BUREAU INTERNATIONAL DES POIDS ET MESURES

COMITÉ CONSULTATIF POUR LA DÉFINITION DU MÈTRE

Rapport de la 8e session
Report of the 8th Meeting
1992

COMITÉ CONSULTATIF POUR LA DÉFINITION DU MÈTRE

SESSION DE 1992

MEETING OF 1992

BUREAU INTERNATIONAL DES POIDS ET MESURES

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LISTE DES SIGLES UTILISÉS DANS LE PRÉSENT VOLUME

LIST OF ACRONYMS USED IN THE PRESENT VOLUME

1. Sigles des laboratoires, commissions et conférences Acronyms for laboratories, committees and conferences

*ASMW	Amt für Standardisierung, Messwesen und Warenprüfung, Berlin (Allemagne)
BFMMP /SZMDM	Bureau fédéral des mesures et métaux précieux/Savezni Zavod za Mere i Dragocene Metale, Belgrade (ex-Yougoslavie)
BCR	Bureau communautaire de référence de la Communauté économique européenne/Community Bureau of Reference of the Commission of the European Communities
BIPM	Bureau international des poids et mesures
BNM	Bureau national de métrologie, Paris (France)
CCDM	Comité consultatif pour la définition du mètre
CCDS	Comité consultatif pour la définition de la seconde
CCE	Comité consultatif d'électricité
CEM	Centro Español de Metrologia, Madrid (Espagne)
CGPM	Conférence générale des poids et mesures
CIPM	Comité international des poids et mesures
CIRP	International Institution for Production Engineering Research
CNAM	Conservatoire national des arts et métiers, Paris (France)
CPEM	Conference on Precision Electromagnetic Measurements
*CSAV	Československa Akademie Ved, Brno et Prague (Tchéco-Slovaquie), voir ISI
CSIR	Council for Scientific and Industrial Research, Division of Production Technology, Pretoria (Afrique du Sud)
CSIRO	Commonwealth Scientific and Industrial Research Organization, Division of Applied Physics, Lindfield (Australie)
CSMU	Československý Metrologický Ústav, Bratislava et Prague (Tchéco-Slovaquie)
DFM	Danish Institute for Fundamental Metrology, Lyngby (Danemark)

* Les laboratoires ou organisations marqués d'un astérisque soit n'existent plus soit figurent sous un autre sigle.

* Organizations marked with an asterisk either no longer exist or operate under a different acronym.

DKD	Deutscher Kalibrierdienst, Braunschweig (Allemagne), *voir* PTB
*DSIR	Department of Scientific and Industrial Research, Lower Hutt (Nouvelle-Zélande), voir MSL
EAM	*voir* OFMET
ETCA	Établissement technique central de l'armement, Arcueil (France)
EUROMET	European Collaboration in Measurement Standards
HUB	Helsinki University of Technology, Accelerator Laboratory, Helsinki (Finlande)
IAU	*voir* UAI
IEEE	Institute of Electrical and Electronics Engineers
IFA/IFTAR	Institute of Atomic Physics, Bucarest (Roumanie)
IGM	Inspection générale de la métrologie, Bruxelles (Belgique)
IMGC	Istituto di Metrologia G. Colonnetti, Turin (Italie)
INM	Institut national de métrologie, Paris (France)
IPL	Institut de physique des lasers de l'Académie des sciences de Russie/Institute of Laser Physics, Academy of Sciences of Russia, Novosibirsk (Féd. de Russie)
IPQ	Instituto Português da Qualidade, Lisbonne (Portugal)
ISI	(ex-CSAV) Institute of Scientific Instruments of the Academy of Sciences of the Czech Republic, Brno (Rép. Tchèque)
ISO	Organisation internationale de normalisation/ International Organization for Standardization
JILA	Joint Institute for Laboratory Astrophysics, Boulder (É.-U. d'Amérique)
KRISS	(ex KSRI) Korea Research Institute of Standards and Science, Taejon (Rép. de Corée)
*KSRI	Korea Standards Research Institute, Taejon (Rép. de Corée), *voir* KRISS
LHA	Laboratoire de l'horloge atomique, Orsay (France)
LMM	Laboratorio de Metrologia y Metrotecnica, Universidad Politecnica de Madrid, Madrid (Espagne)
LNE	Laboratoire national d'essais, Orsay et Paris (France)
LPI	Institut de physique P.N. Lebedev/P.N. Lebedev Physics Institute, Moscou (Féd. de Russie)
LPTF	Laboratoire primaire du temps et des fréquences, Paris (France)
MRI	Metrology Research Institute, Helsinki University of Technology, Helsinki (Finlande)
MSL	(ex DSIR) Measurement Standards Laboratory of New Zealand, Lower Hutt (Nouvelle-Zélande)
*NBS	National Bureau of Standards, Gaithersburg (É.-U. d'Amérique), *voir* NIST

NIM	Institut national de métrologie/National Institute of Metrology, Beijing (Rép. pop. de Chine)
NIST	(ex NBS) National Institute of Standards and Technology, Gaithersburg (É.-U. d'Amérique)
NML	National Measurement Laboratory, Lindfield (Australie), *voir* CSIRO
NPL	National Physical Laboratory, Teddington (Royaume-Uni)
NPLI	National Physical Laboratory of India, New Delhi (Inde)
NRC	Conseil national de recherches du Canada/National Research Council of Canada, Ottawa (Canada)
NRLM	National Research Laboratory of Metrology, Tsukuba (Japon)
OFMET/EAM	Office fédéral de métrologie/Eidgenössisches Amt für Messwesen, Wabern (Suisse)
OMH	Országos Mérésügyi Hivatal, Budapest (Hongrie)
PEL	Physics and Engineering Laboratory, Lower Hutt (Nouvelle-Zélande)
PKNM	Polski Komitet Normalizacji, Miar i Jakości, Varsovie (Pologne)
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig (Allemagne)
SP	Statens Provningsanstalt, Borås (Suède)
TTK	Technical Research Centre of Finland, Helsinki (Finlande)
UAI/IAU	Union astronomique internationale/International Astronomical Union
UPT	Ústav Pristojové Techniký Českosl. Akademie Ved, Institute of Scientific Instruments, Brno (Tchéco-Slovaquie)
VNIIFTRI	Institut des mesures physicotechniques et radiotechniques/All-Russian Research Institute for Physical, Technical and Radio-Technical Measurements, Moscou (Féd. de Russie)
VNIIM	Institut de métrologie D.I. Mendéléev/D.I. Mendeleyev Institute for Metrology, Saint-Pétersbourg (Féd. de Russie)
WECC	Western European Calibration Cooperation

2. Sigles des termes scientifiques
Acronyms for scientific terms

CMM	Coordonnées tri-dimensionnelles/3 D Coordinate Metrology
ULE	Ultra Low Expansion

COMITÉ CONSULTATIF
POUR LA DÉFINITION DU MÈTRE

MEETING OF 1992

Note on the use of the English text

To make its reports and those of its various Comités Consultatifs more widely accessible the Comité International des Poids et Mesures has decided to publish an English version of these reports. Readers should note that the official record is always that of the French text. This must be used when an authoritative reference is required or when there is doubt about the interpretation of the text.

