TASK GROUP ON THE SI (TG-SI) REPORT TO CCT

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Terms of reference: The Terms of Reference follow closely the Recommendation 1 of the 94th meeting of the CIPM in 2005, (CI-2005), "Preparative steps towards new definitions of the kilogram, the ampere, the kelvin and the mole in terms of fundamental constants". The TG-SI is presently tasked with the following two terms:

- monitor closely the results of new experiments relevant to the possible new definition of the kelvin, and to identify necessary conditions to be met before proceeding with changing the definition;
- solicit input from the wider scientific and technical community on this important matter.

The TG-SI members, and a few additional experts (Livio Gianfrani (Univ. Naples), Christophe Daussy (Univ. Paris North), Fernando Pérez (Univ. Valladolid)) covering in particular the field of Doppler broadening thermometry, met to review the present state of the Boltzmann constant determinations at the PTB (Berlin) on 12 March 2013.

This report was requested by the CCT, as stated by the action CCT/A4 of the “Synopsis on the actions and decisions arising from the 26th meeting of the CCT (2012)”. It will be submitted to the CODATA TGFC as well as to the CCU for their 2013 meetings. Compared to the state reported in 2012 in document CCT/12-13 the following progress has been achieved with the different methods:

Acoustic measurements

At the **University of Valladolid** in cooperation with the CEM, a new set of measurements with argon gas has been carried out with their 40 mm radius stainless steel spherical resonator. Special emphasis was given to the purification of the argon gas. Three radial acoustic modes have been used to determine the speed of sound. A complete uncertainty budget has been established with a final result for the relative uncertainty $u(k)/k$ of 20 ppm. The largest contribution originates from the dispersion of the radii determined from 4 different microwave modes.

At the **INRiM**, in cooperation with the LNE-CNAM, the determination of the speed of sound in helium gas is based on the quasi-spherical 50 mm radius copper resonator TCU2. The INRiM cooperated with the Scottish Universities Environmental Research Centre aiming at an accurate determination of the 3He/4He isotopic ratio and the molar fraction of other noble gas impurities in the helium samples. A cross-check of the analyses of gas impurities is planned by using PTB´s mass spectrometer.

Microphone positions where investigated carefully. Results with reduced uncertainties are expected in 2014.

The **LNE-CNAM** repeated the series of measurements of May 2012 using helium gas with the 0.5 liter copper quasi-sphere BCU3 (50 mm radius) but using a new transducer. The relative standard uncertainties were 1.1 ppm and 2.0 ppm respectively and the values are in good agreement with the earlier measurements in argon. The weighted mean of both measurements named LNE3 and LNE4 has a relative standard uncertainty of 0.96 ppm, without taking into account their correlation. For 2014 new results are expected with the 3.1 liter quasi-sphere BCU4 having 90 mm radius to be operated with helium and argon.

The **NPL** concluded analysis of the measurements of 2011 with argon gas and the new 62 mm radius copper sphere. The NPL is publishing a new value for *k* with a relative standard uncertainty of 0.68 ppm. The NPL had extensive gas purity and isotopic composition measurements made on each bottle of argon gas in cooperation with the Scottish Universities Environmental Research Centre.

A single 80 mm fixed-path-length cylindrical cavity resonator was used at the **NIM** to measure the speed of sound in argon at pressures ranging from 50 kPa to 550 kPa. This cavity differs from their 2010 version by a different length, the suspension for the cylinder and an improved bond between fill duct and cavity with a new position. Up to 4 longitudinal modes were used in the measurements and the inconsistency among the modes has been reduced from 7.9 ppm in the 2010 determination to 2.9 ppm in the current one. Small mode-dependent inconsistencies remained in all three runs, indicating that the cylindrical cavity is still imperfect. The results of *k* for run II and run III deviated by 2.7 ppm in a consistent way. The NIM/NIST group suspects that the measured mass M_{Ar} in one or both gas samples was erroneous. Eventually, the NIM will determine M_{Ar} for the working gases by comparison with an isotopically enriched sample of Ar-40. The average of all 3 runs gives a value for *k* with a relative standard uncertainty of 3.7 ppm which will be published in 2013. The next step will be applying a two cylinder arrangement with lengths *l* and 2*l*. Perturbations arising from endplate bending, transducers, ducts, etc. will be completely reduced in principle, as well as the relating halfwidths, if the geometric dimension of the perturbation structure is identical for both cylinders.

The largest uncertainty in the **acoustic values** of *k* determined with **argon** originates in the determination of the relative argon isotopic abundances. The NPL and the LNE-CNAM used different traceability chains. Therefore, their values for the mass M_{Ar} are uncorrelated. Unfortunately their results disagree which means that at least one institute has underestimated its uncertainty. This disagreement is most serious. The reason for the discrepancy is investigated at the LNE-CNAM; if the discrepancy cannot be resolved, the CODATA TGFC may enlarge the uncertainties attributable to the acoustic measurements with argon and the impact of many years of extraordinary work would be reduced.

