Bureau International des Poids et Mesures

Consultative Committee for Length (CCL)

Report of the 11th meeting
(11 – 12 September 2003)
to the International Committee for Weights and Measures

Comité international des poids et mesures

Bureau international des poids et mesures

Organisation intergouvernementale de la Convention du Mètre

Note:

Following a decision made by the International Committee for Weights and Measures at its 92nd meeting in October 2003, reports of meetings of Consultative Committees will henceforth be published only on the BIPM website in the form presented here.

Full bilingual printed versions in French and English will no longer appear.

T.J. Quinn,
Director BIPM,
November 2003

LIST OF MEMBERS OF THE CONSULTATIVE COMMITTEE FOR LENGTH
as of 11 September 2003

President

Dr Chung Myung Sai, member of the International Committee for Weights and Measures, University of Science and Technology, Daejeon.

Executive Secretary

Prof. A.J. Wallard, International Bureau of Weights and Measures [BIPM], Sèvres.

Members

Bureau National de Métrologie, Institut National de Métrologie [BNM-INM], Paris.

Centre for Metrology and Accreditation/Mittatekniikan Keskus [MIKES], Helsinki.

Centro Nacional de Metrología [CENAM], Querétaro.

Czech Metrology Institute/Český Metrologický Institut [CMI], Prague.

D.I. Mendeleyev Institute for Metrology, Gosstandart of Russia [VNIIM], St Petersburg.

Istituto di Metrologia Gustavo Colonnetti of Consiglio Nazionale delle Ricerche [IMGC-CNR], Turin.

Korea Research Institute of Standards and Science [KRISS], Daejeon.

National Institute of Metrology [NIM], Beijing.

National Institute of Standards and Technology [NIST], Boulder and Gaithersburg/Joint Institute for Laboratory Astrophysics [JILA], Boulder.

National Measurement Laboratory CSIRO [NML-CSIRO], Lindfield.

National Metrology Institute of Japan, Advanced Institute of Science and Technology [NMIJ/AIST], Tsukuba.

National Metrology Institute of Turkey/Ulusal Metroloji Enstitüsü [UME], Gebze-Kocaeli.

National Physical Laboratory [NPL], Teddington.

National Research Council of Canada [NRC], Ottawa.

NMi Van Swinden Laboratorium/Nederlands Meetinstituut [NMi VSL], Delft.

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig.

Slovak Institute of Metrology/Slovenský Metrologický Ústav [SMU], Bratislava.

Swiss Federal Office of Metrology and Accreditation/Office Fédéral de Métrologie et d'Accréditation [METAS], Bern-Wabern.

The Director of the International Bureau of Weights and Measures [BIPM], Sèvres.

Observers

Centro Español de Metrologia [CEM], Madrid.
CSIR, Division of Production Technology [CSIR-NML], Pretoria.
Standards, Productivity and Innovation Board [SPRING], Singapore.

1 OPENING OF THE MEETING; APPOINTMENT OF RAPPORTEURS; APPROVAL OF THE AGENDA

The Consultative Committee for Length (CCL)* held its 11th meeting at the International Bureau of Weights and Measures (BIPM), Sèvres, on Thursday 11 and Friday 12 September 2003. Four sessions were held.

The following delegates were present: P. Balling (CMI), R.H. Bergmans (NMi VSL), F. Bertinetto (IMGC-CNR), N. Brown (NML-CSIRO), M.S. Chung (President of the CCL), C.I. Eom (KRISS), R. Fira (SMU), S. Gao (NIM), P. Gill (NPL), J. Helmcke (PTB), L.W. Hollberg (NIST), P. Juncar (BNM-INM), A. Korolev (VNIIM), A. Lassila (MIKES), A. Lewis (NPL), A. Madej (NRC), H. Matsumoto (NMIJ/AIST), A. Onae (NMIJ/AIST), J. Pekelsky (NRC), T.J. Quinn (Director of the BIPM), D. Rovera (BNM-SYRTE), A. Sacconi (IMGC-CNR), H. Schnatz (PTB), J. Stone (NIST), R. Thalmann (METAS), G.-P. Vailleau (BNM-LNE), M. Viliesid (CENAM), T. Yandayan (UME).

Observers: E. Prieto (CEM), O. Kruger (CSIR-NML), S.L. Tan (SPRING).

Guest: Y.S. Domnin (VNIIFTRI).

Also present: P. Giacomo (Emeritus Director of the BIPM); R. Felder, L.-S. Ma, S. Picard, L. Robertsson, A. Samuel, C. Thomas, L.F. Vitushkin, A.J. Wallard (Executive Secretary of the CCL and Director designate of the BIPM), M. Zucco (BIPM).

Dr Chung welcomed the participants to the 11th meeting of the Consultative Committee for Length (CCL). The various participants introduced themselves.

Dr Quinn welcomed the participants on behalf of the BIPM and Prof. Wallard gave some information on security and safety.

Dr Sacconi and Dr Lewis were thanked for their work in preparing the previous minutes. They were kindly asked if they would perform the same role for this meeting. There were no objections, so they were appointed as rapporteurs for the 11th meeting.

2 REPORT ON ACTIONS ARISING FROM THE SEPTEMBER 2001 MEETING

All actions listed in the report of the 10th meeting of the CCL had been carried out. Prof. Wallard addressed the issue raised previously by the CCL Working Group on Dimensional Metrology (WGDM) concerning customs problems encountered when circulating artefacts. The next General Conference on Weights and Measures (CGPM) would have before it a Draft

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* For the list of acronyms, click here.

Resolution on the transfer of artefacts for key comparisons, asking Governments for help where possible.

3 IMPLEMENTATION OF THE MUTUAL RECOGNITION ARRANGEMENT (MRA): REPORT BY THE DIRECTOR OF THE BIPM

Dr Quinn addressed the meeting. On Wednesday 15 October 2003, he would present, to directors of the national metrology institutes (NMIs), a report on the progress to date of the MRA, including details concerning the progress made through the meetings of the Joint Committee of the Regional Metrology Organizations and the BIPM (JCRB). He mentioned that the length community had been in the forefront of implementing the MRA and had moved very quickly to advance the international work in this area. The regional metrology organizations (RMOs) have played a large part in this, working closely with the JCRB and the BIPM. The MRA should now progress from the high workload activity of the interim period to a more steady state. Work on the MRA needed to be continued and in order to do this, there was a need to examine more closely the processes which will continue to be used by the NMIs and the RMOs. The next stage should also include much more interaction with the users of the MRA to ensure that the BIPM key comparison database (KCDB) is more widely applied.

4 REPORT AND SURVEY OF WORK AT THE NATIONAL LABORATORIES (RESPONSES TO QUESTIONNAIRES THAT WERE CIRCULATED IN ADVANCE)

Questionnaires had been distributed in advance of the CCL meeting to the CCL, the WGDM, the new Joint Working Group CCL/CCTF (JWG) and the CCL Working Group on the *Mise en Pratique* (MePWG). The results had been distilled into separate documents which had been placed on the individual websites of the MePWG, the WGDM and the JWG. Additional comments were welcomed from the delegates.

Dr Hollberg reported on some new collaborative work with the BIPM, including work on femtosecond comb comparisons to assess the comb performance.

Dr Gill reported some new frequency measurements including those of the 1.5 µm C_2H_2, Sr^+ quadrupole and Yb^+ quadrupole/octupole transitions in cold ions. The C_2H_2 data had been published and the values agreed well with existing published values. For Sr^+, the published value agreed well with the reported NRC values. The NPL now had a fully operational low repetition rate comb system and a high repetition rate comb was almost complete. An infrared comb and a transportable GPS-referenced comb were being prepared.

Dr Madej reported work on the 1.5 µm C_2H_2, the results were in agreement with those from NPL. Frequency comb technology was being used to calibrate lasers used in dimensional metrology work. Collaborative work on a diode pumped Cr:YAG laser transition had also been undertaken.

Dr Helmcke reported that PTB was continuing its work on cold Ca atoms.

Dr Lassila reported on continued work on iodine-stabilized Nd:YAG and frequency combs. He also described work on using acoustic determination of the speed of sound to improve the accuracy of laser-based measurements.

Dr Bergmans reported that NMi VSL was starting work on frequency locking of a laser which had been obtained from the ILP (St Petersburg), and developed jointly by the BIPM and the ILP.

Prof. Wallard mentioned that the survey had shown that there were seven operational combs in use throughout the NMIs and a further three were being set up. This indicated a substantial level of activity in the area of femtosecond comb research with a good distribution throughout the RMOs.

5 REPORT OF THE WORKING GROUP ON DIMENSIONAL METROLOGY

The chairman asked the meeting to applaud the work of Dr Pekelsky who had been the previous chairman of the WGDM. He indicated that the WGDM chairmanship had been taken over by Dr Brown.

Dr Brown presented his report to the CCL. He mentioned that the full report was available on the WGDM website and so he would only present an overview. During his report, he made suggestions as to where the WGDM felt there was a need for the CCL to make recommendations for the WGDM to follow.

There would be one CCL key comparison final report available for approval by the CCL as well as two NANO pilot studies which the WGDM wished to have re-classified as a CCL supplementary comparison.

Dr Brown brought to the attention of the CCL an important recommendation made by the WGDM at its 8th meeting in 2003.

"The WGDM strongly recommends that pilots of key comparisons provide interim reports to participants as soon as it is technically possible. Where the participant has clearly reported an anomalous result, the participant should be invited to check their results for numerical errors but not be informed of the magnitude or sign of the apparent anomaly."

The reason for this recommendation was that key comparisons take a long time, after the start of the circulation, to reach the stage of the draft A final report. During this time (which could be up to four years), an NMI might continue to offer the measurement service to clients, unaware of any problems which would only be revealed at the time the draft A final report is released. It was far more important for the pilot to inform the NMI as soon as possible, when a (possible) error is detected.

5.1 Approval of key comparison reports

CCL-K2 – Long gauge blocks

Dr Lewis presented a summary of the CCL-K2 final report and executive report. Both of these documents were available on the CCL and WGDM websites. He described the timetable and circulation of the artefacts, and then presented five figures showing the data obtained from the participants, and a summary of the departures of the results from the key comparison reference values (KCRVs). The executive report had drawn specific conclusions in the cases of two laboratories' results and their calibration and measurement capability (CMC) claims. One laboratory needed to make a small alteration to the CMC list, the other required further evidence before their CMC claim could be supported.

Dr Sacconi asked for information on the procedure which should be followed, and on how long it would take, when an NMI had to make changes to their CMC list following publication of results of a key comparison. Dr Thomas replied that this is under the responsibility of the RMO. The SMU reported that it was planning to take part in an RMO key comparison as a result of their performance in CCL-K2. Dr Sacconi stated that it was important for each NMI to have in place a procedure for dealing with anomalous results in key comparisons.

The final report and executive report on CCL-K2 were accepted and Dr Lewis was thanked for his work in piloting the comparison and preparing the various reports.

NANO2 study on step height measurement

Dr Brown made a presentation of the NANO2 final report, which had previously been presented at the 8th WGDM meeting.

This study in nanometrology had been very successful and good agreement on results had been obtained using three different techniques. The study had found some problems with the current definition of step height at this level of accuracy.

This was the second instance where the pilot of a comparison had prepared an executive report. These reports were intended as summaries of the final reports of key comparisons, distilling the most important information and conclusions for use by CMC reviewers.

The WGDM wished to use the results of this comparison to support CMC claims and therefore to re-classify this as a CCL supplementary comparison. In fact, from the start, this and all other NANO pilot studies had deliberately been run along similar guidelines as used for CCL key comparisons so the protocols used by both types of comparison were compatible.

Dr Thalmann expressed his thanks to the PTB and Dr Koenders for running this comparison and for preparing the reports. He mentioned that the METAS had some outlying results reported in this comparison but rather than withdraw and then resubmit CMCs, which it thought would take too much time, METAS was instead working on the problem and would not be providing customer calibrations at this level of uncertainty until the matter was resolved. Dr Quinn responded that, if this was the case, the process of updating CMCs for reasons such as this should be made simpler and faster.

The report was accepted and the request to re-classify the comparison as a CCL supplementary comparison was granted.

NANO3 study on line scale measurement

Dr Brown made a presentation of the NANO3 final report, which had previously been presented at the 8th WGDM meeting in 2003. Although this was classified as a study in nanometrology, the artefacts used were similar to those commonly encountered in NMI line-scale measurement services.

The artefacts for the comparison had been specially prepared by Heidenhain (a German company) and were of very high quality. Two materials, quartz and Zerodur, were used. Temperature changes encountered during transportation had to be taken into account as there was prior information to indicate that hysteresis effects with time constants of several days could be encountered when the material was exposed to significant changes in temperature.

Choice of the KCRVs had been difficult and a consensus decision on selection of which data to include in the calculation of the KCRV had to be made.

The results showed several interesting features including some very close correlations between the results of some participants when length dependent errors were removed; indicating a high accuracy of setting on line features.

There was a question from Dr Stone regarding some errors in the report as presented at the 8th WGDM meeting in San Diego. Dr Brown confirmed that the reports of this comparison and of NANO2 had been corrected and the revised reports had been placed on the website. The comparison participants had been contacted and none had objected to the change in status of the comparisons to CCL supplementary comparisons.

Prof. Wallard asked if the interesting information on the behaviour of Zerodur was to be made more widely available. This was to be published in the proceedings of the San Diego SPIE conference. Dr Schoedel and colleagues at PTB were continuing this work.

Dr Sacconi mentioned a possible improvement to some of the graphs where the zero point was used as a reference for the whole data set. It may be better to give evidence of the uncertainty in the zero point.

Dr Pekelsky raised the issue of how to submit this amount of data into the KCDB. A suggestion may be to produce not just a final graph of the data, but a reduction of each NMI’s data to a representation in the same terms, e.g. Q[a, bL], as used for the CMC entry. Dr Brown responded that the latest version of the executive report on this comparison went some way to performing this analysis.

Dr Thomas asked what format should be used for publication of the data in the KCDB, as normally only the report of a supplementary comparison is placed on the KCDB. Dr Brown responded that this was the intention of the WGDM.

Dr Quinn returned to the point raised in the previous NANO2 report, regarding the speed of updating CMC entries in response to key comparison reports. The process should be much faster and the NMI should send a revised CMC immediately to the RMO Technical Committee (TC) chairman who would request an immediate update directly from the KCDB manager, informing the other RMO TC chairmen about this. (Document JCRB/8-10 gives details of this and can be found on the BIPM website). Re-instatement of the original CMC, after suitable evidence, would be processed through the normal CMC review panel of the RMO.

The comparison report was accepted and the comparison re-classified as a CCL supplementary comparison. Dr Bosse was congratulated for running the comparison and producing the reports.

5.2 Linking key comparisons

Dr Brown referred to a decision made at the 7th WGDM meeting in 2002, and its subsequent decision at the 8th WGDM meeting, to not use numerical links between CCL and RMO key comparisons:

"… the WGDM decided that it would set a precedent, and announced its intention to formally recommend that artefact-based key comparisons in dimensional metrology would not use a numerical link between the CCL key comparison and the corresponding RMO key comparison. Instead, the link would be based on competencies demonstrated by the participant laboratory which took part as linking NMIs in the key comparison and the RMO key comparison. If these linking NMIs were judged to have performed competently in both comparisons (CCL, RMO), then the comparisons were to be regarded as equivalent. The judgment of the competency would be the responsibility of the WGDM."