Note sur l'utilisation du texte anglais

Afin de faciliter l'accès à ses rapports et à ceux des divers Comités consultatifs, le Comité international des poids et mesures a décidé de publier une version en anglais de ces rapports. Le lecteur doit cependant noter que le rapport officiel est toujours celui qui est rédigé en français. C'est le texte français qui fait autorité si une référence est nécessaire ou s'il y a doute sur l'interprétation.

THE BIPM

AND THE CONVENTION DU MÈTRE

The Bureau International des Poids et Mesures (BIPM) was set up by the Convention du Mètre signed in Paris on 20 May 1875 by seventeen States during the final session of the diplomatic Conference of the Metre. This Convention was amended in 1921.

BIPM has its headquarters near Paris, in the grounds (43 520 m^2) of the Pavillon de Breteuil (Parc de Saint-Cloud) placed at its disposal by the French Government; its upkeep is financed jointly by the Member States of the Convention du Mètre*.

The task of the BIPM is to ensure worldwide unification of physical measurements; it is responsible for:

— establishing the fundamental standards and scales for measurement of the principal physical quantities and maintaining the international prototypes;

— carrying out comparisons of national and international standards;

— ensuring the co-ordination of corresponding measuring techniques;

— carrying out and co-ordinating determinations relating to the fundamental physical constants that are involved in the above-mentioned activities.

BIPM operates under the exclusive supervision of the Comité International des Poids et Mesures (CIPM) which itself comes under the authority of the Conférence Générale des Poids et Mesures (CGPM).

The Conférence Générale consists of delegates from all the Member States of the Convention du Mètre and meets at present every four years. At each meeting it receives the Report of the Comité International on the work accomplished, and it is responsible for:

— discussing and instigating the arrangements required to ensure the propagation and improvement of the International System of Units (SI), which is the modern form of the metric system;

— confirming the results of new fundamental metrological determinations and the various scientific resolutions of international scope;

— adopting the important decisions concerning the organization and development of BIPM.

The Comité International consists of eighteen members each belonging to a different State: it meets at present every year. The officers of this committee issue an Annual Report on the administrative and financial position of BIPM to the Governments of the Member States of the Convention du Mètre.

The activities of the BIPM, which in the beginning were limited to the measurements of length and mass and to metrological studies in relation to these quantities, have been extended to standards of measurement of electricity (1927), photometry (1937), ionizing radiations (1960), to time scales (1988) and to amount of substance (1993). To this end the original laboratories, built in 1876-1878, were enlarged in 1929; new buildings were constructed in 1963-1964 for the ionizing radiation laboratories, in 1984 for the laser work and in 1988 a new building for a library and offices was opened.

Some forty physicists or technicians work in the BIPM laboratories. They mainly conduct metrological research, international comparisons of realizations of units and the verification of standards used in the above-mentioned areas. An annual report published

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* As of 31 December 1993, forty-seven States were members of this Convention: Argentina (Rep. of), Australia, Austria, Belgium, Brazil, Bulgaria, Cameroon, Canada, Chile, China (People's Rep. of), Czech Republic, Denmark, Dominican Republic, Egypt, Finland, France, Germany, Hungary, India, Indonesia, Iran, Ireland, Israel, Italy, Japan, Korea (Dem. People's Rep. of), Korea (Rep. of), Mexico, Netherlands, New Zealand, Norway, Pakistan, Poland, Portugal, Romania, Russian Federation, Spain, Slovak Republic, South Africa, Sweden, Switzerland, Thailand, Turkey, United Kingdom, U.S.A., Uruguay, Venezuela.

in the Procès-Verbaux des séances du Comité International des Poids et Mesures gives the details of the work in progress.

In view of the extension of the work entrusted to the BIPM, the CIPM has set up since 1927, under the name of Comités Consultatifs, bodies designed to provide it with information on matters that it refers to them for study and advice. These Comités Consultatifs, which may form temporary or permanent Working Groups to study special subjects, are responsible for co-ordinating the international work carried out in their respective fields and proposing recommendations concerning units. In order to ensure world-wide uniformity in units of measurement, the Comité International accordingly acts directly or submits proposals for sanction by the Conférence Générale.

The Comités Consultatifs have common regulations (*BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1963, **31**, 97). Each Comité Consultatif, the chairman of which is normally a member of CIPM, is composed of delegates from the major metrology laboratories and specialized institutes, a list of which is drawn up by CIPM, as well as individual members also appointed by CIPM and one representative of BIPM. These committees hold their meetings at irregular intervals; at present there are nine of them in existence:

1. The Comité Consultatif d'Électricité (CCE), set up in 1927.
2. The Comité Consultatif de Photométrie et Radiométrie (CCPR), new name given in 1971 to the Comité Consultatif de Photométrie (CCP) set up in 1933 (between 1930 and 1933 the preceding committee (CCE) dealt with matters concerning Photometry).
3. The Comité Consultatif de Thermométrie (CCT), set up in 1937.
4. The Comité Consultatif pour la Définition du Mètre (CCDM), set up in 1952.
5. The Comité Consultatif pour la Définition de la Seconde (CCDS), set up in 1956.
6. The Comité Consultatif pour les Étalons de Mesure des Rayonnements Ionisants (CCEMRI), set up in 1958. In 1969 this committee established four sections: Section I (Measurement of x and γ rays, electrons), Section II (Measurement of radionuclides), Section III (Neutron measurements), Section IV (α-energy standards). In 1975 this last section was dissolved and Section II was made responsible for its field of activity.
7. The Comité Consultatif des Unités (CCU), set up in 1964 (this committee replaced the "Commission for the System of Units" set up by the CIPM in 1954).
8. The Comité Consultatif pour la Masse et les grandeurs apparentées (CCM), set up in 1980.
9. The Comité Consultatif pour la Quantité de Matière (CCQM), set up in 1993.

The proceedings of the Conférence Générale, the Comité International, the Comités Consultatifs, and the Bureau International are published under the auspices of the latter in the following series:

— *Comptes rendus des séances de la Conférence Générale des Poids et Mesures;*
— *Procès-Verbaux des séances du Comité International des Poids et Mesures;*
— *Sessions des Comités Consultatifs;*
— *Recueil de Travaux du Bureau International des Poids et Mesures* (this collection for private distribution brings together articles published in scientific and technical journals and books, as well as certain work published in the form of duplicated reports).

The Bureau International also publishes monographs on special metrological subjects and, under the title "*Le Système International d'Unités (SI)*", a booklet, periodically up-dated, in which all the decisions and recommendations concerning units are collected.

The collection of the *Travaux et Mémoires du Bureau International des Poids et Mesures* (22 volumes published between 1881 and 1966) ceased in 1966 by a decision of the CIPM.

Since 1965 the international journal *Metrologia*, edited under the auspices of the CIPM, has published articles on the more important work on scientific metrology carried out throughout the world, on the improvement in measuring methods and standards, on units, etc., as well as reports concerning the activities, decisions, and recommendations of the various bodies created under the Convention du Mètre.

Comité International des Poids et Mesures

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POUR LA DÉFINITION DU MÈTRE

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National Institute of Metrology [NIM], Beijing.

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

National Physical Laboratory [NPL], Teddington.

National Research Council of Canada [NRC], Ottawa.
National Research Laboratory of Metrology [NRLM], Tsukuba.
Physikalisch-Technische Bundesanstalt [PTB], Braunschweig.
International Astronomical Union [IAU].
B. Edlén, Lunds Universiteit, Lund.
K. Shimoda, Tokyo.