Noise thermometry

The quantum-voltage calibrated Johnson-noise thermometer developed recently at the **NIM** in cooperation with the NIST and the MSL was further developed and first results were obtained. It measures *k* by comparing the thermal noise across a 100 Ω resistor with the pseudo-random frequency-comb voltage waveform synthesized with a bipolar-pulse-driven quantum-voltage-noise source. A commercial 20-bit analog-to-digital converter was used. The flat ratio between the thermal noise and the calculated quantum voltage noise up to 800 kHz, and self-consistent fitting results with different bandwidths, indicate that the systematic uncertainties are greatly reduced. A combined relative standard uncertainty of 7.8 ppm was achieved by accumulating 14 measurement results involving 140 h of measurement time. With further improvements the NIM anticipates an electronic measurement of *k* with a relative standard uncertainty of 6 ppm in the near future.

The quantum-voltage calibrated Johnson-noise thermometer system has been pioneered, developed and improved by the **NIST** over a couple of years. The NIST doubled the sense resistance from 100 Ω to 200 Ω and attempted wider bandwidth electronics, the former enabling a lower statistical uncertainty for the same integration period. The biggest challenge has been matching the transmission line from both signal sources, which is crucial to obtain a flat frequency response. So far they were not able to match both channels at the same time due to technical difficulties. However, applying an integration time of 94 h a type A uncertainty of 4 ppm was obtained. At the same time the NIST is developing a more advanced system for a more efficient measurement: The 2 channel-system will be replaced by a 4 channel-system in a more compact setting with a 4-channel ADC-readout. The bandwidth of the system will be increased by switching to amplifiers with increased bandwidth, with lower or comparable noise and higher linearity.

Very recently at the **NMIJ** a Johnson noise thermometry project based on a quantum voltage noise source has been started. The Josephson junction array chip and the 100 Ω resistor probe were independently developed for this project. A statistical uncertainty of 20 ppm within an 18 h measurement time has been obtained. First results for the Boltzmann constant will be presented at TEMPMEKO 2013.

Dielectric-constant gas thermometry

The **PTB** applies dielectric-constant gas thermometry using helium as measuring gas with theoretically calculated polarizability. A reduction of uncertainty was achieved in 2012 by the use of tungsten-carbide cylindrical capacitors featuring at least a factor of two lower effective compressibility. Improvements of the design of the cylindrical capacitors, involving in particular issues on stray capacitances, isolating materials and assembly, yielded a considerably improved stability during pressure cycling. Also the capacitance bridge was optimized concerning shielding and current equalizing, which resulted in an increase in sensitivity of an order of magnitude. Further progress has been the better temperature stability along the pressure sensing tubes and the refined gas purity measurements by mass spectroscopy. It is expected to publish in 2013 a value for *k* with a relative standard uncertainty around 3 ppm. In 2014, the use of tungsten-carbide ring-shaped cross capacitors and improved pressure determinations opens the possibility to achieve a 2 ppm uncertainty.

Doppler broadening methods

At the **University Paris North** (LPL) a complete analysis of the lineshape of ammonia at 10.35 µm was performed based on a speed-dependent Voigt profile corrected for hyperfine structure. In 2013, a value of *k* with a relative standard uncertainty below 10 ppm will be published. The LPL anticipates a large reduction of the main source of uncertainty coming from collisional effects by using a multi-path gas cell at a pressure around 1 Pa, and a reduction of the statistical uncertainty below 6.4 ppm using quantum cascade lasers.

At the **Second University of Naples** and the Polytechnic of Milan the analysis of spectra acquired in 2011 with the H_2O line at 1.38 µm was continued and demonstrated a statistical uncertainty of 3.6 ppm. A further refinement in a restricted pressure range from 200 Pa to 500 Pa with a partially-correlated speed-dependent hard-collision model for the line shape resulted in a value of *k* with 21 ppm relative standard uncertainty including a 15 ppm statistical contribution. Further reduction of uncertainties is expected by improving the frequency stability of the lasers and by using a long path absorption cell.

Table 1: Development of the relative standard uncertainties for determining the Boltzmann constant *k* applying different methods and involved active institutes. The preliminary uncertainty of the 2013 determination of the LNE-CNAM with Helium gas is derived from a weighted mean of measurements LNE 3 and LNE 4 (see below) without consideration of correlations.