This was in line with the recommendations already set forth in the final reports of both CCL-K1 and CCL-K2, however, it was felt that this needed to be approved at a higher level. The WGDM therefore asked the CCL to make the following decision:

Decision CCL-WGDM-2*

The Consultative Committee for Length,

taking into account the decision by the CCL-WGDM at its 7th meeting that artefact-based key comparisons in dimensional metrology would not use a numerical link between the CCL key comparison and the corresponding RMO key comparison and that instead, the link would be based on competencies demonstrated by the participant laboratory which took part as linking NMIs in the CCL and RMO key comparisons,

decides that artefact-based key comparisons in dimensional metrology will not use a numerical link between a CCL key comparison and any corresponding RMO key comparison. Instead, the link will be based on competencies demonstrated by the participant laboratory which took part as linking NMIs in the CCL and RMO key comparisons. The CCL and RMO key comparisons will be deemed as being equivalent.

For a given topic, linking can also be achieved by running inter-regional RMO key comparisons where there is:

- appropriate inter-regional participation in a network of RMO key comparisons, the coordination of which is assisted by the CCL; and

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* Decision CCL-WGDM-2 is mentioned in the text prior to Decision CCL-WGDM-1.

- use of compatible technical protocols approved by the CCL; and
- final review of the results of the RMO key comparisons by the CCL.

These inter-regional RMO key comparisons may be called CCL RMO key comparisons.

The reasons for requesting this decision (and several others, yet to be presented) had been set forth in a document from the WGDM (*WGDM-03-51b - Background to recommendations on key comparisons*) which had been placed on the WGDM and CCL websites. The main reason was that the WGDM felt that the results obtained in dimensional metrology comparisons involving artefacts were very dependent on the specific artefacts used and that a numerical link was not justified as the numerical offsets would be different if the comparison was repeated with different artefacts.

The WGDM decision was endorsed by the CCL.

5.3 Proposals for new key comparisons

The WGDM had thought that the 2-D CMM artefacts comparison was too expensive to be run frequently, and that the short and long gauge block comparisons could be combined. Some important new topics should be added to the list of comparison topics. This led the WGDM to ask the CCL to make the following decision:

Decision CCL-WGDM-1

The Consultative Committee for Length,

taking into account the experience gained during the first round of CCL key comparisons,

decides that, following the completion of the first round of CCL key comparisons, the list of CCL key comparison topics in dimensional metrology will be revised to be:

CCL-K1	gauge blocks (short and long)
CCL-K2	(reserved for long gauge blocks)
CCL-K3	angle
CCL-K4	diameter
CCL-K5	1-D CMM (step gauges)
CCL-K6	(reserved for 2-D CMM artefacts)
CCL-K7	line scales
CCL-K8	surface roughness

The WGDM decision was endorsed by the CCL.

Dr Brown next presented a chart showing the timetable followed to date by the CCL key comparisons and NANO studies. One of the problems that had been encountered was the requirement for the linking laboratories to take part in both the CCL and RMO key comparisons. This additional burden had created problems in some regions where there were few laboratories able to perform as linking laboratories. This was delaying the instigation and completion of RMO key comparisons in some regions.

This led the WGDM to ask the CCL to make the following decisions:

Decision CCL-WGDM-3

The Consultative Committee for Length,

taking into account the burden of participation by CCL members in both the CCL and RMO key comparisons, which has significantly slowed the progress of RMO key comparisons,

decides that CCL key comparisons in dimensional metrology will be conducted only when there is a technical need that is not satisfied by inter-regional RMO key comparisons.

Decision CCL-WGDM-4

The Consultative Committee for Length,

recognizing the need to ensure suitable NMI participation in key comparisons to support the MRA and that participation in inter-regional RMO key comparisons may be an alternative to participation in bilateral comparisons,

urges the CCL WGDM to work with the RMOs and the JCRB to organize the inter-regional RMO key comparisons on a time-staggered basis, across topics and across regions, so as to even out the comparison workload and to achieve an approximate seven-year cycle for each topic for each NMI.

Discussion of these items then took place.

There was concern on the use of the term ‘CCL RMO key comparison’. The term ‘CCL’ was needed to ensure that these comparisons received due status and commensurate funding.

Requirements on each NMI concerning how frequently it had to take part in key comparisons, would be left to the regions. For example, EUROMET had its own rules on frequency of participation in key comparisons. The overall requirement was to ensure an approximate seven-year cycle of participation in each topic for each NMI. Of course, significant changes at a laboratory, such as change of equipment or staff, require re-participation in a key comparison.

These two decisions (CCL-WGDM-3 and CCL-WGDM-4) were endorsed by the CCL.

5.4 Results from the inter-regional CMC reviews carried out during the San Diego meeting

A formal review of the CMC review process was not carried out at the 8th WGDM meeting in San Diego. While EUROMET had a well established process for running comparisons and carrying out reviews, some of the other regions were still establishing theirs.

APMP were currently restructuring their review process and had identified experts in the various fields. It was apparent that this work rested heavily on a few laboratories. The commitment of these laboratories to the CCL key comparison had left them with little time to be as involved with APMP comparisons.

There was a similar situation in SIM, while COOMET and SADCMET were even further behind. Both APMP and SIM intended submitting new CMC claims later in the year.

5.5 Report of discussions on how best to assure confidence in the calibrations of 633 nm stabilized lasers

At the 8th WGDM meeting, the following recommendations to the CCL were passed:

- The *Mise en Pratique* should be maintained and expanded to continue to provide direct traceability to the SI metre.
- A system for verifying femtosecond combs should be established.
- The working group considers that the BIPM's laser calibration services and technical advice are essential and should be retained.

Dr Gill (chairman of MePWG) responded that the MePWG had taken note of these and would be reporting on these in his presentation. The MePWG agreed that these points should be addressed to the satisfaction of the dimensional metrology community and that the MePWG would be making recommendations to the CCL on these matters.

Dr Quinn agreed to address the third of these items in item 9 of the agenda.

Dr Madej asked which wavelengths were of particular interest to the WGDM. Dr Brown responded that the wavelengths at 633 nm, 612 nm, 543 nm, 532 nm, and also 778 nm were the most commonly used.

Dr Stone added that several spectral line wavelengths were still in use and that they should continue to be given in the *Mise en Pratique*. Dr Gill responded that they would continue but that it was not realistic to expect to offer calibration of such wavelengths using laser sources.

Dr Brown described the change in expertise that had taken place in using stabilized lasers, where initially the only users or operators of these lasers were their constructors. Now, these lasers are available commercially and little expertise is required to operate them. There was a concern that femtosecond comb systems may follow the same route, and that there should be an independent source of comb validation expertise available to assist those NMIs operating any commercially available combs.

Dr Rovera cautioned that the whole measurement process should be compared, not just the local standards, i.e. that any such comparisons should be performed according to key comparison guidelines, rather than just comparing combs. Dr Helmcke indicated that the level of required uncertainty should be specified. There were several types of standards available which could be used, depending on which frequency range and which uncertainty were required. The BEV (Austria) was operating a commercial comb and was unsure of the uncertainty which they may claim for any future CMC based on measurements using the comb. Would there be the possibility of CMC entries related to measurements based on comb techniques in the future? The meeting felt that this was a possibility.

Dr Schnatz drew the distinction between advice on operating combs and on procedures on how to verify their performance. There may be a requirement for the CCL to issue guidelines on the operation of a comb system. These could take the format of a Good Practice Guide. Dr Pekelsky was concerned that until the combs were specified in the *Mise en Pratique*, they may not yet be ready for routine use for constructing chains of traceability. An example was given by Dr Rovera concerning inaccuracies that can be obtained when using commercial combs. The problem lay not with the comb itself, but with the traceability of the associated frequency sources.

With combs, there is a similar potential for error as is possible in the operation of *Mise en Pratique.* Simple adherence to the procedures set out in the *Mise en Pratique* is not sufficient to guarantee accuracy, an independent verification is necessary. Combs are part of a measurement system, composed of the comb and some radiation source. The operation of such a hybrid instrument is far from simple and it is possible to obtain errors unless one takes care.

5.6 Report on needs in nanometrology

The WGDM had held a workshop on needs in nanometrology, the results of which were summarized in the meeting minutes (available from the WGDM website, *WGDM-03-55-minutes*).

5.7 Report on the metrological applications of high performance stabilized lasers

The WGDM had formulated several requirements for future stabilized lasers:

- Short wavelengths (ultra-violet) would be useful for both nanometrology and for refractive index corrections;
- Compact, solid-state lasers would be useful for difficult environments;
- Optical frequency lasers with a few milliwatts power would help improve signal to noise ratios for nanometrology, e.g. to reduce the shot noise limit.

This agenda item was returned to at a later stage in the meeting.

Several Consultative Committees had already formed small committees to discuss which items would need to be considered for future research. Already within Europe, a project entitled “MERA” (Metrology in the European Research Area) was already considering closer cooperation and dependence in metrology research and provision of services. Prof. Wallard encouraged delegates to forward copies of any surveys of industrial needs to the CCL for placing on the website.

Metrologia was planning a special issue on optical frequency standards for 2006. Dr Zucco agreed to act as editor for this special issue. The CCL agreed to support this proposal and to encourage the community to submit papers.

6 REPORT OF THE WORKING GROUP ON THE *MISE EN PRATIQUE*

The MePWG had met earlier in the week and a draft of the MePWG report would be presented by Dr Gill. The exact details of the proposals would be presented at the end of the report rather than during each item.

Questionnaire responses had been collated by Mr Felder. No absolute frequency measurements of new radiations had been proposed and only a few changes in existing values were presented, based on new research which had been published, i.e. data which had been subjected to sufficient scrutiny.

There was a review of new data collected from laser comparisons and laser calibration using combs, and present status of reference sources since the last CCL.

633 nm He-Ne/I_2

Further data had been submitted since the last round of BIPM.L-K10 was completed, and this had changed the overall mean of the data only marginally. The decision had been taken not to issue a modified value for the frequency. It was re-iterated that the 633 nm radiation was still one of the most important working standards for dimensional metrology, and that the MePWG should express this appropriately to the CCL. This has been done under proposal CCL-MePWG-2.

532 nm Nd:YAG/I_2

The global mean had changed due to inclusion of new data. There had been discussion on what criterion to use as the trigger for revising values and uncertainties. There was a general consensus that a shift by 1 σ in the mean should trigger a changed value, but less than 0.5 σ should not, with an intermediate ‘grey area’. In the event, the consensus was not to change the value or uncertainty, but to issue more comprehensive operating conditions.

543 nm He-Ne/I_2

Most CCL member laboratories’ standards had been calibrated by the BIPM femtosecond comb. As a result there was a significantly reduced uncertainty in contrast to previous interferometric measurements. It was felt that the availability of a new value with much reduced uncertainty warranted a change to the CCL value. In addition, it was noted that the recommended a_9 component was inconvenient for most NMIs, and a change to the b_{10} component was considered desirable. However, it was noted that together with the improved value, there was again a need to define operating conditions more comprehensively.

515 nm I_2

Two new frequency measurements had been performed which were in good agreement. The question remained as to what uncertainty to put on the new value taking into account the I_2-cell reproducibility.

778 nm Rb

A number of laboratories had reported activities in the development of this standard, including the BNM, KRISS, NMIJ/AIST, NPL, NRC and UME. At this time, no new and published frequency measurements had been made since 2001.

1.54 μm C_2H_2

This standard is important for traceability in the optical communications region. Both NMIJ/AIST and NPL had reported new results for this standard [Hong F.-L. *et al.*, *Opt. Lett.*, 2003, **28**(23), 2324-2326 and Edwards C.S. *et al.*, *Opt. Lett.*, 2004, **29**(6), 566-568, respectively]. The NRC measurements were in good agreement with these, but were not yet submitted for publication. All the measurements were in good agreement with the CCL value, but with much improved stabilities and reduced stated uncertainties.

3.39 μm CH_4

No new frequency measurements for this standard had been reported. However, the Lebedev Institute had outlined ideas for realizing an improved methane system, using Zerodur type materials, reaching reproducibility in the 10^{-15} region. Such a device would then act as a transportable optical reference for a comb system to provide a number of different outputs across the visible/infrared/microwave spectra as well as GPS-interfaced time domain comparisons. This might be a transportable and cheap alternative to a cold atom or ion referenced optical clock.

10.6 μm OsO_4

Frequency measurements had been made at the LPL, Villetaneuse (France), using a femtosecond comb to measure the near infrared radiations used in the difference mixing to 10.6 μm. This work was published [Amy-Klein A. *et al.*, *Appl. Phys.*, 2004, **B78**, 25-30] but no new values had been obtained. The comb was referenced to the BNM-SYRTE microwave reference via a (43 km) optical fibre link.

Cold atoms

The PTB reported that there were no new frequency measurements of the Ca neutral system, but that they had some preliminary results with the new Sr neutral experiment, but no frequency measurements as yet. NIST had reported that frequency measurements with their μK Ca atom standard were ongoing, and that they had very good agreement with PTB. NIST-JILA had some new results for their Sr neutral experiment, and NIST were also considering the potential of the Yb neutral lattice clock arrangement. Dr T.H. Yoon (KRISS) reported that they had a publication [Park C.Y. and Yoon T.H., *Phys. Rev.*, 2003, **A68**, 055401/1-4] detailing optical trapping of Yb. They were currently developing a diode pumped, doubled LiF_2, colour centre laser for probing the weak transition in Yb. The BNM reported that SYRTE had investigated inter-combination transitions in ^{88}Sr and ^{87}Sr, and also located and measured the very weak 698 nm transition to the $^3P_0$ metastable level with a 20 kHz uncertainty (1 σ) [Courtillot I. *et al.*, *Phys. Rev.*, 2003, **A68**, 030501(R)/1-4].

674 nm $^{88}Sr^{+}$ quadrupole

The NRC reported new frequency measurements on the 674 nm quadrupole transition. The correspondence of these new improved data with the previous data and agreement between laboratories pointed to an updated value/uncertainty, and this was subject to sub-group discussion for this purpose.

282 nm $^{199}Hg^{+}$ quadrupole

The NIST stated that recent frequency measurements of the 282 nm standard were in agreement with the CCL value to within 1 Hz, but the uncertainty remained at 10 Hz since the quadrupole shift had not yet been systematically evaluated. This evaluation was underway now with two traps.

435 nm $^{171}Yb^{+}$ quadrupole

The PTB reported no new quadrupole frequency measurement at this time, but were comparing two traps.

467 nm $^{171}Yb^{+}$ octupole

The NPL reported three new frequency measurements of the octupole transition, well within the 2001 CCL uncertainty, but the 2003 data taken with a 200 Hz-wide probe laser were inconsistent with the 4 kHz-wide 2002 measurements. In the re-analysis of the earlier data, a missing magnetic field calibration factor had been found, and some under-estimation of the ac Stark shift in that case was now considered likely. Both the 2002 [Blythe P.J. *et al.*, *Phys. Rev.*, 2003, **A67**, 020501(R)/1-4] and 2003 data are combined to provide a new value with reduced uncertainty over the CCL value, and this is reported in NPL report CBTLM 28. The analysis was considered within the ion sub-group.

6.1 Results of the sub-groups discussions

The five radiations with proposed changes for the CCL list had been considered by two sub-groups. A small group had looked at the acetylene standard, the strontium ion transition and the ytterbium ion octupole transition, and a second, larger group considered the 543 nm and 515 nm laser standards, together with some discussion of conditions for the 532 nm standard. The outcomes of these discussions had been recorded and formed the basis for a proposal to the CCL for consideration.