The Director of the Bureau International des Poids et Mesures [BIPM], Sèvres.

AGENDA
for the 8th meeting

1. Opening of the meeting. Designation of a rapporteur.
2. Approval of the agenda.
3. Examination of replies to the BIPM questionnaire.
4. Presentations of new results related to items in the questionnaire.
5. Modifications to the 1983 *mise en pratique* of the definition of the metre, including proposals for new recommended radiations.
6. Results of international comparisons of stabilized lasers carried out by national laboratories and the BIPM since 1983.
7. Results of international comparison of angle standards.
8. Future international comparisons concerning:
   a) stabilized lasers;
   b) absorption cells;
   c) line-scale, end-gauge and angle standards;
   d) other.
9. Possible creation of CCDM working groups; tasks and membership.
10. Work at the BIPM:
    — international comparisons of stabilized lasers;
    — research and introduction of new techniques;
    — collaboration with the national laboratories;
    — the future of line-scale and end-gauge work at the BIPM.
11. Recommendations to the CIPM.
12. Any other business
13. Next meeting of the CCDM.

REPORT

OF THE

COMITÉ CONSULTATIF

POUR LA DÉFINITION DU MÈTRE

(8th Meeting — 1992)

TO THE

COMITÉ INTERNATIONAL DES POIDS ET MESURES

by W. R. C. ROWLEY, Rapporteur

The Comité Consultatif pour la Définition du Mètre (CCDM) held its eighth meeting in the Pavillon de Breteuil in Sèvres, Wednesday, Thursday and Friday 9, 10 and 11 September 1992.

Present:

P. B. CLAPHAM, Member of the CIPM, President of the CCDM.

The delegates of the member laboratories:

Bureau National de Métrologie/Institut National de Métrologie [INM], Paris (P. JUNCAR).

CSIRO, Division of Applied Physics [CSIRO], Lindfield (N. BROWN).

D. I. Mendeleyev Institute for Metrology [VNIIM], Saint-Petersburg (L. F. VITUSHKIN).

Istituto di Metrologia G. Colonnetti [IMGC], Turin (A. SACCONI, F. BERTINETTO).

Korea Research Institute of Standards and Science [KRISS], Taejon (M. S. CHUNG).

National Institute of Metrology [NIM], Beijing (ZHAO KEGONG, XU YI).

National Institute of Standards and Technology [NIST], Gaithersburg (J. A. Stone)/Joint Institute for Laboratory Astrophysics [JILA], Boulder (J. L. Hall).

National Physical Laboratory [NPL], Teddington (W. R. C. Rowley).

National Research Council [NRC], Ottawa (J. R. Pekelsky, J. Vanier).

National Research Laboratory of Metrology [NRLM], Tsukuba (T. O'ishi).

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig (J. Helmcke, F. Riehle).

The Director of the Bureau International des Poids et Mesures [BIPM] (T. J. Quinn).

Invited guests:

All-Russian Research Institute for Physical, Technical and Radio-Technical Measurements [VNIIFTRI], Moscow (V. Tatarenkov, Yu. S. Domnin).

Československý Metrologický Ústav [CSMU], Bratislava (I. Brezina).

CSIR — Division of Production Technology [DPT], Pretoria (O. Cramer).

Laboratoire National d'Essais [LNE], Paris (M. Priel).

Office Fédéral de Métrologie [OFMET], Wabern (B. Vaucher).

Also attending the meeting: P. Giacomo (Director Emeritus of the BIPM); J.-M. Chartier, R. Felder, S. Picard and L. Robertsson (BIPM).

Absent:

International Astronomical Union, Messrs. B. Edlén and K. Shimoda.

1. Opening of the meeting. Designation of a rapporteur

The President opened the meeting by welcoming the delegates, particularly those from non-member laboratories attending by invitation. He noted that as the previous meeting had been ten years earlier, most of the delegates were, as he was himself, attending for the first time. He would thus value particularly the experience of those few who had attended previously.

Mr Rowley was nominated Rapporteur, and the agenda was approved.

2. Progress made since 1982 concerning the stabilized-laser radiations recommended for the practical realization of the metre

The previous meeting of the CCDM in 1982 recommended that the definition of the metre be changed from that based on the wavelength of a krypton-86 radiation, to a definition based on the speed of light. This recommendation was subsequently endorsed by the CIPM and the new definition was adopted by the 17th CGPM in 1983.

In 1982 the CCDM had recommended three principal means for the realization of the unit, to accord with the new definition. Of these three, the method most often used is by means of one of a number of recommended radiations. These radiations, when produced under specified conditions and in accordance with accepted good practice, have stated frequency and wavelength values that are reproducible within given uncertainties.

One of the principal tasks for the 8th CCDM was to review and update the list of recommended radiations. In the years since the previous meeting considerable advances had taken place. The techniques used for stabilizing the frequencies of laser radiations had become more precise and it was possible to establish their values with reduced uncertainty. There were also additional radiations that had been proposed for inclusion.

Details of these developments were contributed by member laboratories prior to the meeting in the form of replies to a questionnaire that had been circulated by the BIPM (Document CCDM/92-1). These replies were supplemented by references to further details contained in more than 130 published articles. The task of analyzing these documents was facilitated by a summary (Document CCDM/92-3) that had been prepared by the BIPM and circulated before the meeting. On behalf of the meeting the President thanked the Bureau for this valuable preparatory work.

Methane-stabilized laser (88 THz, 3,39 μm)

The frequency of the radiation emitted by the methane-stabilized helium-neon laser was the most accurately known among the frequencies of the radiations recommended in 1982 for the realization of the metre. In their submissions, several laboratories reported new measurements of the frequency with significantly lower uncertainty, and proposed that both the frequency value and its uncertainty should be revised. This proposal was unanimously approved by the CCDM.

For the guidance of the committee, Mr Felder (BIPM) gave a short presentation, summarizing all the data of which the BIPM was aware, involving results from eight laboratories. Five laboratories had frequency-chain systems for measuring the frequency of sixteen lasers from seven laboratories; three were stabilized on the resolved hyperfine structure of the methane absorption line, and the thirteen others stabilized on the unresolved structure. One laser in particular had been measured in several frequency chains. The dispersion of the results for this laser was only ± 300 Hz, whereas the dispersion for all the results was ± 3 kHz. The major source of dispersion was the variability of the portable form of laser (with unresolved structure) which was affected by design and operating conditions such as saturating power, mirror curvature, and detector position.

In discussion of these results it became clear that it would probably be appropriate to consider separately the situations of resolved and unresolved hyperfine structure. For the resolved structure case, the main problem was how to deal with the second-order Doppler shift, which affected some, but not all, of the measurements. For the unresolved structure, however, the main problem was to specify suitable operating conditions for which the relevant scientific basis was not fully understood. A much greater uncertainty would thus be associated with this frequency value.

The President suggested that, acting under this guidance, the details of the numerical value, uncertainty and associated operating conditions to be recommended, could best be determined by a small working group during breaks in the main session. Accordingly an *ad hoc* group, comprising the delegates from the VNIIM, JILA, PTB, NPL, INM, NIM, IMGC and NRC, together with Mr Chartier and Mr Felder of the BIPM, was established under the chairmanship of Mr Helmcke.