Method	gas	up to 2011	2013	2014 possibility	institute
AGT	Ar	-	20 ppm	?	CEM+UVa
AGT	He	**7.5 ppm**	-	?	INRiM
AGT	He	**2.7 ppm**	0.96 ppm	0.6 ppm	LNE-CNAM
AGT	Ar	**1.2 ppm**	-	?	LNE-CNAM
AGT	Ar	7.9 ppm	3.7 ppm	?	NIM
AGT	Ar	**3.1 ppm**	0.68 ppm	-	NPL
DCGT	He	7.9 ppm	3 ppm	2 ppm	PTB
JNT	-	-	7.8 ppm	6 ppm	NIM
JNT	-	12 ppm	-	5 ppm	NIST
JNT	-	-	80 ppm	< 20 ppm	NMIJ
DBT	NH_3	50 ppm	< 10 ppm	?	LPL+LNE-CNAM
DBT	H_2O	160 ppm	21 ppm	?	UniNA+INRiM

Table 1 gives an updated **summary overview** of the potentials of the presently relevant primary thermometers for the institutes where research work to determine *k* is continued. It has been deduced from the meeting of TG-SI in March 2013 and compared to the findings described in the report of 2012, document CCT/12-13. The uncertainties of the determinations taken into account in the **CODATA adjustment of 2010 are marked in bold** in the third column. Within 2014, it exists the possibility of achieving a relative standard uncertainty for the adjusted value of the Boltzmann constant *k* at around 0.5 parts in 10^6 (0.5 ppm) based on measurements applying different methods.

Correlations

The TG-SI discussed in detail the importance of correlations between measurements carried out using the same method. Roberto Gavioso's correlation worksheets were the base for the evaluation of correlations between the acoustic measurements in the CODATA adjustment of 2010. Mike Moldover is willing to look at these worksheets critically and will make recommendations to Roberto Gavioso in order to update the worksheet, and to revise it if necessary. The resulting correlation worksheet will be forwarded to the CODATA TGFC for the next adjustment with the endorsement of the TG-SI.

Most evident are the correlations in the numerous French acoustic determinations of the Boltzmann constant. For easy reference, Laurent Pitre provided the following overview of the measurements performed so far. Table 2 lists the main features of these experiments from which possible correlation can be judged. LNE 1 and LNE 2 denote the measurements that contributed to the CODATA 2010 adjustment. Between LNE 1 and LNE 2 correlations of 3.2 % were taken into account by the CODATA TGFC. As the more recent measurements all use the resonator BCU3 it is expected that the correlations between them will be significantly larger.

Table 2: Overview about Boltzmann constant determinations performed at the LNE-CNAM

denomination	**LNE 1**	**LNE 2**	**LNE 3**	**LNE 4**
gas	Helium	Argon	Helium	Helium
date	April 2009	Dec 2010	May 2012	Jan 2013
resonator	0.5 L quasi-spherical copper resonator, hand polished inner surface	BCU3: 0.5 L quasi-spherical copper resonator, diamond turned inner surface	BCU3: 0.5 L quasi-spherical copper resonator, diamond turned inner surface	BCU3: 0.5 L quasi-spherical copper resonator, diamond turned inner surface
transducer changed	-	-	-	with new transducer
thermostat	thermostat a	thermostat b	thermostat b	thermostat b
thermometer	thermometer α	thermometer β	thermometer β	thermometer γ
gas handling	gas handling Λ	gas handling Φ	gas handling Λ'	gas handling Λ'
relative uncertainty / ppm	2.7	1.2	1.1	2.0

Conditions for the new definition of the kelvin

The TG-SI reviewed Recommendation T2 (2010) of the CCT submitted to the CIPM and agreed that the conditions included in the document are still valid and scientifically sound. Further, the TG-SI took into account the 1% cut-off criterion of the CODATA TGFC which means that for a result to be included in the adjustment, its uncertainty must be no more than a factor of 10 larger than the uncertainty of the adjusted value of that quantity. Considering in Table 1 the envisaged results and their uncertainties for 2013, it was concluded that with the acoustic thermometry and the dielectric constant gas thermometry two independent methods would presently contribute to an adjusted value of the Boltzmann constant. Hence, the conditions in recommendation T2 (2010) would be fulfilled.

In 2014, even more methods may contribute. However, in the very improbable case that the adjusted value of the Boltzmann constant would be significantly below 0.5 ppm, the 1% cut-off criterion may lead to the exclusion of the dielectric constant gas thermometry contribution. Hence, another method with sufficiently low uncertainty would be required to fulfil the CCT conditions for a new definition of the kelvin.

Due to the inconsistency of the present available data relevant to the redefinition of the kilogram and the unlikelihood of new data becoming available to resolve the current discrepancies in time to report at the 2013 CCU meeting a new timescale very recently proposed by the CCM is under discussion. Nevertheless, to be included in the CODATA report for the 2013 CCU meeting, authors must submit their results to the CODATA TGFC by **10 June 2013**.