1.54 μm C_2H_2

Two recent comb measurements at the NMIJ/AIST [Hong F.-L. *et al.*, *Opt. Lett.*, 2003, **28**(23), 2324-2326] and NPL [Edwards C.S. *et al.*, *Opt. Lett.*, 2004, **29**(6), 566-568] are in good agreement (2.3 kHz different and close to the original CCL number and well within its uncertainty).

The values obtained were:

NPL: 194 369 569 385.9 (3.0) kHz

NMIJ/AIST: 194 369 569 383.6 (1.3) kHz

The NPL value and uncertainty corresponded to the unweighted mean for two different acetylene stabilized systems, the uncertainty accounting for a reproducible 3.6 kHz offset between systems. The NMIJ/AIST uncertainty (1.3 kHz) corresponded to the reproducibility of one acetylene stabilized system only, and the equivalent reproducibility for one NPL system was 400 Hz. Unpublished results from the NRC confirmed these measurements, giving a value intermediate between the NPL and NMIJ/AIST measurements. A conservative uncertainty of 10 kHz was chosen which accounted for the root-sum square of the final uncertainties together with maximum expected extent of the frequency shift dependencies on various operating parameters, based on measurements of these dependencies.

674 nm $^{88}Sr^+$ quadrupole

The two recent measurements of the $^{88}Sr^+$ quadrupole transition are:

NPL: 444 779 044 095.52 (10) kHz Margolis H.S. *et al.*, *Phys. Rev.*, 2003, **A67**, 032501/1-5.

NRC: 444 779 044 095.49 (5) kHz Bernard J.E. *et al.*, *Proc. IEEE IFCS*, 2003, 162-167.

The unweighted mean gives the current CCL value, when rounded to the level appropriate to the overall uncertainty. Very good agreement between laboratories and with the existing CCL value was evident, but with the lack of any extensive evaluation of systematics in either case, it was considered prudent by the MePWG to adopt the larger uncertainty of 100 Hz as the conservative uncertainty.

467 nm $^{171}Yb^+$ octupole

Three recent measurements between 2002 and 2003 at NPL, with 4 kHz and <200 Hz linewidths, respectively, gave the following values (NPL Report CBTLM 28):

NPL: 642 121 496 771. 69 (28) kHz

NPL: 642 121 496 772. 69 (16) kHz

NPL: 642 121 496 772. 55 (21) kHz

resulting in an unweighted mean of 642 121 496 772.3 kHz. The range of values relative to the combination of individual uncertainties suggests that an additional systematic has not been fully accounted for. This is thought likely to relate to the ac Stark shift determination for the broad-linewidth high intensity data of 2002. The uncertainty was thus derived by treating the three results as a rectangular distribution with an uncertainty of 0.6 kHz given by the standard factor for the three sample case. In light of the fact that these measurements are from one laboratory only, the MePWG considered it prudent to attribute an uncertainty of 1 kHz to the CCL value.

543 nm He-Ne/I_2

The recommendation from sub-group deliberations was that the $^{127}I_2$ R(106) 28-0 component b_{10} be adopted as the 543 nm recommended radiation. Taking into account the recent calibrations at BIPM involving lasers from the BIPM, CENAM, CMI, DFM, MIKES, NIM and SPRING Singapore, the mean value for the frequency of the radiation was:

f = 551 580 162 400 (25) kHz (provisionally published in *Rapport BIPM*-2004/16)

for operating conditions of:

- (0 ± 2) ºC cold point temperature;*
- frequency modulation width, peak-to-peak (2 ± 0.5) MHz.

It was felt appropriate not to define the laser type in the proposal to the CCL.

515 nm I_2

Sub-group discussion centred on the two separate sets of measurements at the LPL Paris and NIST-JILA obtained from very different absorption cell arrangements. At NIST-JILA, data from three different sealed absorption cells had given a final value of:

NIST-JILA: 582 490 603 441.8 (5.2) kHz R.J. Jones *et al.*, *Appl. Phys.,* 2002, **B74**, 597-601.

The unpublished LPL results from a low-pressure flowing gas absorption cell (which should have minimal contamination contribution) were within 0.4 kHz of the NIST-JILA value, when corrected for pressure shift. Since the published values are only from one laboratory, the group considered it prudent to double the uncertainty published by NIST-JILA to 10 kHz for the recommended radiation value.

The final CCL value chosen was 582 490 603 442 (10) kHz. The operating conditions specified by the group were:

- (-5 ± 2) ºC cold point temperature, corresponding to a I_2 pressure of (2.4 ± 0.5) Pa;
- saturating beam intensity < 40 mW cm^{-2}.

As with 543 nm, it was decided not to specify the laser type in the CCL list.

532 nm Nd:YAG/I_2

In response to the suggestion that the operating conditions for the 532 nm standard should be more comprehensively defined, Dr Robertsson (BIPM) proposed on behalf of the sub-group the following conditions:

- (-15 ± 1) ºC cold point temperature;
- frequency modulation width, peak-to-peak (1 ± 0.2) MHz for 3f detection cases;
- saturating beam intensity of (17 ± 11) mW cm^{-2}.

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* In this report, for the specification of operating conditions, such as temperature, modulation width and laser power, the symbols ± refer to a tolerance, not to an uncertainty.

6.2 Considerations of optical frequency standards within the CCL list of recommended radiations

The main decision of the Joint Working Group (JWG) CCL/CCTF had been to have just one list of recommended radiations, with some radiations recommended by CCL as realizations of the metre or by the Consultative Committee for Time and Frequency (CCTF) as secondary realizations of the second, or recommended by both committees. The CCTF would need to have more stringent criteria than those used currently by the CCL for future considerations of secondary realizations of the second.

The WGDM did not require significant changes to the list of recommended radiations as they were primarily interested in iodine stabilized lasers.

There was a feeling that it was too soon to draw up a joint list and only one candidate radiation had been proposed.

6.3 Femtosecond comb measurements and comparisons

Two international comparisons of femtosecond laser combs had been carried out. At the BIPM, the optical frequency difference among two BIPM combs and the ECNU (East China Normal University) comb when transferring the frequency of the microwave standard up to the optical range was found to be below hertz level. In a subsequent comparison at the NIST in Boulder using two transportable combs (from BIPM and ECNU) and a NIST broadband comb (fibreless), results showed that the accuracy can be considerably higher when making the transfer from the optical to the microwave domain.

Laser heterodyne comparisons were relatively easy for certain radiations such as 633 nm, whereas combs were currently not so easy to use routinely and this needed to be balanced against the basic requirement for accurate values for the laser standards. Clearly there needed to be confidence in the comb measuring performance, but the primary issue for the WGDM was fast and simple access to comb outputs. Travelling combs might not be so interesting, and the output requirement was the same irrespective of whether comb calibration or laser heterodyne comparisons were made.

It was felt that for the BIPM travelling combs to be used to verify gas-cell laser standards in the field was a significant undertaking of a size and complexity perhaps even greater than laser heterodyne comparisons. It was felt that one way to address this was to offer some alternatives such as:

- laser heterodyne comparisons and laser calibration by comb at BIPM, as before;
- BIPM travelling comb measurements and comb comparisons at laboratories with high performance, highly reproducible optical standards;
- calibration of working laser standards by comb measurements could be offered by those laboratories on a regional basis.

6.4 MePWG proposals to the CCL

The MePWG tabled four proposals for agreement by the CCL.

CCL-MePWG-1

The Consultative Committee for Length,

considering that:

- improved frequency values for radiations of some high-stability cold ion standards already documented in the list of recommended radiations have recently become available;
- improved frequency values for the infra-red gas cell-based optical frequency standard in the optical telecommunications region, already documented in the recommended radiations' list, have been determined;
- femtosecond comb-based frequency measurements for certain iodine gas-cell standards on the subsidiary recommended source list have recently been made for the first time, leading to significantly reduced uncertainty;

proposes that the *recommended radiations*' list be revised to include the following:

- updated frequency values for the single trapped $^{88}Sr^+$ ion quadrupole transition and the single trapped $^{171}Yb^+$ ion octupole transition;
- an updated frequency value for the C_2H_2-stabilized standard at 1.54 μm;
- updated frequency values for the I_2-stabilized standards at 543 nm and 515 nm.

CCL-MePWG-2

The Consultative Committee for Length,

considering that:

- the 2001 list of recommended radiations for the realization of the metre, including radiations of other optical frequency standards, was comprehensively re-organized and recently published in *Metrologia* 2003 and is available on the BIPM website;
- the number (five) of proposed changes to the values already contained within the list is small;
- no new radiations are suggested;

proposes that:

- these changes be incorporated into the recommended radiations' database maintained on the BIPM website in a manner which highlights the updated values relative to the 2001 list;
- these changes also be published as a short supplementary report in *Metrologia*.

Furthermore, **considering** that:

- there are a significantly increased number of frequency measurements, from both femtosecond comb measurements and laser heterodyne comparisons, for the important iodine-stabilized 633 nm He-Ne and 532 nm Nd:YAG standards;

- it is not necessary to change the recommended values for these radiations on account of issues related to I_2-cell reproducibility;

proposes that:

- updated values for the global mean of the totality of frequency values resulting from BIPM.L-K11* for the 633 nm and 532 nm standards be maintained by the BIPM in accessible form;
- the recommended operating conditions for the 532 nm standard be:
  - cold point temperature (-15 ± 1) °C;
  - frequency modulation width, peak-to-peak (1.0 ± 0.2) MHz (for 3*f* detection cases);
  - saturating beam intensity (17 ± 11) mW cm^{-2}.

CCL-MePWG-3

The Consultative Committee for Length **proposes** that the CIPM adopt the following updated values for existing recommended radiations:

Part I of the list

Absorbing molecule $^{13}C_2H_2$ *P(16)* $(\nu_1 + \nu_3)$ *transition*

The values f = 194 369 569 385 kHz

λ = 1 542 383 712.37 fm

with a relative standard uncertainty of 5×10^{-11}, apply to the radiation of a laser stabilized using the third harmonic detection technique to an external $^{13}C_2H_2$ cell within an enhancement cavity and subject to the following conditions:

- C_2H_2 pressure range from 1.3 Pa to 5.3 Pa;
- frequency modulation width, peak-to-peak (1.5 ± 1.0) MHz;
- one-way intracavity beam intensity of (25 ± 13) W cm^{-2}.

Absorbing ion $^{88}Sr^+$, $5\,^2S_{1/2} - 4\,^2D_{5/2}$ *transition*

The values f = 444 779 044 095.5 kHz

λ = 674 025 590.863 1 fm

with a relative standard uncertainty of 2.2×10^{-13}, apply to the radiation of a laser stabilized to the transition observed with a trapped and cooled strontium ion. The values correspond to the centre of the Zeeman multiplet.

* See Section 8.

Absorbing ion $^{171}Yb^{+}$, $^{2}S_{1/2}$ (F = 0, m_F = 0) – $^{2}F_{7/2}$ (F =3, m_F = 0) transition

The values f = 642 121 496 772.3 kHz

λ = 466 878 090.060 7 fm

with a relative standard uncertainty of 1.6×10^{-12}, apply to the octupole transition after correction for the ac Stark shift and second-order Zeeman shift.

Part II of the list

Absorbing molecule $^{127}I_2$, a_3 component, P(13) 43-0 transition

The values f = 582 490 603 442 kHz

λ = 514 673 466.368 fm

with a relative standard uncertainty of 1.8×10^{-11}, apply to the radiation of a laser stabilized to an external iodine cell and subject to the following conditions:

- cold point temperature (-5 ± 2) °C, corresponding to a I_2 pressure of (2.4 ± 0.5) Pa;
- saturating beam intensity < 40 mW cm^{-2}.

Absorbing molecule $^{127}I_2$, b_{10} component, R(106) 28-0 transition

The values f = 551 580 162 400 kHz

λ = 543 515 663.608 fm

with a relative standard uncertainty of 4.5×10^{-11}, apply to the radiation of a laser stabilized to an external iodine cell and subject to the following conditions:

- cold point temperature (0 ± 2) °C;
- frequency modulation width, peak-to-peak (2.0 ± 0.5) MHz.

CCL-MePWG-4

The Consultative Committee for Length,

considering:

- the high level of agreement already demonstrated in comparisons between the travelling femtosecond combs from the BIPM and the ECNU with the comb system at the NIST;
- the requirement for validation of comb measurement capability at different laboratories used to provide absolute frequency measurements of optical frequency standards and stabilized lasers;
- the potential for future BIPM.L-K11 key comparisons to incorporate both laser heterodyne comparisons and calibration by combs;
- the relative complexity of current comb facilities compared to portable laser standards;
- the impracticality of BIPM travelling combs to undertake a large programme of comb comparisons;

recommends that:

- the BIPM undertake travelling comb comparisons only at the highest level of comparison accuracy, which would require a high level of stability and reproducibility on the part of the optical frequency standard;
- calibration of most stabilized laser standards and validation of comb facilities measuring such stabilized laser standards at other laboratories could proceed on a regional basis, by accessing the regional comb systems participating in the high-level comb comparisons;
- the BIPM continue to offer laser calibration using comb and laser heterodyne comparisons, where appropriate, in its own laboratories.

Discussion on the proposals then took place.

Dr Quinn suggested that rather than a wholesale revision of the *Mise en Pratique* document, a separate list of 2003 modifications should be prepared and labelled as such.

Dr Madej wished to clarify the situation of statements of traceability for wavelength measurements made using combs. Dr Schnatz was of the opinion that this was already covered by method (b) of the *Mise en Pratique* – the frequency is measured and then converted to a wavelength. The BIPM had discussed this when considering its own laser wavelength calibration service using combs and had concluded that in certificates issued, they would state the uncertainty of the comb system. ISO 17025 would require such measurement methods to be validated and calibrated standards to be used.

Proposal CCL-MePWG-4 generated discussion on what was meant by the "highest level", however, this was left to the CCL to interpret.

The four proposals from the MePWG were accepted by the meeting. They were renumbered for final presentation in section 11 of these minutes.

7 DISCUSSION ON NEW OPTICAL STANDARDS AND COMPARISON TECHNIQUES AT THE JOINT WORKING GROUP CCL/CCTF

This agenda item mostly concerned a report on the meeting of the JWG which followed the MePWG, and was chaired by F. Riehle (PTB) chairman of the CCTF working group (CCTFWG) and P. Gill (NPL) MePWG chairman. A separate report on the outcome of this meeting would be forthcoming. In brief, the JWG agreed the criteria that should apply to the inclusion of optical or microwave standards as secondary representations of the second, and discussed the methodology of ratifying standards. It was agreed that the approval of such proposed radiations lay with the CCTF, but that the JWG would be responsible for evaluating the various proposals prior to submission to the CCTF, and that the CCL would be kept fully informed of the proposals of the JWG and decisions of the CCTF. The JWG construction would be a subset of the MePWG together with some members from the CCTFWG and specific experts as necessary. The next JWG meeting would be immediately prior to the CCTF next year, where considerations of the Rb microwave standard would take place. It was not expected that optical radiations would be considered at that time, as they were not yet ready.