In subsequent meetings of this group it was noted that four out of the six independent resolved-structure frequency measurements had been made on either cold methane molecules or with such low optical powers that the saturation process was restricted to slow-moving molecules. In either case the second-order Doppler shift would be very small. It was decided that the few results with the molecular beam stabilization system should be corrected by + 200 Hz so that they also referred to near-stationary molecules*. The frequency value would thus apply to the majority of practical systems.

The working group was able to agree the frequency values and uncertainties applicable to both the resolved-structure and the unresolved-structure systems, and reported these back to the main committee.

Iodine-stabilized laser (473 THz, 633 nm)

The iodine-stabilized helium-neon laser system at 473 THz, 633 nm, is the most widely implemented of the recommended radiations, being used by all national laboratories. A new measurement of its frequency made at the Laboratoire Primaire du Temps et des Fréquences (LPTF), Paris,

* Subsequent correspondence from J. L. Hall indicates that this correction is, in fact, unwarranted as a technique had already been employed to infer this effective beam velocity distribution and correct to zero effective shift.

was reported by the INM. Mr Juncar noted that the standard deviation determined from over 600 measurements was only 3,4 kHz (7×10^{-12}), and that the new result was within the uncertainty of the 1982 recommended value. Mr Juncar also outlined the results of two recent measurements of the Rydberg constant (Document CCDM/92-19*n*), one of which was based on the methane reference and the other on the 473 THz reference. The agreement between the two results was excellent (deviation 3×10^{-12}, with a standard uncertainty of 3×10^{-11}) if they were corrected to correspond to the new methane frequency and the new INM 473 THz value. The meeting greeted the statement of these results with applause and, on behalf of all present, the President expressed congratulations to the INM on the excellence of their contribution. The CCDM agreed without reservation that these results be used as the basis for respecifying the recommended 473 THz value.

A proposal on this basis had been made by the BIPM (Document CCDM/92-20*a*) with a suggested combined uncertainty of 11 kHz. Mr Helmcke queried whether such a small uncertainty could be justified, but Mr Chartier considered that it was justified by the agreement noted during the many laser comparisons carried out by the BIPM over the last ten years (Document CCDM/92-20*a* and 92-3). During such comparisons the initial disagreement might be as great as 50 kHz, but this was due to the wide tolerances on operating conditions permitted by the 1982 specification. Agreement within ± 10 kHz was nearly always reached when the operating conditions were adjusted to the centres of their permitted ranges. Accordingly, the BIPM had proposed that these ranges be reduced (Document CCDM/92-20*a*). Several delegates expressed reservations concerning the proposed tolerances, regarding them as rather stringent and difficult to attain. It was suggested that, if typical magnitudes were quoted for the effects of variations from the specified conditions, it would permit laboratories to relax one or more of the tolerances in situations where the best reproducibility was not required. It was agreed that the discussion had provided clear guidance, and that the details for a recommendation should be drafted by the working group that had already been established to consider the methane frequency.

The group subsequently agreed that, as far as possible, the tolerances for the operating conditions of this laser should be such that they each separately contributed uncertainties comparable to that of the new frequency measurement. A larger uncertainty, however, was necessary in the case of the operating power, because the coefficient of variation was less predictable. The working group also considered that the recommended frequency value should be that corresponding to the laser BIPM4 because the large number of international comparisons that had been made with this laser indicated that it was close to the world-wide mean. On this basis, the working group produced a draft for the specification of the 473 THz reference radiation, setting out the numerical values and operating conditions.

Other recommended radiations

The 1982 list of recommended radiations included three stabilized laser systems in addition to the two discussed above. Several other radiations were now being proposed for inclusion in a revised list (Document CCDM/92-3, section 3.2). Consideration was given to a suggestion that one or more of the 1982 radiations might be removed from the list, to be replaced by new proposals in the same general frequency/wavelength region. It became clear, however, that each of the originally recommended radiations commanded sufficient support to justify its retention.

In 1982 the frequencies of these radiations were all related to either the methane or the 473 THz iodine references. It was thus necessary to modify all their values and uncertainties to take into account the proposed changes to these references. These adjustments were judged to be non-controversial. In addition, there were some recent interferometric frequency-ratio measurements that needed to be taken into account. These matters were referred for the attention of the working group that was considering the other numerical values. The working group did not have time to complete all the necessary work before the end of the meeting, but sufficient progress was made for the work to be completed by correspondence within a few weeks, including revised/extended tables of the frequency differences between alternative hyperfine components.

New radiations

Of the stabilized laser radiations that had been developed and studied since 1982, three systems were proposed by two or more laboratories for addition to the list of recommended radiations. Five laboratories proposed the 543 nm iodine-stabilized He-Ne laser, five the 640 nm iodine-stabilized He-Ne laser, and two the calcium-stabilized laser at 657 nm.

The 543 nm system was considered to be of particular practical importance because measurements of the frequency of He-Ne lasers stabilized using the power curve are used for the measurement of gauge blocks by the beat frequency method. The 640 nm system had been developed by cooperation between the NIM, PTB, CSMU and the NPL ; and the NIM had reported on its good stability and reproducibility. The calcium system, although not yet widely used, offered the potential of exceptional reproducibility. The PTB reported that the line centre could already be located within an uncertainty of 10^{-12} and that ultimately the performance might reach 10^{-14}.

It was unanimously agreed that all three radiations should be included in the recommended list. The task of drawing up the necessary specifications for frequency values, uncertainties, operating conditions and hyperfine intervals, was again referred to the working group that was already revising the values of the 1982 list.

The working group established a small sub-group, comprising Mr Riehle, together with Messrs Bertinetto, Zhao Kegong, Vitushkin and Robertsson, to collate the available data on these radiations and to make suggestions for their exploitation.

Recommendation

Towards the end of the session, the working group presented to the full committee the results of its deliberations and the (incomplete) compilation of a revised list of recommended radiations. The written draft contained details only of the proposals for the methane and 473 THz stabilized laser radiations. This draft was accepted without reservation. The principles outlined above for the revision of the other values of the 1982 list were also endorsed.

For the new 543 nm radiation, only two precise measurements of comparable uncertainty were available, and it was proposed to take their unweighted mean. For the 640 nm radiation there were three measurements with significantly different uncertainties. After discussion it was decided that a weighted mean would be more appropriate in this case, and a similar procedure was agreed for the 657 nm radiation for which the only two measurements had widely different uncertainties.

In conclusion the CCDM adopted in principle the partially completed Recommendation M 1 (1992), and requested that the CIPM delegate to the CCDM the task of completing the text, according to the procedures that had been agreed.

3. International comparisons

Angle standards

At its meeting in 1979 the CCDM initiated a comparison of angle standards with the NRLM as pilot laboratory. The project was completed in 1986 (Document CCDM/92-13*t*). A summary report on the project (Document CCDM/92-13*a*) was presented by Mr O'ishi. Eleven laboratories had participated, making measurements on each of two 12-sided polygons supplied by the VNIIM and the NRLM. A number of conclusions could be drawn from the results. In particular, compatibility between laboratories within ± 0,1" was attained. The differences between laboratories were much greater than the statistical uncertainties within laboratories. Different measuring methods did not seem to be the cause of the differences, which were attributed to small misalignments of the optical instruments and to imperfections in the planarity and orientation of the faces of the polygons. Differences in the measurement errors with the two polygons were attributed to their different surface areas. As a result of the comparison, several laboratories had been able to improve their measurement facilities.

