- New mass lifting device
- New weighing pan
- New force comparator, vacuum compatible
- Laser source for interferometers

- Modifications made to accommodate the apparatus
- Also some new components
- Fully operational in air
New components for the watt balance

- In-situ calibration of weighing cell
- Mass exchanger
- Dynamic alignment system
- New magnet

Vacuum: < 0.01 Pa
- No air convection; no air buoyancy
- No air refractive index correction

Most mechanical parts available
- To be integrated into suspension
- Ready for measurements in 2014
Fabrication planning for the new magnet

Last step: assembly
New magnet: fabrication of parts

- Inner cover
- Outer cover
- Housing
- Sm$_2$Co$_{17}$ magnets

- All parts now at BIPM
- All components meet the specifications
- Trial assembly (without the magnets) and uniformity of the gap width verified (<1 µm)
New magnet: verification

Measurement setup for gap detection (assembly without magnets)

2 capacitive sensors in opposition
New magnet: verification

profile at 30°

up  down  up

1 µm

profile at 60°

up  down  up

1 µm
New magnet: assembly nearly finished

Some problems with too tight tolerances: now solved
Sources of the surrounding vibration noise (1)

- Three noisiest units identified
- To be replaced or removed by October 2013
Sources of the surrounding vibration noise

Red: air conditioners ON
Blue: air conditioners OFF

- 28-29 Hz
- 34 Hz
- 48-49 Hz
- 65 Hz
- 18 Hz
Periodical non-linearity error (1)

\[ \Delta \phi = 4\pi \frac{\Delta I}{\lambda_2} \]

\[ I_R = \frac{1}{2} E_0^2 \left[ \cos(2\pi(f_2 - f_1)t) + \Delta \phi_0 \right] \]

\[ I_M = \frac{1}{2} E_0^2 \left[ \cos(2\pi(f_2 - f_1)t) + \Delta \phi_0 + \Delta \phi + \Delta \phi_{nl}(\Delta \phi) \right] \]

Extra phase term: periodic deviations (optical quality & alignment)
Periodical non-linearity error (2)

Example of the observed non-linearity errors (sampling rate of 25 kHz)

1st order non-linearity
Doppler frequency of about 600 Hz

Significant 2nd order non-linearity

short term:  
- better alignment  
- mathematical reduction

long term:  
- new interferometer (2014)  
  with physical separation of beams
Various methods evaluated
- Two of them (averaging and polynomial fitting) used
- Gave similar results in the present measurement conditions

Relative std. dev. (averaging method):
- 1 pt: $2.8 \times 10^{-4}$
- 2 periods: $7.6 \times 10^{-5}$
- 3 periods: $9.3 \times 10^{-5}$
- 6 periods: $3.2 \times 10^{-4}$
Voltage-to-velocity ratio

\[
\frac{U}{v} = BL
\]

\[
\frac{U(z)}{v(z)} \left(1 + \varepsilon_N(z)\right)
\]

Further reduction

- 28 Hz peak
  - \( \rightarrow \) stiffer coil (Macor)

- residual non-linearity error
  - \( \rightarrow \) new interferometer

- vibration noise
  - \( \rightarrow \) investigation under way

- phase resolution
  - \( \rightarrow \) better phase detection

- ..etc.

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\( \sigma = 2 \times 10^{-4} \) (normal coil \( U/v = 500 \text{ V.s/m} \))

\( \sigma = 8 \times 10^{-5} \) (bifilar coil \( U/v = 250 \text{ V.s/m} \))

Position in air gap / mm

Single up measurement
Force measurement

\[ F(z) \left(1 + \varepsilon_N(z)\right) \]

\[ I(z) \]

- 20 mg \(\rightarrow\) \(2 \times 10^{-4}\) (100 g test mass)
- 20 mg
- corrected force \(\sigma = 3 \times 10^{-5}\)
- single up measurement
Next steps
- assembly of the new magnet  done
- integration of new measurement facilities
- vibration reduction (repl. of air cond.)
- new stiffer coil  done
- new alignment reference
- next $h$ measurements spring 2014
- new interferometer (2014)
BIPM watt balance team

Full-time

Hao Fang  
principal physicist

Adrien Kiss  
engineer

Thomas Lavergne  
engineer  
(mechanics, since May 2013 for 2 years)

Part-time

Michael Stock  
(project leader; magnet)

Lennart Robertsson  
(interferometry)

Estefania de Mirandés  
(coil alignment, gravimetry)

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