Prof. Wallard gave a presentation on the JWG requirements for consideration as secondary representations of the second and conclusions of the meeting:

- The JWG would consider its area of interest as being between the CCL, which was concerned with the *Mise en Pratique*, and the CCTF, which was concerned with secondary representations of the second.
- The SI value of the unperturbed frequency of a quantum transition suitable as a secondary representation of the second must have an uncertainty that is evaluated and documented so as to meet the requirements adopted for the primary frequency standard for use in International Atomic Time.
- This uncertainty should be no larger than about a factor of ten of the primary standards *of that date* that serve as the best realizations of the second.
- The JWG should review and discuss the uncertainty budgets of the proposed standards and evaluate their validity before making their recommendation to the CCTF for the standard being added to the list of frequencies appropriate for secondary representations of the second. The JWG would keep the CCL fully informed about its activity and decisions of the CCTF.

8 PROPOSALS FOR NEW KEY COMPARISONS

Proposals for new key comparisons in dimensional metrology had been discussed in item 5.3 and there was nothing further to report.

The MePWG considered a continuation of BIPM.L-K10 key comparison but had no formal request for instigation of a key comparison at the time. November 2003 would be the next period when the BIPM would be able to receive laser systems for calibration. Formally, the results of such a calibration would be the property of the client, but it was hoped that they would allow them to be made public.

The issue was raised as to what was the period of validity of the BIPM.L-K10 key comparison data. This was a BIPM key comparison and was not therefore entered into the KCDB under the CCL. Dr C. Thomas, the KCDB coordinator, informed the meeting that the key comparison was considered closed and any further work should be under the heading of a new key comparison.

Many NMIs now had the capability, through the use of combs, to make their own absolute frequency measurements. This gives two possibilities: independent absolute frequency measurements by the NMIs or calibration of NMI standards by the BIPM (or *vice versa*). These could lead to two different types of key comparisons.

Existing examples from the KCDB were mentioned. Some subsequent bilateral comparisons (performed as a result of poor KC performance) are recorded in the KCDB as an additional element linked to the original key comparison. There were also examples of bilateral comparisons which were entered into the KCDB as a key comparison.

Dr Robertsson presented a summary of a short discussion which had taken place during a break in the meeting. The conclusions were:

- to close BIPM.L-K10, which was limited to 633 nm and reported laser frequency differences averaged over 4 I_2-hyperfine structure components;
- to propose BIPM.L-K11 as a key comparison of primary realizations of the metre for use in dimensional metrology;
- to include in BIPM.L-K11 both absolute frequency measurements with combs and laser heterodyne comparisons;
- to set up a BIPM.L-K11 working group to determine the exact context and conditions for the key comparison, with the following representatives:

  WGDM: Dr Brown

  MePWG: Dr Gill

  Combs: Dr Gill

  BIPM: Dr Robertsson or Prof. Wallard

These details would be tabled as a proposal to the CCL from the MePWG. There was discussion on whether or not the subject was that of a calibration or of a comparison. It was important to distinguish between the BIPM service used to provide traceability for those NMIs without the necessary facilities, and the testing of standards maintained and operated by NMIs. There is a distinction between using a comb to obtain an absolute frequency for a client laser, compared with direct comparison between two lasers. The first is a calibration, the latter is a validation. There is a distinction between a scientific comparison and a comparison for legal requirements – traceability is a prerequisite before being able to make comparisons. The meeting agreed to let the small BIPM.L-K11 discussion group prepare the details of the key comparison protocol, however, the formal decision to start this key comparison was tabled:

The Consultative Committee for Length,

considering that:

- the BIPM.L-K10 key comparison for the comparison of laser frequencies is complete;
- this comparison applied only to 633 nm lasers;
- a wider variety of laser standards of different wavelength continue to require validation;
- methods of frequency comparison now include direct comb measurements as well as frequency heterodyne comparisons;

decides that:

- a new CCL key comparison, BIPM.L-K11 will be established for the calibration and validation of primary realizations of the metre for use in dimensional metrology;
- this CCL key comparison would include both absolute frequency measurements and frequency heterodyne comparisons;
- a small working group will be set up to determine procedures for such calibration and validation.

The meeting accepted the tabled decision.

9 REPORTS AND DISCUSSION ON THE PROGRESS OF WORK AT THE BIPM

Prof. Wallard introduced this agenda item by reminding the meeting of the forthcoming CGPM meeting, and the need to prepare submissions to be put before the meeting.

9.1 BIPM comb projects

Two international comparisons of femtosecond laser combs had been carried out, one at the BIPM and the second at NIST. At NIST, using two transportable combs (from BIPM and ECNU) and a NIST broadband comb (fibreless), results showed that the accuracy can be considerably higher when doing the transfer from the optical down to the microwave domain than *vice versa*.

The 3.39 µm (He-Ne)/CH_4 radiation was the most often measured with classical frequency chains. Measurement of this wavelength was being prepared at the BIPM using the BIPM comb.

The current status of this experiment was:

- the laser tubes had been replaced with new tubes containing the appropriate isotope mixture and the laser amplifiers were ready;
- the infrared optical setup was nearly ready;
- the infrared optical fibre link was in place and working;
- the PPLN crystal and furnace had been commissioned.

Results were expected in a few months.

9.2 Frequency measurements of optical and infrared lasers

The BIPM operates both fixed and portable femtosecond combs; it provides absolute frequency calibrations for red and green lasers twice a year. It monitors laser BIPM-4, offers comb comparisons and investigation services both on site and within the regions and will be able to measure the 3.39 µm He-Ne laser frequency; the next laser calibration being scheduled for November 2003.

Over many years, forty lasers from 36 countries had been compared regularly under key comparison BIPM.L-K10 by heterodyne techniques.

To date, using the comb facility, the BIPM has made 23 calibrations: 13 He-Ne lasers at 633 nm, 8 He-Ne lasers at 543 nm, and 2 Nd:YAG lasers at 532 nm.

9.3 Iodine cell filling and quality techniques

The BIPM's iodine filling system had been recently rebuilt. It could handle cells, which were supplied upon order from a commercial manufacturer, ranging in size from 1 cm to 180 cm, of many geometries, with final cleaning, filling and testing being carried out at the BIPM. To date, over 300 cells had been made for external customers.

9.4 Dimensional metrology including nanometrology

High power, short-term highly stable diode pumped solid state lasers had been produced, operating at 532 nm and 515 nm for use in general displacement interferometry as a core competency of BIPM for application in gravimetry, the watt balance and the calculable capacitor projects.

Beam tracing software (INTERFBEAM) had been produced for simulation of interferometers. A laser interference diffractometer was available for calibration of 1-D and 2-D gratings for scanning probe microscope calibration. Holographic diffraction gratings had been developed by BIPM and HOLOGRATE of St Petersburg and had been supplied to ten countries. Comparisons of measurements on these gratings with those made by the PTB and the METAS were in agreement to within 20 pm.

9.5 Technology transfer including a report on the March 2003 comb workshop

Since the last meeting of the CCL, 23 calibrations had been performed, 26 papers/presentations had been written/presented, and 108 visitors had come to take advice on laser or comb technology, and new internet pages were being prepared, to be launched in time for the CGPM.

The BIPM comb workshop attracted nearly 60 attendees and provided them with a good insight in how to set up and operate their own comb systems. The workshop attendees requested:

- training;
- technical consulting;
- more workshops or study groups;
- local validation of comb performance;
- gathered publications;
- website.

There was currently no plan to re-run the workshop, however, the BIPM would be open to suggestions.

9.6 Installation of the BIPM quality management system in the Length section

The BIPM quality management system (QMS) for the Length section had been set up according to ISO/IEC 17025, and was in conformance with the MRA. The system was self declared and would be subject to external peer review by Dr Brown. Some activities were covered by the QMS but would not be formally assessed.

9.7 Future possibilities to be addressed by the BIPM

The CIPM had proposed closure of the BIPM's Length section in 2006, largely on grounds of cost, completion of the heterodyne measurements on 633 nm lasers and the promise of comb technology.

Since then, WGDM had recommended that BIPM's programmes of comparisons of lasers and combs were essential and should be extended beyond 2006 and one outcome of the 2003 MePWG meeting was that frequency measurement using comb at BIPM should continue.

The 8.5 % budget increase proposed by the CGPM was already earmarked for increased activities in chemistry with a special emphasis on laboratory medicine, the KCDB and collaboration with international bodies. Given current priorities, the budget would not pay for more staff in the Length section.

The meeting discussed this agenda item. Dr Quinn gave an overview of the funding and programme formulation of the BIPM. For some years, the BIPM had benefited from global inflation and several new facilities had been built through savings made during this time. However, recent low inflation rates had led to more limited funding being available to the BIPM through the dotations from Member States; BIPM's current annual budget being about 9 million euros. Large States each contribute about 10 % of the total. In 1999, the CGPM had voted for an increase in activities but without commensurate increase in funding. Member States had to be informed nine months in advance (of each CGPM) of the BIPM's proposals for its budgetary requirements. A scaled down BIPM programme would require an additional 1.1 million euros, however, the Member States had indicated that they could not support this proposal and that BIPM should be proposing something smaller, probably in the region of 0.45 million euro. Consequently, the CIPM had decided that the photometry and radiometry work would have to cease immediately, together with a closure of the Length section in 2006, in order to balance the BIPM budget in 2008.

The BIPM has unique responsibility for the kilogram prototype and establishing and diffusing TAI. In other areas, there are no similar direct responsibilities for SI units.

Some of the activities originally proposed for research at the BIPM were too ambitious, but the maintenance of an expertise in combs was highly desirable. The dotation from some Member States comes directly from their budgets for their NMIs and increased dotation to the BIPM would directly result in staff redundancies at these NMIs.

Dr Chung reminded the meeting that the BIPM was created out of the Metre Convention and that it would be extremely unfortunate for the BIPM to lose its Length section and the connection with the metre.

Alternative suggestions which were recommended by the CIPM were:

- short-term NMI secondments at the BIPM;
- short-term BIPM staff secondments at the NMIs;
- NMIs to sponsor research fellowships at the BIPM.

During a break, Dr Madej had prepared some words which he hoped could form the basis of a recommendation to the CIPM. These were tabled (see below) and discussed.

Dr Sacconi asked if the CIPM could reconsider the issue, but rather than in terms of extremes, to consider in detail which areas have priority and to spread the budget reduction across a wider area. Dr Quinn responded that all possible considerations had been made but it was felt that the Length section was already at critical intellectual mass, and further reduction, however small, would have a large effect.

Dr Viliesid asked if the iodine cell facility was to close. There were no plans to close it but without expertise in laser work, the facility would struggle in the future.

Dr Quinn added that it was not viable to join some of the length activity with the time group, as the BIPM time activity is mainly in time scales and there is no laboratory work on frequency standards.

The meeting discussed the proposed recommendation on future BIPM work in laser and length metrology, tabled by Dr Madej. This was adopted as Recommendation CCL 1 (2003).

10 CCL MEMBERSHIP AND MEMBERSHIP OF WORKING GROUPS, TERMS OF REFERENCE AND WORKING GROUPS

South Africa has applied for membership of the CCL. This would be discussed at the next CIPM meeting.

There had been no requests for changes in memberships of the two CCL working groups.

The MePWG was asked to interpret its terms of reference more broadly than in the past, to allow it to consider a wider range of radiations.

11 DECISIONS OF THE CCL AND RECOMMENDATIONS TO THE CIPM

This section of the minutes summarizes the decisions made by the CCL and the recommendations to the CIPM. All tabled decisions and proposals were agreed and were reformatted and numbered, according to their status. The proposals were subject to some minor grammatical editing after the meeting, with these changes being approved by the working group chairmen. This section of the minutes contains the agreed texts and is therefore to be considered definitive.

Decision CCL-MePWG-1

The Consultative Committee for Length,

considering that:

- the BIPM.L-K10 key comparison for the comparison of laser frequencies is complete;
- this comparison applied only to 633 nm lasers;
- a wider variety of laser standards of different wavelength continue to require validation;
- methods of frequency comparison now include direct comb measurements as well as frequency heterodyne comparisons;

decides that:

- a new CCL key comparison, BIPM.L-K11 will be established for the calibration and validation of primary realizations of the metre for use in dimensional metrology;
- this CCL key comparison would include both absolute frequency measurements and frequency heterodyne comparisons;
- a small working group will be set up to determine procedures for such calibration and validation.

Decision CCL-WGDM-1

The Consultative Committee for Length,

taking into account the experience gained during the first round of CCL key comparisons,

decides that, following the completion of the first round of CCL key comparisons, the list of CCL key comparison topics in dimensional metrology will be revised to be:

- CCL-K1 gauge blocks (short and long)
- CCL-K2 (reserved for long gauge blocks)
- CCL-K3 angle
- CCL-K4 diameter
- CCL-K5 1-D CMM (step gauges)
- CCL-K6 (reserved for 2-D CMM artefacts)
- CCL-K7 line scales
- CCL-K8 surface roughness

Decision CCL-WGDM-2

The Consultative Committee for Length,

taking into account the decision by the CCL-WGDM at its 7th meeting that artefact-based key comparisons in dimensional metrology would not use a numerical link between the CCL key comparison and the corresponding RMO key comparison and that instead, the link would be based on competencies demonstrated by the participant laboratory which took part as linking NMI in the CCL and RMO key comparisons,

decides that artefact-based key comparisons in dimensional metrology will not use a numerical link between a CCL key comparison and any corresponding RMO key comparison. Instead, the link will be based on competencies demonstrated by the participant laboratory which took part as linking NMI in the CCL and RMO key comparisons. The CCL and RMO key comparisons will be deemed as being equivalent.

For a given topic, linking can also be achieved by running inter-regional RMO key comparisons where there is:

- appropriate inter-regional participation in a network of RMO key comparisons, the coordination of which is assisted by the CCL; and
- use of compatible technical protocols approved by the CCL; and
- final review of the results of the RMO key comparisons by the CCL.

These inter-regional RMO key comparisons may be called CCL RMO key comparisons.

Decision CCL-WGDM-3

The Consultative Committee for Length,

taking into account the burden of participation by CCL members in both the CCL and RMO key comparisons, which has significantly slowed the progress of RMO key comparisons,

decides that CCL key comparisons in dimensional metrology will be conducted only when there is a technical need that is not satisfied by inter-regional RMO key comparisons.

Decision CCL-WGDM-4

The Consultative Committee for Length,

recognizing the need to ensure suitable NMI participation in key comparisons to support the MRA and that participation in inter-regional RMO key comparisons may be an alternative to participation in bilateral comparisons,

urges the CCL WGDM to work with the RMOs and the JCRB to organize the inter-regional RMO key comparisons on a time-staggered basis, across topics and across regions, so as to even out the comparison workload and to achieve an approximate seven-year cycle for each topic for each NMI.

The CCL approved three recommendations:

- Recommendation CCL 1 (2003): Future BIPM work in laser and length metrology;
- Recommendation CCL 2 (2003): Revision of the *Mise en Pratique* list of recommended radiations (Recommendation CCL 2a, 2b and 2c);
- Recommendation CCL 3 (2003): Future organization of optical frequency measurements.

12 OTHER BUSINESS

Dr Chung mentioned that Dr Helmcke would retire at the end of 2003 and thanked him on behalf of the meeting and the length metrology community for all of his work in this field. Dr Helmcke responded that he had enjoyed his work in length metrology very much and thanked the meeting for their appreciation.

Dr Chung also mentioned that Dr Quinn would retire as the Director of the BIPM at the end of 2003. Dr Sacconi, speaking as the only NMI Director present at this CCL meeting, expressed his deep gratitude to Dr Quinn for his stimulating ideas which he had contributed to the metrology community.

The meeting expressed its best wishes to both Dr Quinn and Dr Helmcke for their futures.