Stabilized lasers

Many international comparisons of lasers were noted in the questionnaire replies, most involving 633 nm iodine-stabilized lasers and the BIPM. Mr Chartier reported on the many comparisons in which the BIPM had taken part. Most member States of the Convention du Mètre had been involved. He also summarized the results of the iodine absorption-cell comparisons that were carried out by the BIPM in 1991. Forty cells had been measured, sixteen gave results within ± 5 kHz of the mean and twenty-three within ± 10 kHz of the mean. The uncertainty of measurement was about 5 kHz. Whereas most ‘bad’ cells gave negative shifts, a few cells, paradoxically, gave results 10 kHz more positive than the mean. The BIPM had filled about thirty iodine cells during the six months preceding the present meeting.

This report was applauded both for the excellence of the work and for the clarity of its presentation. Nearly all laboratories had stated that they wished to participate in future international comparisons of lasers and iodine cells. The majority of requests were for wavelengths of 633 nm and 543 nm, but each of the recommended radiations (except 576 nm) was requested by one or more of the laboratories.

Working Group on International Comparisons (CCDM Working Group on Dimensional Metrology)

The CCDM had not previously considered it necessary to have any working groups, except on a temporary basis to draft recommendations during sessions. The attention of the CCDM, however, was drawn to Recommendation E 1 (1992) of the CCE. This notes that many measurement comparisons are carried out within regional groups of countries to demonstrate the traceability of standards for the purpose of international trade. It recommends that members keep the BIPM informed of such comparisons, so that the results may be used, where appropriate, to supplement CCE-sponsored comparisons. It also recommends that consideration be given to carrying out complementary comparisons, and so to form links between the regional groups.

Several delegates spoke in favour of this approach and all agreed that the CCDM should adopt a similar procedure. For this purpose it was agreed that the CCDM should establish a permanent working group, which could also advise the CCDM on the needs and priorities for CCDM-initiated comparisons of dimensional metrology standards. The working group would need closely specified terms of reference.

The precise membership of the working group was not decided during the session, as delegates needed to consult with their laboratories. It was agreed that the membership would be determined by correspondence through the BIPM. Members of the working group need not be actual members of the CCDM, but should be nominated through the national laboratories of member States of the Convention du Mètre. It was hoped that one member would be proposed from each regional organization. Mr Pekelsky was proposed as chairman, and indicated his assent. Messrs Brown, Sacconi and Zhao Kegong also indicated their willingness to participate.

After some discussion the CCDM adopted the following terms of reference for the working group, which will be known as the CCDM Working Group on Dimensional Metrology.

CCDM Working Group on Dimensional Metrology

Terms of reference:

To maintain links with the regional metrological cooperation organizations, seeking to ensure the involvement of the BIPM or member laboratories of the CCDM in major comparisons, thereby providing the means for assuring world-wide traceability of measurements at the highest levels of accuracy.

To make recommendations to the CCDM on the needs and priorities for additional international comparisons under the auspices of the CCDM.

To act as a focus for information exchange on international comparisons of dimensional metrology standards and techniques.

Note

The term ‘dimensional metrology’ is taken to include the measurement of length, displacement, angle, form and deformation, and also those quantities and physical properties involved in their measurement such as the refractive index of air and the thermal expansion coefficient of standards.

Gauge blocks

In reply to the questionnaire, laboratories had indicated their requirements for dimensional international comparisons. These would now be referred to the new working group for further consideration or action. Many laboratories, however, stressed the need for gauge block comparisons, for which an international comparison was already in progress under EUROMET. Mr Vaucher said that the EUROMET international comparison involved gauges between 1 mm and 100 mm, and that the first set of measurements had revealed some problems with phase-shift errors and difficulties with wringing. Results of measurements in a second set had, so far, shown agreement within ± 25 nm. Mr O'ishi noted his need to link the Asia/Pacific measurements with those in Europe and elsewhere.

It was agreed that a limited, small scale, international comparison should be initiated as soon as possible. Mr Vaucher agreed that the OFMET should be the pilot laboratory, and proposed that five of the gauges (1, 3, 8, 40 and 100 mm) from the EUROMET comparison might be used. The delegates from the CSMU, NIST, CSIRO and the NIM agreed to participate and so link the regions of Central and Eastern Europe, North America and Asia/Pacific.

4. BIPM activity

Mr Quinn asked for the views of the CCDM on the balance of the programme of BIPM work, as approved by the 19th CGPM. The activity fell into three categories:

international comparisons,

the dissemination of expertise to member laboratories (advice on technology and 'accepted good practice') and

a modest amount of research so as to maintain expertise.

The essential role of the BIPM with regard to international comparisons of lasers had already been noted, and it was assumed that this would continue and be extended in particular to the new 543 nm radiation. It was recognized, however, that the BIPM could not maintain all forms of recommended radiation, and should not start work on the novel sources being developed elsewhere. The need for more work on the problem of contamination of iodine absorption cells was agreed, and the BIPM was asked to intensify its activity in this area, perhaps using mass spectrometry and external-cell stabilized lasers.

The BIPM still maintains a facility for the calibration of line-standards, scales and long end-gauges; but the equipment is seldom used and is in need of considerable refurbishment. It was noted that it is difficult for the BIPM to maintain expertise when only a few measurements are made. Noting the alternative facilities available in national laboratories, it was considered that the BIPM should gradually withdraw from these activities.

5. Other business

Among the various matters discussed, was that of possible future international comparisons concerning linear optical gratings and sub-micrometre standards: this was referred for the consideration of the proposed Working Group on Dimensional Metrology. For measuring distances greater than 25 m, time-of-flight measurements are normally used and the refractive index of air becomes a problem. The Edlén formula is often used, but a more accurate formulation is now needed based on up-to-date data. Also the formula does not cover the important infrared region. Other organizations are also concerned with refractive index, so the matter might also be considered by the new working group. Distances greater than 50 km are now measured by timing methods using Earth satellites (Global Positioning System). It was suggested that the problems of timing in this context are more appropriate for consideration by the CCDS. The attention of delegates was drawn to a proposal being discussed within the ISO to use 23 °C instead of 20 °C as the reference temperature for length measurement. Any such change could, for example, make measurements of thermal expansion coefficients very important. Delegates were advised to inform their colleagues of these developments and to note the possible need for further work on thermal expansion measurements.

The CCDM noted that for some areas of fundamental metrology the radiations in the recommended list were scarcely accurate enough. Many laboratories were thus engaged in the development of improved references, and the CCDM wished to encourage this activity. It was also noted that the improvements to the uncertainties of the radiations now being recommended, were due largely to the development of heterodyne and frequency-mixing techniques for the measurement of laser frequencies. It was important to extend these techniques and to make them more convenient, in order to link the improved references now being developed. In recognition of this the CCDM adopted Recommendation M 2 (1992).