13 NEXT MEETING OF THE CCL

It was felt that the two-year periodicity of the CCL meeting was appropriate, though there had been some comments that September was a holiday period in the northern hemisphere.

The meeting agreed to meet again in September 2005, at the BIPM. The President thanked all participants for a lively and very productive meeting. The meeting was closed.

Dr A. Lewis and Dr A. Sacconi, Rapporteurs

January 2004

Recommandations du

Comité consultatif des longueurs

présentées au

Comité international des poids et mesures

RECOMMANDATION CCL 1 (2003) :
Activités futures du BIPM dans les domaines de la métrologie des lasers et des longueurs

Le Comité consultatif des longueurs,

considérant que

- certaines activités de la section des longueurs du Bureau international des poids et mesures (BIPM) constituent une composante essentielle de l'infrastructure servant à la validation et à l'étalonnage des réalisations de l'unité de longueur ;
- la métrologie des longueurs joue un rôle clé pour l'industrie, le commerce et les échanges entre les États membres ;
- le projet de fermer la section des longueurs au BIPM en 2006 aurait un impact sérieux sur l'activité mondiale dans le domaine de la métrologie dimensionnelle et sur le système international de traçabilité des mesures de fréquences et de longueurs d'ondes de lasers ;
- le coût pour les États membres de la Convention du Mètre d'une répartition des activités de la section des longueurs du BIPM entre les laboratoires nationaux de métrologie serait bien plus élevé que la poursuite de ces activités au BIPM ;

recommande que

- le Comité international des poids et mesures (CIPM) revoie les décisions prises concernant les activités à long terme de la section des longueurs du BIPM ;
- le CIPM établisse un groupe d'experts pour examiner comment le BIPM pourrait satisfaire les besoins fondamentaux à long terme des laboratoires nationaux de métrologie dans les domaines de la métrologie dimensionnelle et des fréquences laser ; et

soutient les propositions

- de mettre à la disposition de la section des longueurs du BIPM, dans le cadre des actions éventuelles pour aider cette activité, du personnel des laboratoires nationaux de métrologie ;
- de mettre en place un programme de chercheurs associés au BIPM pour maintenir à niveau la formation du personnel hautement qualifié des laboratoires nationaux de métrologie et satisfaire les besoins concernant les activités internationales dans les domaines de la métrologie des étalons de longueur et de la métrologie dimensionnelle, au moyen de projets d'intérêt commun.

RECOMMANDATION CCL 2 (2003) :
Révision de la liste des radiations recommandées pour la mise en pratique de la définition du mètre

RECOMMANDATION CCL 2a (2003)*

Le Comité consultatif des longueurs,

considérant que

- l'on dispose depuis peu de meilleures valeurs des fréquences des radiations de certains étalons à ions refroidis très stables, valeurs déjà publiées dans la liste des radiations recommandées ;
- l'on a déterminé de meilleures valeurs des fréquences des étalons de fréquence optique, fondés sur des cuves à gaz, dans le domaine des télécommunications optiques, dans l'infrarouge, valeurs déjà publiées dans la liste des radiations recommandées ;
- l'on a effectué récemment et pour la première fois des mesures de fréquence à l'aide de peignes à impulsions femtosecondes de certains étalons fondés sur des cuves à iode, qui figurent sur la liste complémentaire de radiations recommandées, mesures qui conduisent à une réduction considérable de l'incertitude ;

propose que la liste des radiations recommandées soit révisée pour y inclure :

- les valeurs mises à jour des fréquences de la transition quadripolaire de l'ion piégé de $^{88}Sr^{+}$ et de la transition octupolaire de l'ion piégé de $^{171}Yb^{+}$;
- la valeur mise à jour de la fréquence de l'étalon asservi sur l'acétylène à 1,54 µm ;
- des valeurs mises à jour de la fréquence d'étalons asservis sur l'iode à 543 nm et à 515 nm.

* Cette recommendation a été adoptée par le CIPM comme Recommandation 1 (CI-2003) lors de sa 92e session en octobre 2003.

RECOMMANDATION CCL 2b (2003)

Le Comité consultatif des longueurs,

considérant que

- la liste de 2001 des radiations recommandées pour la mise en pratique de la définition du mètre, qui comprend aussi d'autres radiations d'étalons de fréquence optique, a été entièrement réorganisée et publiée récemment dans *Metrologia* en 2003 ainsi que sur le site Web du Bureau international des poids et mesures (BIPM) ;
- le nombre (cinq) de changements proposés aux valeurs déjà publiées dans la liste est restreint ;
- aucune radiation nouvelle n'est proposée ;

propose que

- ces changements soient intégrés dans la base de données sur les radiations recommandées, placée sur le site Web du BIPM, en mettant en évidence les valeurs mises à jour depuis la liste de 2001 ;
- ces changements soient aussi publiés sous forme d'un bref rapport dans *Metrologia*.

De plus, **considérant** que

- le nombre des mesures de fréquence s'est considérablement accru, à la fois grâce aux mesures de peignes à impulsions femtosecondes et aux comparaisons hétérodynes de lasers pour les étalons à He-Ne asservis sur l'iode à 633 nm et les étalons Nd:YAG à 532 nm, qui sont particulièrement importants ;
- il n'est pas nécessaire de changer les valeurs recommandées de ces radiations, compte tenu des problèmes relatifs à la reproductibilité des cuves à iode ;

propose

- que des valeurs mises à jour pour la moyenne globale de l'ensemble des valeurs des fréquences des lasers étalons à 633 nm et à 532 nm obtenues dans le cadre de la comparaison clé BIPM.L-K11 soient conservées au BIPM sous une forme accessible ;
- de recommander les conditions de fonctionnement suivantes pour les étalons à 532 nm :
  - point froid à la température de (-15 ± 1) °C* ;
  - largeur de modulation de fréquence, crête à creux $(1{,}0 \pm 0{,}2)$ MHz (dans le cas de la détection en 3*f*) ;
  - intensité de saturation du faisceau (17 ± 11) mW cm^{-2}.

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* Dans cette recommandation, pour la spécification des conditions de fonctionnement telles que la température, la largeur de modulation et la puissance laser, les symboles ± font référence à la tolérance et non à l'incertitude.

RECOMMANDATION CCL 2c (2003)

Le Comité consultatif des longueurs **propose** au Comité international des poids et mesures d'adopter les valeurs mises à jour des radiations recommandées suivantes :

Partie I de la liste

Molécule absorbante $^{13}C_2H_2$, *transition* $P(16)$ $(\nu_1 + \nu_3)$

Les valeurs f = 194 369 569 385 kHz

λ = 1 542 383 71,37 fm

avec une incertitude-type relative de 5×10^{-11}, s'appliquent à la radiation d'un laser asservi à l'aide de la technique de détection du troisième harmonique, avec une cuve à $^{13}C_2H_2$ située à l'extérieur du laser dans une cavité à absorption renforcée par effet Fabry-Perot, lorsque les conditions suivantes sont respectées :

- pression d'acétylène comprise entre 1,3 Pa et 5,3 Pa ;
- largeur de modulation de fréquence, crête à creux (1,5 ± 1,0) MHz* (dans le cas de la détection en $3f$) ;
- puissance surfacique transportée par le faisceau dans un seul sens à l'intérieur de la cavité (25 ± 13) W cm^{-2}.

Ion absorbant $^{88}Sr^{+}$, *transition* $5\ ^2S_{1/2} - 4\ ^2D_{5/2}$

Les valeurs f = 444 779 044 095,5 kHz

λ = 674 025 590,863 1 fm

avec une incertitude-type relative de $2,2 \times 10^{-13}$, s'appliquent à la radiation d'un laser asservi sur la transition que l'on observe à l'aide d'un ion de strontium piégé et refroidi. Les valeurs correspondent au centre du multiplet Zeeman.

Ion absorbant $^{171}Yb^{+}$, *transition* $^2S_{1/2}\ (F = 0, m_F = 0) - {}^2F_{7/2}\ (F = 3, m_F = 0)$

Les valeurs f = 642 121 496 772,3 kHz

λ = 466 878 090,060 7 fm

avec une incertitude-type relative de $1,6 \times 10^{-12}$, s'appliquent à la transition octupolaire, corrigées pour tenir compte du décalage de Stark en courant alternatif et du décalage de Zeeman du second ordre.

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* Dans cette recommandation, pour la spécification des conditions de fonctionnement telles que la température, la largeur de modulation et la puissance laser, les symboles ± font référence à la tolérance et non à l'incertitude.

Partie II de la liste

Molécule absorbante $^{127}I_2$, composante a_3, transition P(13) 43-0

Les valeurs f = 582 490 603 442 kHz

λ = 514 673 466,368 fm

avec une incertitude-type relative de $1,8 \times 10^{-11}$, s'appliquent à la radiation d'un laser asservi à l'aide d'une cuve à iode située à l'extérieur du laser, lorsque les conditions suivantes sont respectées :

- point froid à la température de (−5 ± 2) °C, correspondant à une pression de (2,4 ± 0,5) Pa ;
- intensité du faisceau saturant <40 mW cm^{-2}.

Molécule absorbante $^{127}I_2$, composante b_{10}, transition R(106) 28-0

Les valeurs f = 551 580 162 400 kHz

λ = 543 515 663,608 fm

avec une incertitude-type relative de $4,5 \times 10^{-11}$, s'appliquent à la radiation d'un laser asservi à l'aide d'une cuve à iode située à l'extérieur du laser, lorsque les conditions suivantes sont respectées :

- point froid à la température de (0 ± 2) °C ;
- largeur de modulation de fréquence, crête à creux (2,0 ± 0,5) MHz.

RECOMMANDATION CCL 3 (2003) :
Organisation à venir des mesures de fréquences optiques

Le Comité consultatif des longueurs,

considérant

- le très bon accord déjà observé dans les comparaisons de peignes à impulsions femtosecondes voyageurs du Bureau international des poids et mesures (BIPM) et de l'East China Normal University (ECNU) avec celui du National Institute of Standards and Technology (NIST) ;
- la nécessité de valider la capacité des laboratoires à mesurer au moyen de peignes les fréquences absolues des étalons de fréquence optique et des lasers asservis ;
- la possibilité d'incorporer à la fois les comparaisons par technique hétérodyne et l'étalonnage de lasers au moyen de peignes dans la future comparaison clé BIPM.L-K11 ;
- la relative complexité des systèmes à peigne actuels par rapport aux lasers étalons transportables ;
- qu'il n'est pas réaliste d'utiliser les peignes voyageurs du BIPM dans un vaste programme de comparaison de peignes ;

recommande que

- le BIPM entreprenne des comparaisons de peignes voyageurs uniquement au niveau d'exactitude le plus élevé, ce qui demande une stabilité et une reproductibilité élevées de la part de l'étalon de fréquence optique utilisé ;
- l'étalonnage de la plupart des lasers étalons asservis et la validation des systèmes à peigne servant à les mesurer dans d'autres laboratoires se fasse au niveau régional, par rattachement aux systèmes à peigne de la région qui participent aux comparaisons de peignes de haut niveau ;
- le BIPM continue à offrir l'étalonnage de lasers à l'aide de peignes et des comparaisons de lasers par technique hétérodyne, si besoin est, dans ses propres laboratoires.

Recommendations of the
Consultative Committee for Length

submitted to the
International Committee for Weights and Measures

RECOMMENDATION CCL 1 (2003):
Future BIPM work in laser and length metrology

The Consultative Committee for Length,

considering that:

- some of the activities of the International Bureau of Weights and Measures (BIPM) Length section form an important underpinning of the infrastructure for the calibration and validation of realizations of the unit of length;
- length metrology forms a key role in the basis of all industry, trade and commerce in the Member States;
- the proposed closure of the BIPM Length section in 2006 is viewed as having a severe impact on the world activity in dimensional metrology and international system of traceability in laser frequency (wavelength) measurement;
- the cost to Member States of the Metre Convention of distributing the activities of the BIPM Length section throughout the national metrology institutes (NMIs) would be far greater than the cost of maintaining this work at the BIPM;

recommends that:

- the International Committee for Weights and Measures (CIPM) review the decisions made concerning the long-term operational activity of the Length section of the BIPM;
- the CIPM establish a group of experts to review how the BIPM can satisfy the NMIs base-line needs for dimensional and laser frequency metrology in the long term;

and **supports** the proposals for:

- secondment of NMI personnel to the BIPM Length section as part of the possible action to supporting this activity;
- a programme of research fellowships at the BIPM as part of maintaining the training of highly qualified personnel from the NMIs and addressing the needs of world-wide work in length standards and dimensional metrology through projects of common interest.

RECOMMENDATION CCL 2 (2003): Revision of the *Mise en Pratique* list of recommended radiations

RECOMMENDATION CCL 2a (2003)*

The Consultative Committee for Length,

considering that:

- improved frequency values for radiations of some high-stability cold ion standards already documented in the list of recommended radiations have recently become available;
- improved frequency values for the infra-red gas cell-based optical frequency standard in the optical telecommunications region, already documented in the recommended radiations' list, have been determined;
- femtosecond comb-based frequency measurements for certain iodine gas-cell standards on the subsidiary recommended source list have recently been made for the first time, leading to significantly reduced uncertainty;

proposes that the *recommended radiations'* list be revised to include the following:

- updated frequency values for the single trapped $^{88}Sr^+$ ion quadrupole transition and the single trapped $^{171}Yb^+$ ion octupole transition;
- an updated frequency value for the C_2H_2-stabilized standard at 1.54 μm;
- updated frequency values for the I_2-stabilized standards at 543 nm and 515 nm.

* This recommendation was adopted as Recommendation 1 (CI-2003) by the CIPM at its 92nd meeting in October 2003.

RECOMMENDATION CCL 2b (2003)

The Consultative Committee for Length,

considering that:

- the 2001 list of recommended radiations for the realization of the metre, including radiations of other optical frequency standards, was comprehensively reorganized and recently published in *Metrologia* 2003 and is available on the website of the International Bureau of Weights and Measures (BIPM);
- the number (five) of proposed changes to the values already contained within the list is small;
- no new radiations are suggested;

proposes that:

- these changes be incorporated into the recommended radiations's database maintained on the BIPM website in a manner which highlights the updated values relative to the 2001 list;
- these changes also be published as a short supplementary report in *Metrologia*.

Furthermore, **considering** that:

- there are a significantly increased number of frequency measurements, from both femtosecond comb measurement and laser heterodyne comparisons, for the important iodine-stabilized 633 nm He-Ne and 532 nm Nd:YAG standards;
- it is not necessary to change the recommended values for these radiations on account of issues related to I_2-cell reproducibility;

proposes that

- updated values for the global mean of the totality of frequency values resulting from BIPM.L-K11 key comparison for the 633 nm and 532 nm standards be maintained by the BIPM in accessible form;
- the recommended operating conditions for the 532 nm standard be:
    - cold point temperature (−15 ± 1) °C*;
    - frequency modulation width, peak-to-peak (1.0 ± 0.2) MHz (for 3*f* detection cases);
    - saturating beam intensity (17 ± 11) mW cm^{-2}.

* In this Recommendation, for the specification of operating conditions such as temperature, modulation width and laser power, the symbols ± refer to a tolerance, not to an uncertainty.

RECOMMENDATION CCL 2c (2003)

The Consultative Committee for Length **proposes** that the International Committee for Weights and Measures adopt the following updated values for existing recommended radiations:

Part I of the list

Absorbing molecule $^{13}C_2H_2$*, P(16)* $(\nu_1 + \nu_3)$ *transition*

The values f = 194 369 569 385 kHz

λ = 1 542 383 712.37 fm

with a relative standard uncertainty of 5×10^{-11}, apply to the radiation of a laser stabilized using the third harmonic detection technique to an external $^{13}C_2H_2$ cell within an enhancement cavity and subject to the following conditions:

- C_2H_2-pressure range from 1.3 Pa to 5.3 Pa;
- frequency modulation width, peak-to-peak (1.5 ± 1.0) MHz* (for 3f detection cases);
- one-way intracavity beam power density of (25 ± 13) W cm^{-2}.

Absorbing ion $^{88}Sr^+$*,* $5\ ^2S_{1/2} - 4\ ^2D_{5/2}$ *transition*

The values f = 444 779 044 095.5 kHz

λ = 674 025 590.863 1 fm

with a relative standard uncertainty of 2.2×10^{-13}, apply to the radiation of a laser stabilized to the transition observed with a trapped and cooled strontium ion. The values correspond to the centre of the Zeeman multiplet.

Absorbing ion $^{171}Yb^+$*,* $^2S_{1/2}\ (F = 0, m_F = 0) - {}^2F_{7/2}\ (F = 3, m_F = 0)$ *transition*

The values f = 642 121 496 772.3 kHz

λ = 466 878 090.060 7 fm

with a relative standard uncertainty of 1.6×10^{-12}**,** apply to the octupole transition after correction for the ac Stark shift and second-order Zeeman shift.

* In this Recommendation, for the specification of operating conditions such as temperature, modulation width and laser power, the symbols ± refer to a tolerance, not to an uncertainty.

Part II of the list

Absorbing molecule $^{127}I_2$, a_3 component, P(13) 43-0 transition

The values f = 582 490 603 442 kHz

λ = 514 673 466.368 fm

with a relative standard uncertainty of 1.8×10^{-11}, apply to the radiation of a laser stabilized to an external iodine cell and subject to the following conditions:

- cold point temperature (–5 ± 2) °C, corresponding to a I_2 pressure of (2.4 ± 0.5) Pa;
- saturating beam intensity < 40 mW cm^{-2}.

Absorbing molecule $^{127}I_2$, b_{10} component, R(106) 28-0 transition

The values f = 551 580 162 400 kHz

λ = 543 515 663.608 fm

with a relative standard uncertainty of 4.5×10^{-11}, apply to the radiation of a laser stabilized to an external iodine cell and subject to the following conditions:

- cold point temperature (0 ± 2) °C;
- frequency modulation width, peak-to-peak (2.0 ± 0.5) MHz.

RECOMMENDATION CCL 3 (2003):
Future organization of optical frequency measurements

The Consultative Committee for Length,

considering:

- the high level of agreement already demonstrated in comparisons between the travelling femtosecond combs from the International Bureau of Weights and Measures (BIPM) and the East China Normal University (ECNU) with the comb system at the National Institute of Standards and Technology (NIST);
- the requirement for validation of comb measurement capability at different laboratories used to provide absolute frequency measurements of optical frequency standards and stabilized lasers;
- the potential for future BIPM.L-K11 key comparison to incorporate both laser heterodyne comparisons and calibration by comb;
- the relative complexity of current comb facilities compared to portable laser standards;
- the impracticality of BIPM travelling combs to undertake a large programme of comb comparisons;

recommends that:

- the BIPM undertake travelling comb comparisons only at the highest level of comparison accuracy, which would require a high level of stability and reproducibility on the part of the optical frequency standard;
- calibration of most stabilized laser standards and validation of comb facilities measuring such stabilized laser standards at other laboratories could proceed on a regional basis, by accessing the regional comb systems participating in the high-level comb comparisons;
- the BIPM continue to offer laser calibration using comb and laser heterodyne comparisons, where appropriate, in its own laboratories.

Appendix L 1.
Working documents submitted to the CCL at its 11th meeting

Working documents submitted to the CCL at its 11th meeting are on restricted access.

Appendix L 2.
Report of the meeting of the *Mise en Pratique* Working Group
BIPM, Sèvres, 8-9 September 2003

The following report highlights the discussions and outcomes of the meeting of the CCL *Mise en Pratique* Working Group (MePWG), held at the BIPM on 8–9 September 2003.

The following were present: P. Balling (CMI), F. Bertinetto (IMGC-CNR), M.S. Chung (President of the CCL), P. Gill (NPL, Chairman of the MePWG), R. Hamid (UME), J. Helmcke (PTB), L.W. Hollberg (NIST), A. Madej (NRC), H. Matsumoto (NMIJ/AIST), K. Nyholm (MIKES), A. Onae (NMIJ/AIST), D. Rovera (BNM-SYRTE), H. Schnatz (PTB), J. Stone (NIST), S. van den Berg (NMi VSL), J.-P. Wallerand (BNM-INM), T.H. Yoon (KRISS).

Observers and guests: R. Fíra (SMU), S. Gao (NIM), M. Gubin (VNIIM), S. Ohshima (NMIJ/AIST), P. Juncar (BNM-INM).

Also present: P. Giacomo (Emeritus Director of the BIPM); R. Felder, L.-S. Ma, S. Picard, L. Robertsson, L. Vitushkin, A.J. Wallard (Executive Secretary of the CCL and Director designate of the BIPM), M. Zucco (BIPM).

The meeting was attended by 17 MePWG delegates, 5 observers and guests, and members of the BIPM, and presided over by the President of the CCL, Dr Myung Sai Chung, and the Director designate of the BIPM, Prof. Andrew Wallard. The MePWG chairman was Dr Patrick Gill of the NPL.

Executive summary

- Review of laser measurements

Laser measurement results since the last CCL for iodine-stabilized standards at 633 nm, 543 nm and 532 nm were reviewed. These data have resulted mainly, but not exclusively from comb measurements. For the 633 nm and 532 nm cases, it was decided that new CCL values for these radiations were not necessary, though the working group considered it appropriate that the BIPM undertake new measurements to compute rolling mean values. In the 543 nm case, the availability of comb measurements with accuracies an order of magnitude better than the existing CCL uncertainty suggested that a new value be adopted.

- Review of measurements at other wavelengths/frequencies

The extent of measurement activity in respect of the other CCL radiations was reviewed, including other iodine-stabilized standards, infrared gas cell-based stabilized standards, and cold atoms and ions. New measurements offered here included the C_2H_2-stabilized standard at 1.54 μm, cold $^{88}Sr^+$ ion and cold $^{171}Yb^+$ ion transitions at 674 nm and 467 nm, respectively, and the 515 nm iodine-stabilized standard.

- Sub-group discussions and decisions

Following detailed discussions concerning new measurements, five new values and uncertainties for existing recommended radiations were proposed for adoption by the CCL and incorporation into the CCL list of recommended radiations. These were:

194 THz/1.54 µm C_2H_2-stabilized standard

445 THz/674 nm single cold $^{88}Sr^+$ ion quadrupole transition

642 THz/467 nm single cold $^{171}Yb^+$ ion octupole transition

552 THz/543 nm I_2-stabilized standard

582 THz/515 nm I_2-stabilized standard

- Femtosecond comb measurement review

Discussion of comb measurement techniques and capabilities centred on recent comb comparison data between the BIPM and ECNU travelling combs and the NIST comb. These results showed microwave referenced comb comparisons agreeing at the part in 10^{14} level, with better results for optical referenced combs. It was agreed that comb comparisons involving BIPM should only be undertaken at the highest accuracy level possible, and lower accuracy comparisons could proceed on a regional basis as appropriate.

- Proposals to the CCL

A proposal for the revision of the *Mise en Pratique* list of recommended radiations was drawn up. This comprised four parts, including the proposal to update the values for the five radiations quoted above, a listing of the proposed CCL values and uncertainties, a proposal to update the *MeP* list by means of the BIPM website and a supplementary note in *Metrologia*, rather than a full revision, and a proposal to restrict comb comparisons involving BIPM to the highest levels of accuracy.

Note: A decision was taken at the following CCL meeting to establish a new CCL key comparison, BIPM.L-K11, for the absolute frequency measurements with combs of primary realizations of the metre for dimensional metrology which could include both comb and frequency heterodyne comparisons.

- Discussions of the Joint Working Group CCL/CCTF (JWG)

Following the MePWG, the JWG developed the structure, acceptance criteria and working procedures for proposing potential secondary realizations of the second to the CCTF for acceptance. Criteria included performance within an order of magnitude of the primary standard of the day, and a fully evaluated uncertainty budget. No optical radiations were ready at this time, and the first consideration in 2004 would be of the Rb microwave standard.

Introduction

At the opening of the meeting, M. Zucco of the BIPM was appointed secretary to the meeting, and the proposed agenda was approved with an approximate anticipation of timescales necessary to deal with the various items.

The meeting began in earnest with a short review by R. Felder of the BIPM in respect of the totality of returned questionnaires, which highlighted recent changes to the values and uncertainties of some of the radiations in the CCL list of recommended radiations. In fact, no absolute frequency measurements of new radiations were proposed, and only a few changes in values or uncertainties were presented. Some of these were not available at the time of the questionnaire return in July 2003, but those that were submitted in the run-up to the *MeP* meeting were backed by reports in the form of existing publications, submitted publications or authorised standards laboratory reports. This was in accordance with the stated procedure introduced to avoid the submission of last minute measurements which, perhaps, might not have been subject to suitably rigorous internal scrutiny at the measuring laboratory, and to which the working group might have difficulty in offering considered comment at the *MeP* meeting itself.

Review of laser comparisons and comb measurements

There was a review of new data resulting from various laser comparisons and comb measurements since the last CCL, and then a brief review of new measurements in some specific cases within the recommended list. The laser data was coordinated and presented by L. Robertsson of the BIPM, and covered the iodine-stabilized 633 nm and 543 nm He-Ne standards and the 532 nm iodine-stabilized Nd:YAG standard.

633 nm He-Ne/I_2

With the formal conclusion of the BIPM.L-K10 key comparison, there had subsequently been some comb frequency measurements of this wavelength, which had resulted in the availability of a significantly increased body of data since the 2001 CCL. The resulting global mean was ……..603.3 kHz with a standard deviation of 7.6 kHz. The question was raised as to whether modification of the CCL-agreed value was needed, and the consensus was that this was not necessary, and indeed not desirable, given that there was no particular sign of convergence within the field of measurements, which reflects the major contribution to uncertainty from iodine cell variations. However, it was re-iterated that the 633 nm radiation was still one of the most important working standards for dimensional metrology, and that the *MeP* should express this appropriately to the CCL. This has been done under the proposed Recommendation CCL 2b to the CCL. L. Robertsson was charged with capturing future measurements and comparisons in order to record any longer term changes.

532 nm Nd:YAG/I_2

L. Robertsson also presented results of 532 nm comb measurements and laser comparisons and noted that the global mean had changed since 2001 from ……..513.2 kHz to ……..511.5 kHz with a standard deviation of 2.6 kHz. J.-P. Wallerand (BNM) stated that the existing 5 kHz uncertainty was low, given that it was not difficult to generate 20 kHz–30 kHz shifts due to beam alignment, etalon effects and other technical problems. It was noted that I_2-cell reproducibilities generally seemed to be better for the iodine transitions in the green (~2 kHz) compared to the red. A. Madej (NRC) asked the general question as to where the threshold for adopting a new value for such systems like 633 nm and 532 nm should be set. There was a general consensus that a shift by 1 σ in the mean should trigger a changed value, but less than 0.5 σ should not, with an intermediate "grey area". In the event, the consensus was not to change the 532 nm value or uncertainty, but the issue of defining more comprehensively the operating conditions was raised, and considered an appropriate sub-group task for later in the meeting.

543 nm He-Ne/I_2

The other working standard that had been the subject of a fairly extensive comb measurements and laser comparisons at the BIPM in 2002 was the 543 nm transition. In fact, most of the member laboratories' standards had been calibrated by the BIPM femtosecond comb at that comparison. As a result, there was a significantly reduced uncertainty resulting from this period in contrast to previous interferometric measurements of the 543 nm standard. The old uncertainty of 130 kHz had been reduced to 25 kHz due to the comb measurements of some five systems. This radiation had been moved to part 2 of the list of recommended radiations at the last meeting, but it was an important source for multi-wavelength interferometry, and it was felt that the availability of a new value with much reduced uncertainty due to the availability of comb measurements warranted a change to the CCL value. In addition, it was felt that the recommended a_9 component was inconvenient for most laboratories, and a change to the b_{10} component was considered desirable. However, it was noted that together with the improved value, there was again a need to define operating conditions more comprehensively.

Review of comb measurements at other wavelengths

515 nm I_2

L. Hollberg (NIST) reported improved values from JILA for the 515 nm system, with an uncertainty of 5.2 kHz derived from the use of three different iodine cells (R.J. Jones *et al.*, *Appl. Phys.,* 2002, **B74**, 597-601). J.-P. Wallerand also reported on comb measurements at the LPL, Villetaneuse (France), of the 515 nm absorption in a 4 m-long low-pressure continuously-pumped gas cell, which avoid impurity effects to a large extent. This gave the same value as JILA when corrected for pressure shift. J. Helmcke (PTB) reminded the meeting that at very low pressures the pressure shift was not linear. The LPL results were not published. The question remained as to what uncertainty to put on the new value which took account of the cell reproducibility issue, and this radiation was also identified as appropriate for some sub-group discussion.

Infrared laser standards

778 nm Rb two-photon

A number of laboratories reported activities in the development of the 778 nm standard, including the BNM, KRISS, NMIJ/AIST, NPL, NRC and UME. No new and published frequency measurements had been made since 2001 at this time.

1.54 μm C_2H_2

This standard is important for traceability in the optical communications region. It is operated by means of saturated absorption in a cavity enhanced external acetylene cell. It was added to the list of recommended radiation in 2001, following the first measurements by the NMIJ/AIST with 100 kHz uncertainty. Both A. Onae (NMIJ/AIST) and P. Gill (NPL) reported new results for this standard [Hong F.-L. *et al.*, *Opt. Lett.*, 2003, **28**(23), 2324-2326 and Edwards C.S. *et al.*, *Opt. Lett.*, 2004, **29**(6), 566-568, respectively]. A. Madej commented that the NRC measurements were in good agreement with these, but were not yet submitted for publication. All the measurements were in good agreement with CCL value, but with much improved stabilities and reduced stated uncertainties. Single cell reproducibilities in the range of 1 kHz, and below, were reported with an offset of 3.6 kHz observed where two separate systems had been compared (NPL). Sub-group activity was scheduled to determine an appropriate CCL value and uncertainty.

3.39 μm CH_4

No new measurements for this standard were reported. However, M. Gubin (Lebedev) outlined ideas for achieving an improved methane system, using Zerodur-type materials, reaching reproducibilities in the 10^{-15} region. Such a device would then act as a transportable optical reference for a comb system to provide a number of different outputs across the visible/infrared/microwave spectra as well as GPS-interfaced time domain comparisons. This might be a transportable and cheap alternative to a cold atom or ion referenced optical clock.

10.6 μm OsO_4

J.-P. Wallerand reported LPL measurements of the transition $^{190}OsO_4$ P(55) made using a femtosecond comb to measure the near infrared radiations used in the difference mixing to 10.6 μm. This work had been published [Amy-Klein A. *et al.*, *Appl. Phys.*, 2004, **B78**, 25-30], but no new values were obtained. The comb was referenced to the BNM-SYRTE microwave reference via a 43 km optical fibre link. A. Madej (NRC) reported hydrogen maser referenced chain measurements of a line different to the recommended one, with improved accuracy at the 400 Hz level, and asked for an update to the relevant table.