In closing the session, the President suggested that another meeting might be appropriate in about two years time. He thanked the delegates for their hard work and helpful contributions; Mr Helmcke and the other members of the working group for their industrious efforts; Mr Rowley for agreeing to act as Rapporteur; and the BIPM for its hospitality and the excellence of the organization for the session. Mr Hall noted with sorrow the recent death of Mr Chebotayev, whose work on the methane standard, on the techniques of non-linear Doppler-free spectroscopy and optical Ramsey techniques, had greatly influenced the work of the committee. Mr Xu Yi also thanked all concerned with the organization of the meeting, and noted the excellent level of international collaboration and cooperation enjoyed by the committee. He presented the BIPM with a laser emitting the 640 nm radiation that had just been added to the list of recommended radiations.

In conclusion Mr Giacomo congratulated the President on his conduct of the 8th meeting of the CCDM.

October 1992

Recommendations of the Comité Consultatif pour la Définition du Mètre submitted to the Comité International des Poids et Mesures

Revision of the mise en pratique of the definition of the metre

RECOMMENDATION M 1 (1992)*

The Comité Consultatif pour la Définition du Mètre,

recalling

— that in 1983 the 17th Conférence Générale des Poids et Mesures (CGPM) adopted a new definition of the metre;

— that in the same year the CGPM invited the Comité International des Poids et Mesures (CIPM)

- — to draw up instructions for the practical realization of the metre;
- — to choose radiations which can be recommended as standards of wavelength for the interferometric measurement of length and draw up instructions for their use;
- — to pursue studies undertaken to improve these standards and in due course to extend or revise these instructions;

— that in response to this invitation CIPM made a number of Recommendations in 1983 concerning the practical realization of the metre (the 'mise en pratique');

considering

— that science and technology continue to demand improved accuracy in the realization of the metre;

— that since 1983 work in national laboratories, BIPM and elsewhere has substantially improved the reproducibility of radiations which are suitable for the practical realization of the metre;

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* This Recommendation was approved by the CIPM as Recommendation 3 (CI-1992) at its 81st meeting, see page M 134.

— that such work has also substantially reduced the uncertainty in the determined values of the frequencies and wavelengths of some of these radiations;

recommends that the list of radiations recommended by CIPM in 1983 be revised.

Future work

RECOMMENDATION M 2 (1992)

The Comité Consultatif pour la Définition du Mètre,

considering

— that science and technology are continuously demanding more accurate realizations of the metre;

— that requirements for advanced dimensional metrology continue to increase;

— that improved methods are needed for the accurate comparison of wavelengths and frequencies, particularly between the microwave and visible regions;

recommends that national laboratories

— continue to maintain and develop techniques to meet the growing demands in the field of dimensional metrology;

— continue their efforts to develop and evaluate new standards for length, wavelength and frequency based on such techniques as cooled, trapped ions or atoms, slow atomic or molecular beams, solid state lasers or semi-conductor laser diodes;

— continue their efforts to improve mixing and harmonic generation techniques to increase the accuracy and ease of frequency comparisons.

Recommendation of the Comité Consultatif pour la Définition du Mètre adopted by the Comité International des Poids et Mesures

Revision of the mise en pratique of the definition of the metre

RECOMMENDATION 3 (CI-1992)*

The Comité International des Poids et Mesures,

recalling

— that in 1983 the 17th Conférence Générale des Poids et Mesures (CGPM) adopted a new definition of the metre;

— that in the same year the CGPM invited the Comité International des Poids et Mesures (CIPM)

— to draw up instructions for the practical realization of the metre;

— to choose radiations which can be recommended as standards of wavelength for the interferometric measurement of length and draw up instructions for their use;

— to pursue studies undertaken to improve these standards and in due course to extend or revise these instructions;

— that in response to this invitation CIPM made a number of Recommendations in 1983 concerning the practical realization of the metre (the 'mise en pratique');

considering

— that science and technology continue to demand improved accuracy in the realization of the metre;

* Recommendation M 1 (1992) has been adopted by the CIPM as Recommendation 3 (CI-1992), with the List of recommended radiations, 1992, completed after the CCDM meeting.

— that since 1983 work in national laboratories, BIPM and elsewhere has substantially improved the reproducibility of radiations which are suitable for the practical realization of the metre;

— that such work has also substantially reduced the uncertainty in the determined values of the frequencies and wavelengths of some of these radiations;

decides that the list of recommended radiations given by the CIPM in 1983 (Recommendation 1 (CI-1983)) be replaced by the list of recommended radiations given below.

List of recommended radiations, 1992

This list replaces the one published in *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1983, **51**, 25-28 and *Metrologia*, 1984, **19**, 165-166.

In this list, the values of the frequency f and of the wavelength λ should be related exactly by the relation $\lambda f = c$, with c = 299 792 458 m/s but the values of λ are rounded.

The data and analysis used for the compilation of this list are set out in the associated Appendix: Source Data for the List of Recommended Radiations, 1992 and its Annotated Bibliography**.

It should be noted that for several of the listed radiations, few independent values are available, so that the estimated uncertainties may not, therefore, reflect all sources of variability.

Each of the listed radiations can be replaced, without degrading the accuracy, by a radiation corresponding to another component of the same transition or by another radiation, when the frequency difference is known with sufficient accuracy. It should be also noted that to achieve the uncertainties given here it is not sufficient just to meet the specifications for the listed parameters. In addition, it is necessary to follow the best good practice concerning methods of stabilization as described in numerous scientific and technical publications. References to appropriate articles, illustrating accepted good practice for a particular radiation, may be obtained by application to a member laboratory of the CCDM, or to the BIPM.

** *See* Appendix M 2, page M 140.

1. *Radiations of Stabilized Lasers*

1.1 Absorbing molecule CH_4, transition ν_3, P (7), component $F_2^{(2)}$.

1.1.1 The values f = 88 376 181 600,18 kHz

λ = 3 392 231 397,327 fm

with an estimated relative standard uncertainty of 3×10^{-12} apply to the radiation of a He-Ne laser stabilized to the central component [(7-6) transition] of the resolved hyperfine-structure triplet, the mean of recoil splitting, for effectively stationary molecules, i.e. the values are corrected for second order Doppler shift.

1.1.2 The values f = 88 376 181 600,5 kHz

λ = 3 392 231 397,31 fm

with an estimated relative standard uncertainty of $2{,}3 \times 10^{-11}$ apply to the radiation of a He-Ne laser stabilized to the centre of the unresolved hyperfine structure of a room temperature methane cell, within or external to the laser, subject to the following conditions:

— methane pressure $\leqslant$ 3 Pa
— mean one-way axial intracavity surface power density^{+} $\leqslant 10^4$ W m^{-2}
— radius of wavefront curvature $\geqslant$ 1 m
— inequality of power between counter-propagating waves $\leqslant$ 5 %
— detector placed at the output facing the laser tube.

1.2 Absorbing atom ^{40}Ca, transition $^3P_1 - {}^1S_0$; $\Delta m_J = 0$.

The values f = 455 986 240,5 MHz

λ = 657 459 439,3 fm

with an estimated relative standard uncertainty of $4{,}5 \times 10^{-10}$ apply to the radiation of a laser stabilized with a thermal atomic beam.

1.3 Absorbing molecule $^{127}I_2$, transition 8-5, P(10), component a_9 (or g).

The values f = 468 218 332,4 MHz

λ = 640 283 468,7 fm

with an estimated relative standard uncertainty of $4{,}5 \times 10^{-10}$ apply to the radiation of a He-Ne laser stabilized with an internal iodine cell having a cold finger temperature of (16 $\pm$ 1) °C and a frequency modulation width, peak to peak, of (6 $\pm$ 1) MHz.

1.4 Absorbing molecule $^{127}I_2$, transition 11-5, R(127), component a_{13} (or i).

The values f = 473 612 214 705 kHz

λ = 632 991 398,22 fm

with an estimated relative standard uncertainty of $2{,}5 \times 10^{-11}$ apply to the radiation of a He-Ne laser with an internal iodine cell, subject to the conditions:

- — cell-wall temperature: (25 ± 5) °C
- — cold finger temperature: (15 ± 0,2) °C
- — frequency modulation width, peak to peak: (6 ± 0,3) MHz
- — one-way intracavity beam power⁺: (10 ± 5) mW, for an absolute value of the power shift coefficient ⩽ 1,4 kHz/mW.

These conditions are by themselves insufficient to ensure that the stated standard uncertainty will be achieved. It is also necessary for the optical and electronic control systems to be operating with the appropriate technical performance. The iodine cell may also be operated under relaxed conditions, leading to the larger uncertainty specified in Appendix M 2 of the CCDM Report (1992).

1.5 Absorbing molecule $^{127}I_2$, transition 9-2, R(47), component a_7 (or o).

The values f = 489 880 354,9 MHz

λ = 611 970 770,0 fm

with an estimated relative standard uncertainty of 3×10^{-10} apply to the radiation of a He-Ne laser stabilized with an iodine cell, within or external to the laser, having a cold finger temperature of (– 5 ± 2) °C.

1.6 Absorbing molecule $^{127}I_2$, transition 17-1, P(62), component a_1.

The values f = 520 206 808,4 MHz

λ = 576 294 760,4 fm

with an estimated relative standard uncertainty of 4×10^{-10} apply to the radiation of a dye laser (or frequency-doubled He-Ne laser) stabilized with an iodine cell, within or external to the laser, having a cold-finger temperature of (6 ± 2) °C.

1.7 Absorbing molecule $^{127}I_2$, transition 26-0, R(12), component a_9.

The values f = 551 579 482,96 MHz

λ = 543 516 333,1 fm

with an estimated relative standard uncertainty of $2{,}5 \times 10^{-10}$ apply to the radiation of a frequency stabilized He-Ne laser with an external iodine cell having a cold-finger temperature of (0 ± 2) °C.

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

The values f = 582 490 603,37 MHz

λ = 514 673 466,4 fm

with an estimated relative standard uncertainty of $2{,}5 \times 10^{-10}$ apply to the radiation of an Ar^{+} laser stabilized with an iodine cell external to the laser, having a cold-finger temperature of (– 5 ± 2) °C.

Note

+ The one-way intracavity beam power is obtained by dividing the output power by the transmittance of the output mirror.

2. *Radiations of Spectral Lamps*

2.1 Radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the atom of ^{86}Kr.

The value $\lambda = 605\,780\,210{,}3$ fm

with an estimated overall relative uncertainty of $\pm 4 \times 10^{-9}$ [equivalent to three times the relative standard uncertainty of $1{,}3 \times 10^{-9}$] applies to the radiation emitted by a lamp operated under the conditions recommended by the CIPM (*BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1960, **28**, 71-72 and *BIPM Comptes Rendus 11^e^ Conf. Gén. Poids et Mesures*, 1960, 85)].

2.2 Radiations of atoms ^{86}Kr, ^{198}Hg and ^{114}Cd recommended by the CIPM in 1963 (*BIPM Com. Cons. Déf. Mètre*, 1962, **3**, 18-19 and *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1963, **52**, 26-27), with the indicated values for the wavelengths and the corresponding uncertainties.

APPENDIX M 1

Working documents
submitted to the CCDM at its 8th Meeting

(*see* the list of documents on page M 20)

ANNEXE M 1

Documents de travail présentés à la 8e session du CCDM*

Ces documents de travail peuvent être obtenus dans leur langue originale sur demande adressée au BIPM.

Document CCDM/

92-1 Questionnaire, 2 p.

92-2 BIPM, Chartier J.-M., Picard-Fredin S., Chartier A., International Comparison of Iodine Cells, *Rapport BIPM*-92/4, 1992, 17 p. + annexes.

92-3 BIPM analysis of laboratories' responses to the questionnaire, revised November 1992, 42 p.

NRC (Canada)

92-4 *a*. Response to the questionnaire, 13 p.

b. Whitford B. G., Hanes G. R., Frequency of a Methane-stabilized Helium-neon Laser, *IEEE Trans. Instrum. Meas.*, 1988, **IM-37**, 179-184.

CSIRO (Australie)

92-5 *a*. Response to the questionnaire, 3 p.

b. Ciddor P. E., Rueger J. M., Refractive Index of Air: Are New Equations Needed?, 4 p.

Appendix A. First Velocity Correction for Precise Electro-optical Distance Measurement, 3 p.

c. Current Projects at CSIRO Australia related to CCDM interests, 1 p.

* Les documents sont classés par laboratoire et numérotés de manière alphabétique, le document *a* correspondant toujours à la réponse au questionnaire envoyé par le BIPM.

Document
CCDM/

IMGC (Italie)

92-6 *a*. Response to the questionnaire, 7 p.

b. BERTINETTO F., SASSI M. P., BAVA E., GODONE A., Frequency Stability and Reproducibility Measurements of $^{3}He^{22}Ne/CH_4$ Stabilized Lasers, *Alta Frequenza*, 1984, **LIII**, 231-235.

c. BERTINETTO F., PICOTTO G. B., CORDIALE P., FONTANA S., He-Ne Laser at 612 nm Stabilized to $^{127}I_2$ Using FM Spectroscopy, In *Proc. of the Fourth Symposium, Frequency Standards and Metrology, Ancona, 5-9 Sept. 1988*, Berlin: Springer-Verlag, 1988, 465-466.

d. GODONE A., SASSI M. P., CALDERA C., BAVA E., Frequency Measurement of the NH_3 81,5 and 263,4 μm Lines, *Optics Commun.*, 1989, **71**, 59-60.

e. SASSI M. P., BERTINETTO F., GODONE A., BAVA E., Frequency Measurement of the CO_2R_1 (32) Line with Respect to a 3,39 μm He^{22}-Ne/CH_4 Standard, *Int. J. Infra. Milli. Waves*, 1985, **6**, 629-633.

f. SASSI M. P., BERTINETTO F., GODONE A., BAVA E., Frequency Measurement of RuO_4 Transitions in the ν_3 Vibrational Band, *Optics Commun.*, 1986, **60**, 376-377.

g. SNELS M., SASSI M. P., QUACK M., High-resolution Fourier-transform Infrared Spectroscopy of the ν_3 (F_2) Fundamental of RuO_4, *Mol. Phys.*, 1991, **72**, 145-158.

h. ZINK L. R., SASSI M. P., PREVEDELLI M., PAVONE F. S., Direct Frequency Measurements of OsO_4 ν_3-Q Branch Lines near the 10 μm R(0) CO_2 Laser Line, *The 14th International Conference on Infrared and Millimeter Waves, Würzburg, 2-6 Oct. 1989, Conference Digest*, M. Von Ortenberg ed., 1989, **1240**, 113-114.

i. SASSI M. P., Spettroscopia Sub-doppler di Molecule a Simmetria Sferica: Applicazioni alla Sintesi di Frequenza nella Regione dei 10 μm, *Tesi Dottorato di Ricerca in Metrologia*, 1987, pp. 4.40 et 5.22.

j. SASSI M. P., GODONE A., BERTINETTO F., Mixing Properties of MIM Diodes in the Infrared, Plenum, 1987, 291-297.

k. BERTINETTO F., CORDIALE P., FONTANA S., PICOTTO G. B., Recent Progresses in He-Ne Lasers Stabilized to $^{127}I_2$, *IEEE Trans. Instrum. Meas.*, 1985, **IM-34**, 256-261.