Cold atoms

J. Helmcke (PTB) reported that there were no new measurements of the Ca neutral system, and also that they had some preliminary results with the new Sr neutral experiment, but no frequency measurements as yet. L. Hollberg (NIST) reported that frequency measurements with their μK Ca atom standard were ongoing, and that they had very good agreement with measurements from the PTB. NIST-JILA had some new results for Sr neutral experiment, and NIST were also considering the potential of the Yb neutral lattice clock arrangement. T.H. Yoon (KRISS) reported that they had a paper [Park C.Y. and Yoon T.H., *Phys. Rev.*, 2003, **A68**, 055401/1-4] detailing optical trapping of Yb. They were currently developing a diode pumped doubled LiF_2 colour centre laser for probing the weak transition in neutral Yb. F. Bertinetto (IMGC) reported that LENS/University of Florence have measured the ^{88}Sr intercombination transition in a strontium beam. D. Rovera (BNM) reported that the SYRTE had investigated intercombination transitions in ^{88}Sr and ^{87}Sr, and also located and measured the very weak 698 nm transition to the $^3P_0$ metastable level in ^{87}Sr with a 20 kHz uncertainty [Courtillot I. *et al.*, *Phys. Rev.*, 2003, **A68**, 030501(R)/1-4]. J. Helmcke (PTB) commented that he did not think it appropriate to include this value in the CCL list at this stage, as it was lower accuracy than say the He-Ne standard, and also not practical for the *MeP*.

Single cold ions

674 nm $^{88}Sr^+$ quadrupole

A. Madej (NRC) reported new measurements on the 674 nm quadrupole transition over the period August–November 2002, resulting in a new value with 50 Hz uncertainty. These measurements were taken with a 500 Hz-wide probe laser [Bernard J.E. *et al.*, *Proc. IEEE IFCS*, 2003, 162-167]. Recent measurements with a 100 Hz-wide laser are in good agreement with the earlier ones. P. Gill (NPL) pointed to 2002 strontium ion measurements [Margolis H.S. *et al.*, *Phys. Rev.*, 2003, **A67**, 032501(R)/1-5], which had a 100 Hz uncertainty and were in good agreement with the NRC. Recent measurements with a transform-limited 200 Hz probe were again in good agreement. The correspondence of these new improved data with the previous data and agreement between laboratories pointed to an updated value/uncertainty, and this was subject to sub-group discussion for this purpose.

282 nm $^{199}Hg^+$ quadrupole

L. Hollberg (NIST) stated that recent measurements at NIST of the 282 nm standard were in agreement with the CCL value to within 1 Hz, but the uncertainty remained at 10 Hz since the quadrupole shift had not yet been systematically evaluated. This was now underway with two traps.

435 nm $^{171}Yb^+$ quadrupole

J. Helmcke reported that PTB had no new quadrupole measurement at this time, but were comparing two traps, with peak-to-peak differences of a few Hz.

467 nm $^{171}Yb^+$ octupole

P. Gill reported three new measurements of the octupole transition (one in 2002 and another in 2003). Both were well within the 2001 CCL uncertainty, but the 2003 data taken with 200 Hz-wide probe laser were inconsistent with the 4 kHz-wide 2002 measurements. In the re-analysis of the earlier data, a missing magnetic field calibration factor had been found, and some under-estimation of the ac Stark shift was now considered likely. With the recent data, using a narrow linewidth, the contribution from the ac Stark effect is much smaller, allowing greater confidence in the ac Stark extrapolation to zero power. Both the 2002 [Blythe P.J. *et al.*, *Phys. Rev.*, 2003, **A67**, 020501(R)/1-4] and 2003 data are combined to provide a new value with reduced uncertainty over the CCL value, and this is reported in NPL Report CBTLM 28. The analysis was considered within the ion sub-group.

Results of sub-groups discussions

The five radiations with proposed changes for the CCL list were considered by two sub-groups, one small group looking at the acetylene standard, the strontium ion quadrupole transition and the ytterbium ion octupole transition, and the other larger group considering the 543 nm and 515 nm laser standards, together with some discussion of conditions for the 532 nm standard.

The outcomes of these discussions have been captured and form the basis for the proposed Recommendation CCL 2c to the CCL.

1.54 μm C_2H_2 P(16) transition

The two recent comb measurements at the NMIJ/AIST [Hong F.-L. *et al.*, *Opt. Lett.*, 2003, **28**(23), 2324-2326] and NPL [Edwards C.S. *et al.*, *Opt. Lett.*, 2004, **29**(6), 566-568] are in good agreement (2.3 kHz different and close to the original CCL number and well within its uncertainty). The values obtained were:

NPL:	194 369 569 385.9 (3.0) kHz
NMIJ/AIST:	194 369 569 383.6 (1.3) kHz

The NPL value and uncertainty corresponded to the unweighted mean for two different acetylene stabilized systems, the uncertainty accounting for a reproducible 3.6 kHz offset between systems. The NMIJ/AIST uncertainty (1.3 kHz) corresponded to the reproducibility of one acetylene stabilized system only, and the equivalent reproducibility for one NPL system was 400 Hz. Unpublished results from the NRC confirmed these measurements, giving a value intermediate between the NPL and NMIJ/AIST measurements. A conservative uncertainty of 10 kHz was chosen which accounted for the root-sum square of the final uncertainties together with maximum expected extent of the frequency shift dependencies on various operating parameters, based on measurements of these dependencies.

674 nm $^{88}Sr^+$ quadrupole transition

The two recent measurements of the $^{88}Sr^+$ quadrupole transition are:

NPL: 444 779 044 095.52 (10) kHz	Margolis H.S. *et al.*, *Phys. Rev.*, 2003, A**67**, 032501/1-5.
NRC: 444 779 044 095.49 (5) kHz	Bernard J.E. *et al.*, *Proc. IEEE IFCS*, 2003, 162-167.

The unweighted mean gives the current CCL value, when rounded to the level appropriate to the overall uncertainty. Very good agreement between laboratories and with the existing CCL value is evident, but with the lack of any extensive evaluation of systematics in either case, it was considered prudent by the MePWG to adopt the larger uncertainty of 100 Hz as the conservative uncertainty.

467nm $^{171}Yb^+$ octupole transition

Three recent measurements between 2002 and 2003 at NPL, with 4 kHz and <200 Hz linewidths respectively, gave the following values (NPL Report CBTLM 28):

NPL: 642 121 496 771. 69 (28) kHz

NPL: 642 121 496 772. 69 (16) kHz

NPL: 642 121 496 772. 55 (21) kHz

resulting in an unweighted mean of 642 121 496 772.3 kHz. The range of values relative to the combination of individual uncertainties suggests that an additional systematic error had not been fully accounted for. This is thought likely to relate to the ac Stark shift determination for the broad-linewidth high intensity data of 2002. The uncertainty was thus derived by treating the three results as a rectangular distribution with an uncertainty of 0.6 kHz given by the standard factor for the 3 sample case. In light of the fact that these measurements are from one laboratory only, the MePWG considered it prudent to attribute an uncertainty of 1 kHz to the CCL value.

543 nm He-Ne/I_2

The recommendation from sub-group deliberations was that the $^{127}I_2$ R(106) 28-0 component b_{10} be adopted as the 543 nm recommended radiation. Taking into account the recent calibrations at BIPM involving lasers from the BIPM, CENAM, CMI, DFM, NIM, MIKES and SPRING Singapore, the mean value for frequency of the radiation was:

f = 551 580 162 400 (10) kHz (provisionally published in *Rapport BIPM*-2004/16)

for operating conditions of:

- (0 ± 2) °C cold point temperature;*
- frequency modulation width, peak-to-peak (2 ± 0.5) MHz.

It was felt appropriate not to define the laser type in the proposal to the CCL.

515 nm I_2

Sub-group discussion centred on the two separate sets of measurements at the LPL Paris, and NIST-JILA, and obtained from very different absorption cell arrangements. At NIST-JILA, data from three different sealed absorption cells had given a final value of

NIST-JILA: 582 490 603 378.8 (5.2) kHz R.J. Jones *et al*., *Appl. Phys.*, 2002, **B74**, 597-601.

The unpublished LPL results from a low pressure flowing gas absorption cell (which should have minimal contamination contribution) were within 0.4 kHz of the NIST-JILA value, when corrected for pressure shift. Since there were published values only from one laboratory, the group considered it prudent to double the uncertainty published by NIST-JILA to 10 kHz for the recommended radiation value. The final CCL value chosen was 582 490 603 442 (10) kHz. The operating conditions specified by the group were:

- (-5 ± 2) °C cold point temperature, corresponding to a pressure of (2.4 ± 0.5) Pa;
- saturating beam intensity <40 mW cm^{-2}.

As with 543 nm, it was decided not to specify the laser type in the CCL list.

* For the specification of operating conditions, such as temperature, modulation width and laser power, the symbols ± refer to a tolerance, not to an uncertainty.

532 nm Nd:YAG/I_2

In response to the suggestion that the operating conditions for the 532 nm standard should be more comprehensively defined, L. Robertsson (BIPM) proposed on behalf of the sub-group the following conditions:

- (-15 ± 1) °C cold point temperature;
- frequency modulation width, peak-to-peak (1 ± 0.2) MHz for 3*f* detection cases;
- saturating beam intensity of (17 ± 11) mW cm^{-2}.

Considerations of optical frequency standards within the CCL list of recommended radiations

A.J. Wallard opened this discussion by observing that a number of attendees with links to the CCTF were present, and mindful of the CCTF request for the identification of likely candidates both optical and microwave which might act as secondary representations of the second, asked for an appraisal of the state-of-the-art in optical frequency standards, and the rate of improvement in these standards. What were the likely candidates in the medium term. It was noted that progress on the Cs fountain primary frequency standard was likely to be limited, so the question was when the optical standards might challenge the fountain.

An additional point was as femtosecond combs were now in fairly widespread use within, of order, ten laboratories, the question arises as to comb validation, which was a critical issue, bearing in mind the criticality of the comb to the high accuracy frequency linkage between the optical and microwave.

J. Helmcke and H. Schnatz (PTB) commented that there was already the comprehensive list of recommended radiations derived and updated as part of the work of the MePWG. They observed that the possibility of a separate list maintained by the CCTF for secondary representations purposes was not desirable. The scenario where the CCTF might operate its own list of optical frequency standards, which might be the same radiations as in the CCL list, but with different values, would be wholly undesirable, especially given the connectivity through physics and application to fundamental constants.

The possibility to maintaining a single list, where each radiation might be approved by the CCL as recommended for the realization of the metre, and other optical standard applications (e.g. telecommunications applications), or by the CCTF as a secondary representation of the second, or by both Consultative Committees.

So one of the critical considerations was to determine the criteria that should be applied for agreeing inclusion of a radiation as a realization of the metre or representation of the second. It was clearly evident that the criteria for the approval by the CCTF would need to be more stringent than those traditionally operated by the MePWG in its consideration of new radiations, and it was anticipated that the activity of a JWG comprising a sub-set of the MePWG, the appropriate CCTF Working Group (CCTFWG) and specific experts, as necessary, would probably be desirable.

L. Hollberg (NIST) noted that there was no consensus at the moment in respect of optical standards for the representation of the second. However, a number of the cold atom and ion optical standards were demonstrating short-term stabilities much better than the Cs fountain standard. Reproducibilities were approaching 10^{-15}, but to date no optical standards had been fully evaluated at this 10^{-15} level. It was expected that this would take place in the next few years. L. Hollberg also outlined some comments *vis-à-vis* the acceptance criteria, which included possibilities for acceptance being based on the standard being within a factor of ten of the best primary standards at the time, the requirement for a fully evaluated and published uncertainty budget, and the desirability of having particular standards in more than one laboratory. These issues were considered to be more appropriate for the discussion of the meeting of the JWG to follow the following day, and the discussion on this criteria issue was postponed until then.

A.J. Wallard (BIPM) observed that the WGDM were primarily interested in iodine-stabilized laser working standards, and did not really require significant changes to the list of recommended radiations. However, the WGDM recognised that the availability of femtosecond comb technology made the process of verifying traceability for these laser standards easier.

A. Madej (NRC) commented that the NIST observations seemed a useful basis. He agreed that the true horizon in respect of optical standards capability would probably not be available until the next cycle of Consultative Committee meetings. J. Helmcke (PTB) felt it would be too conservative to take only existing radiations, and consideration of future possibilities was desirable.

A.J. Wallard (BIPM) commented that it sounded as if there was a potential list of interesting standards encapsulated by the family of cold ion and neutral atom standards.

H. Schnatz (PTB) agreed that it was too early to draw up a list. In effect, the family comprised potential candidates, which would need full systematics and uncertainty evaluation before going forward, with further critical peer review.

Femtosecond comb measurements and comparisons

As an introduction to this topic, L.-S. Ma (BIPM) gave a review of very recent comb comparisons carried out with two travelling combs (one from the BIPM and one from the ECNU) at the BIPM, and then transported to Boulder and compared with the NIST comb. L.-S. Ma commented that the comb measurement capability pointed to an exciting future for optical frequency standards, particularly if transferring the optical standard to other optical and microwave regions. Significantly, L.-S. Ma found that the difference between systems could be ~1 Hz for comb transfer up from microwave references, whereas transfer could be much better going from an optical reference down in frequency.

L.-S. Ma presented the very recent comb comparison results at NIST by describing initial activity at BIPM prior to moving to NIST, whereby the 532 nm laser standard was measured, showing (0.1 ± 0.7) Hz agreement between both combs. The combs were then moved to Boulder and the same radiation (Ca probe laser at 657 nm) was measured by the two combs again both referenced to a hydrogen maser reference, with 0.4 Hz observed difference. At this point the NIST broadband comb (of a different design, i.e. without photonic crystal fibre) was also used for measurements at 657 nm, with differences of few Hz. Was this a result of transportation or use of photonic crystal fibre, for example? It was then decided to do the comparisons with the combs referenced to the Ca probe laser (10^{-15} stability at 1 s, linewidth < 100 Hz) rather than the microwave standard, and then compare the now optically-controlled comb repetition rates. This then gave very impressive improvement in performance depending on exactly how the repetition rate differences were detected and monitored. Whilst this is a very impressive state-of-the-art performance, L.-S. Ma was cautious about the exact nature of the agreement, both due to the fact that the measurements were very recent and not yet subject to full scrutiny by the BIPM, the ECNU and NIST workers, and also about the more general issue of potential aspects which could significantly reduce performance.

L. Robertsson (BIPM) presented the BIPM quality system relative to calibration and comparison of laser standards. He reminded the meeting that the *MeP* gives a list of the recommended radiations for the realization of the metre according to method (c). Standards realized in this way need to be compared in order to comply with ISO/IEC 17025. The absolute frequency measurement using the comb is in effect an application of method (b) described in the *Mise en Pratique*, i.e. the wavelength in *vacuum* is obtained from the frequency measurement and the speed of light.

Both F. Bertinetto (IMGC-CNR) and R. Hamid (UME) commented that they would like to make a comparison with the transportable BIPM comb as soon as their comb systems are available. A. Madej (NRC) proposed a comparison with the BIPM transportable comb using the 674 nm stabilized laser probe from the Sr^+ ion system.

The main message was that optically-referenced combs were likely to perform better than microwave-referenced combs at the highest level of performance. However, the two different referencing methods were equally applicable for lower accuracy measurement of gas cell-based laser standards. It should also be noted that operation of a microwave-referenced comb at measuring accuracy levels appropriate to that needed for laser standard calibration was not necessarily intrinsically free of error, and the situation of a stand-alone comb measurement of a laser standard would benefit from comb comparison against some of these higher-accuracy comb systems, or comparison with laser results by heterodyne comparison, or the comb measurement of a transfer laser standard.

One comment from N. Brown (NML) relevant to the WGDM was that laser heterodyne comparisons were relatively easy for certain radiations such as 633 nm, whereas combs were not so easy at this time to use routinely, and this needed to be weighed up against the basic requirement for accurate number for the laser standards. Clearly there needed to be confidence in the comb measuring performance, but the primary issue for the WGDM was fast and simple access to comb outputs. Travelling combs might not be so interesting, and the output requirement was the same irrespective of whether comb calibrations or laser heterodyne comparisons were made. A.J. Wallard confirmed that easy access to laser values was the key issue. L. Hollberg (NIST) commented that probably combs provided most opportunity in the calibration of lasers in the green and ultra violet. J. Stone (NIST) complemented this, saying industrial requirements remained overwhelmingly targeted on 633 nm calibration, with a small percentage in the green. Ultra-violet source requirements were primarily aimed at nanotechnology and space related measurements. A. Madej (NRC) commented that this again demonstrated the importance of 633 nm measurement information. J. Helmcke (PTB) also observed that repeated comb measurements of the 633 nm standard were not likely to change very much the accepted value of the radiation. However, such measurements do provide verification of traceability to an individual laboratory’s laser.

A.J. Wallard (BIPM) commented that the BIPM would continue to offer comb calibrations for this purpose. Alternatively, might there be a possibility of similar measurements from travelling combs? P. Gill (NPL) felt that for the BIPM travelling combs to be used to verify gas-cell laser standards in the field was a significant undertaking of a size and complexity perhaps even greater than laser heterodyne comparisons. He felt that one way to address this was to offer some alternatives such as:

- laser heterodyne comparisons and laser calibration by comb at BIPM as before;
- BIPM travelling comb measurements and comb comparisons at those laboratories with high performance, high reproducibility optical frequency standards; thereby validating the comb systems in those laboratories;
- comb calibrations of working laser standards could be offered by those laboratories to other laboratories on a regional basis.

A proposal to the CCL has been drafted on this topic.

APPENDIX L 3.
Report of the meeting of the Joint Working Group CCL/CCTF BIPM, Sèvres, 9-10 September 2003

The following report highlights the discussions and outcomes of the meeting of the Joint Working Group CCL/CCTF (JWG) held at the BIPM on Tuesday 9 and Wednesday 10 September 2003.

The following delegates were present: J. Bergquist (NIST), F. Bertinetto (IMGC-CNR), N. Brown (NML CSIRO), M.S. Chung (President of the CCL), Yu. S. Domnin (VNIIFTRI), P. Gill (NPL, Chairman of the CCL MePWG), C.I. Eom (KRISS), A. Godone (IEN), M. Gubin (Lebedev Institute), R. Hamid (UME), J. Helmcke (PTB), D. Henderson (NPL), L.W. Hollberg (NIST), A. Lassila (MIKES), S. Leschiutta (President of the CCTF), A. Madej (NRC), H. Matsumoto (NMIJ/AIST), S.-I. Ohshima (NMIJ/AIST), A. Onae (NMIJ/AIST), J. Pekelsky (NRC), T.J. Quinn (Director of the BIPM), F. Riehle (PTB, Chairman of the CCTF WG), D. Rovera (BNM-SYRTE), H. Schnatz (PTB), J. Stone (NIST), S. van den Berg (NMi VSL), M. Viliesid (CENAM), J.-P. Wallerand (BNM-INM), T. Yandayan (UME), T.H. Yoon (KRISS).

Observers and guests: P. Balling (CMI), S. Gao (NIM), P. Juncar (BNM-INM), O. Kruger (CSIR-NML), S.L. Tan (SPRING Singapore).

Also present: P. Giacomo (Emeritus Director of the BIPM); F. Arias (Executive Secretary of the CCTF), R. Felder, L.-S. Ma, G. Petit, S. Picard, L. Robertsson, L. Vitushkin, A.J. Wallard (Executive Secretary of the CCL and Director designate of the BIPM), P. Wolf, M. Zucco (BIPM).

The meeting was attended by 27 delegates drawn from the CCL and the CCTF, 5 observers and guests, and members of BIPM staff. The meeting was presided over by the President of the CCL, Dr Chung, and the Director of the BIPM, Dr Quinn. The chairmen were Dr Riehle from the PTB and Dr Gill from the NPL.

Executive summary

- Criteria for acceptance and working procedures for proposing potential secondary representations of the second to the CCTF.

The JWG developed the structure, acceptance criteria and working procedures for proposing potential secondary representations of the second for acceptance by the CCTF. Criteria include a performance within an order of magnitude of the primary standard of that date, and a fully evaluated uncertainty budget.

- List of frequencies appropriate for secondary representations of the second.

No optical radiations were selected during the meeting, the only candidate would, however, seem to be the Rb microwave standard. This possibility will be discussed during the next JWG that will be held at the BIPM on 30 March 2004.

Introduction

At the opening of the meeting, Dr Zucco of the BIPM was appointed secretary of the meeting, and the proposed agenda was approved. Since the JWG was formed by members belonging to the two different time and length communities, Prof. Leschiutta opened the meeting. He presented the role and aim of the CCTF and the reasons that had led to the establishment of a working group whose task was to draw up a list of frequency sources that CCTF could use as secondary representations of the second.

Dr Riehle presented a review of the discussions that had led to the present meeting and reported on the meeting of the CCTF working group in 2001, mentioned by Prof. Leschiutta, whose task was to propose to the next CCTF meeting a list of radiations to be used as secondary representations of the second. As a consequence, the CCTF accepted Recommendation CCTF 1 (2001) that a list of secondary representations of the second should be established. In September 2001, the CCL formulated a recommendation to the CIPM for an updated list of radiations for the practical realization of the metre (*Mise en Pratique*). Later in 2001, the CIPM recommended that discussions between the CCTF and the CCL should continue, possibly leading to a Joint Working Group CCL/CCTF to establish a single list of frequencies that would include reference frequencies for the realization of the SI metre, and frequencies used as secondary representations of the second.

In February 2002, a questionnaire (document CCL-CCTF/03-04) was sent to the members of the CCTF working group (CCTFWG) by their chairman, Dr Riehle. Later, in May 2003, the CCTFWG with guests from the CCL had an informal meeting in Tampa (Florida, United States) during the joint meeting of the 17th EFTF and the 2003 IEEE IFCS. The meeting agreed on the purpose of the list of secondary representations of the second, and on the necessity that a single list should be prepared and periodically updated by the joint working group. It was agreed that each entry should carry labels stating either that the transition is approved as a reference transition for the realization of the metre, or that the transition is approved as a secondary representation of the second or both. The number of CCTF attributed transitions would currently be small and should, deliberately, be kept small by applying stringent requirements. From the answers to the questionnaire, there was no complete agreement about the relative uncertainty that the secondary representations of the second should have. Another possible outcome was that a detailed paper in a peer-reviewed journal should be published, which could detail the uncertainty for realizing the unperturbed transition frequency. The group also discussed the extent to which this uncertainty should be larger than that of the current primary frequency standard. The group came to the view that this uncertainty should be substantially lower than that of a high quality GPS-disciplined oscillator, and preferentially be not more than a factor ten above the current uncertainty of primary frequency standards. To gain confidence in the suitability for the purpose, there should either be a number of repeated, independent measurements with respect to a primary frequency standard, or measurements using standards in different laboratories should be available.

Dr Gill (NPL), chairman of the CCL Working Group on the *Mise en Pratique* (the MePWG), presented the results of the MePWG meeting held on 8 and 9 September at the BIPM. During this meeting, only a few existing radiations of the *MeP* had been reviewed. No new radiations had been proposed. Finally, the discussion of the list of possible secondary representations of the second was postponed pending the outcome of the CCL/CCTF meeting.

Prof. Ma (BIPM) presented the latest results of comb comparisons carried out between two travelling combs, one portable from the BIPM and one portable from the ECNU at the BIPM, and then transported to Boulder and compared with the NIST fixed comb on the other end. Prof. Ma pointed out that the comb measurement capability promised an exciting future for optical frequency standards, particularly when transferring the performance of optical standards to other optical or to the microwave region.

It was agreed that the JWG would sit between the CCTF, which is concerned with secondary representations of the second, and the CCL, which is concerned with the realization of the definition of the metre. It confirmed that there would be only one list of recommended radiations, within which some radiations would relate to the realization of the metre, some would relate to the secondary representations of the second, and some for both use. The JWG should review and discuss the uncertainty budgets of the proposed standards, and should evaluate its validity before making their recommendation to the CCTF that the standard be added to the list of frequencies as appropriate for secondary representations of the second. The JWG would keep the CCL fully informed about its activity.

Following this, the discussion centred on the list of radiations common to the CCL and the CCTF. Prof. Leschiutta reminded the meeting that this was required by the next meeting of the CCTF in 2004 as given in Recommendation CCTF 1 (2001). However, it was agreed that it was too soon to draw up a common list.

The discussion then looked at the other points of the agenda, namely the criteria for identification of possible candidates for a secondary representation of the second (or a potential future redefinition of the second). The proposal from the NIST/JILA group (document CCL-CCTF/03-24, restricted access) served as a basis for discussion. Finally, it was agreed that:

1 The SI value of the unperturbed frequency of a quantum transition suitable as a secondary representation of the second must have an uncertainty that is evaluated and documented so as to meet the requirements adopted for the primary frequency standards for use in International Atomic Time.
2 This uncertainty should be no larger than about a factor ten of the primary standards *of that date* that serve as the best realizations of the second.

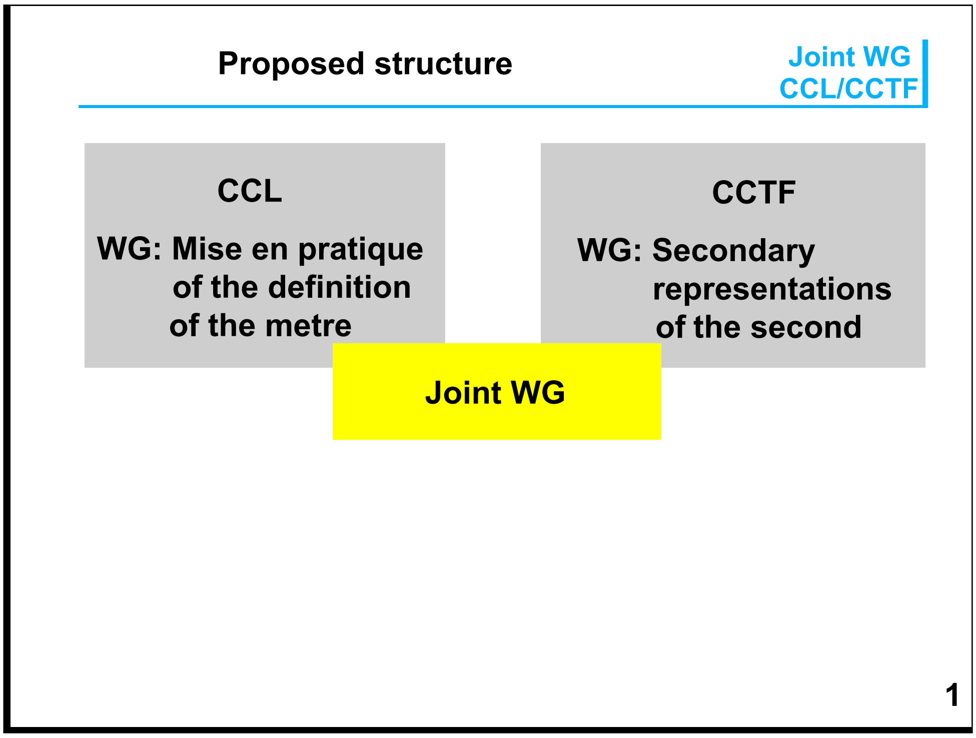
It was finally agreed that the JWG should meet on 30 March 2004 immediately prior to the CCTF. The JWG membership would be drawn from the BNM, IEN, NIST, NMIJ/AIST, NPL, NRC, PTB and VNIIFTRI, under the joint chairmanship of Dr Gill (NPL) and Dr Riehle (PTB). Consensus was achieved that the list of members has to be regarded as a dynamical one.

The main aim of this working group would be to discuss the Rb microwave standard as a possible candidate for the secondary representation of the second.

The three PowerPoint presentation slides agreed by the meeting are attached as Annex 1

Annex 1: The three PowerPoint slides agreed by the meeting

Slide 1



Slide 2

Requirements for consideration as secondary representations of the second

Joint WG
CCL/CCTF

1) The SI value of the unperturbed frequency of a quantum transition suitable as a secondary representation of the second must have an uncertainty that is evaluated and documented so as to meet the requirements adopted for the primary frequency standard for use in International Atomic Time.

2) This uncertainty should be no larger than about a factor of 10 of the primary standards *of that date* that serve as the best realisations of the second.

2

Slide 3

Working procedure

Joint WG
CCL/CCTF

The joint CCTF and CCL working group should review and discuss the proposed standard's uncertainty budget and evaluate its validity before making their recommendation to the CCTF for the standard being added to the list of frequencies appropriate for secondary representations of the second.

The joint working group would keep the CCL fully informed about its activity

3

Ad hoc Joint Working Group CCL/CCTF discussions

These followed the MePWG, and were chaired by F. Riehle (PTB), CCTFWG chairman, and P. Gill (NPL), MePWG chairman. A separate report on the outcome of this meeting will be forthcoming. Three main issues were discussed and subsequently summarised in a presentation from A.J. Wallard (BIPM), including:

1 proposed structure of the JWG, going forward;

2 criteria for consideration and acceptance of a radiation as a secondary representation of the second;

3 JWG working procedure.

In respect of the proposed JWG structure, it was agreed that the JWG should consider its area of interest as being between the CCL MePWG and the CCTFWG, and that the approval of proposed secondary representation radiations lay with the CCTF, but that it would be responsible for evaluating the various proposals prior to submission to the CCTF, and that the CCL would be kept fully informed of proposal and decision. The JWG construction would be a sub-set of the MePWG together with some members from the CCTFWG and specific experts as necessary.

There was significant discussion of the criteria (item 2) that should apply to the consideration and acceptance of optical or microwave standards as secondary representations of the second. Two main criteria were developed by the JWG:

- The SI value of the unperturbed frequency of a quantum transition suitable as a secondary representation of the second must have an uncertainty that is evaluated and documented so as to meet the requirements adopted for the primary frequency standard for use in International Atomic Time.
- This uncertainty should be no larger than about a factor of ten of the primary standards of that date that serve as the best realizations of the second.

The working procedure developed (item 3) proposed that the JWG should review and discuss the proposed standard's uncertainty budget and evaluate its validity before making their recommendation to the CCTF for the standard being added to the list of frequencies appropriate for secondary representations of the second.

The JWG would keep the CCL fully informed about its activity.

It was decided that the next JWG meeting would be immediately prior to the CCTF next year, where considerations of the Rb microwave standard would take place. It was not expected that optical radiations would be considered at that time, as they were not yet ready.