Document
CCDM/

92-6 *l.* Bertinetto F., Cordiale P., Fontana S., Picotto G. B., Helium-neon Lasers Stabilized to Iodine at 605 nm, *IEEE Trans. Instrum. Meas.*, 1987, **IM-36**, 609-612.

m. Godone A., Sassi M. P., Bava E., High Accuracy Capabilities of an OsO_4 Molecular-beam Frequency Standard, *Metrologia*, 1989, **26**, 1-8.

VNIIM (Fédération de Russie)

92-7 *a*. Response to the questionnaire, 3 p.

b. Vitushkin L. F., Korotkov V. I., Pul'kin S. A., A Laser Interference Diffractometer for Period Measurement of Diffraction Gratings and Periodic Small-Length Line Scales, 8 p.

c. Vitushkin L. F., Zeilikovich I. S., Korotkov V. I., Pul'kin S. A., Laser Interference-diffractometric Comparator for Measurement of Periodic Small-length Line Scales, 11 p.

d. Vitushkin L. F., Korotkov V. I., Lazaryuk S. V., Pul'kin S. A., Toptygina G. I., Narrow Resonances of Atomic Medium Polarization in a Strong Polyharmonic Field and their Application for Producing Frequency References, 29 p.

LEBEDEV INSTITUTE (Fédération de Russie)

92-8 *a*. Response to the questionnaire, 4 p.

b. Gubin M. A., Tyurikov D. A., Koval'chuk E. V., Schelkovnikov A. S., Computer Controlled Transportable Optical Frequency Standard with the Reproducibility $\sim 10^{-13}$, *CPEM'92 Digest*, 1992, 38-39.

c. Basov N. G., Gubin M. A., Nikitin V. V., Nikul'chin A. V., Protsenko E. D., Tyurikov D. A., Schelkovnikov A. S., Transportable Optical Frequency Standard and Results of its Metrological Tests, *Sov. J. Quantum Electron.* (traduction), 1987, **17**, 545-547.

VNIIFTRI (Fédération de Russie)

92-9 *a*. Material concerning the He-Ne/CH_4 laser absolute frequency, 2 p.

Document
CCDM/

NIM (République populaire de Chine)

92-10 *a*. Response to the questionnaire and Research Findings in Realizing the Definition of the Metre. Measurement/Intercomparison of Frequency (Wavelength) and Geometrical Standard of Length, 32 p.

92-10-1 *a*. *Voir* document CCDM/92-18*b*.

b. Comparison of Iodine Stabilized He-Ne Laser Between China and New Zealand, 1 p.

c. An Jialuan, Li Chengyang, Liu Xiuying, The Improvements and the International Comparison of the 633 nm $^{127}I_2$ Stabilized He-Ne Laser, 4 p.

d. *Voir* document CCDM/92-2.

e. Iodstabilisierter Argon-ionenlaser der Wellenlänge 514,5 nm nach dem Frequenz-Modulations-Verfahren, 2 p.

f. Liu Lingling,, Brand U., The Frequency Stabilization of Ar^+ Laser at 515 nm (en chinois), *Chin. J. Quant. Elect.*, 1991, **8**, 281-283 (+ traduction en anglais).

g. Liu Lingling,, Brand U. (rapport en chinois), 4 p.

h. Ni Yucai, Qian Jin, Zhao Kegong, Chen Rong, Li Yimin, Wang Qingji, Frequency Stabilization of 780,1 nm Semiconductor Laser Using Saturated Absorption Line of ^{85}Rb, 8 p.

i. Chen Rong, Wang Qingji, Qian Jin, Ni Yucai, Zhao Kegong, Frequency Stabilization of Semiconductor Laser by Overtone Spectrum of Molecule (en chinois), *Acta Metrologia Sinica*, 1992, **13**, 88-92.

j. Liu Zhong-You, Zhou Zu-Lian, Ma Ming-De, Yang Fen-Liang, Li Yin-Zhu, Liu Xiu-Ying, Accurate Measurements of the Wavelength Ratios in Vacuum between Methane and Iodine Stabilized He-Ne Lasers (en chinois), *Acta Metrologia Sinica*, 1984, **5**, 188-193.

92-10-2 *a*. Dshao Kegung, Xu Jie, Li Chen-Yang, Liu Han-Tian, Hyperfine Structure in Iodine Observed at the 612 nm and 640 nm ^3He-^{22}Ne Laser Wavelengths (en chinois), *Yanjiu Jianbao*, s.d., 322-323.

Document
CCDM/

92-10-2 *b*. ZHAO K. G., HELMCKE J., Jodstabilisierter ^{3}He-^{22}Ne Laser für 640 nm Wellenlänge, Abteilung 1, *PTB Jahresbericht*, 1983, 116-117.

c. ZHAO K. G., BLABLA J., HELMCKE J., $^{127}I_2$-stabilized ^{3}He-^{22}Ne Laser at 640 nm Wavelength, *IEEE Trans. Instrum. Meas.*, 1985, **IM-34**, 252-256.

d. ZHAO Kegong, LI Hua, Hyperfine Structure of Iodine at 640 nm ^{3}He-^{22}Ne Laser Wavelength and Identification (en chinois), *Acta Optica Sinica*, 1983, **3**, 673-677.

e. ZHAO Kegong, LI Hua, Analysis and Calculation of Hyperfine Lines of Iodine Molecule (en chinois), *Acta Optica Sinica*, 1985, **6**, 83-88.

f. ZHAO Kegong, LI Chengyang, LI Hua, XU Jie, WANG He, Investigations of $^{127}I_2$ Stabilized He-Ne Laser at 640 nm (en anglais), *Acta Metrologica Sinica*, 1987, **8**, 88-95.

92-10-4 *a*. XU Yi, YE Xiaoyou, LI Chengyang, XU Jie, GAO Feng, Precise Determination of 633 nm He-Ne Laser Wavelength in Air (en anglais), 4 p.

b. Asia/Pacific Metrology Programme, Final Report on Inter-comparison of a Line Standard of Length (en anglais), 5 p.

c. Measurement Report on a Quartz Scale (160 mm long) (NIM) (en anglais), 3 p.

d. Measurement report on a 1 metre scale (NIM) (en anglais), 4 p.

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APPENDIX M 2

Source data for the list of recommended radiations, 1992

Source data

This Appendix has been derived from Document CCDM/92-3 taking into account the new data presented at the 8th meeting of the CCDM, 1992, and those of 1982 published in Appendix M 4 of the report of the 7th meeting of the CCDM, 1982 [1]. The numbers in square brackets refer to the bibliography and notes at the end of this Appendix.

Values of frequency (and wavelength) may be influenced by certain experimental conditions such as the pressure and the purity of the absorbing medium, the power transported by the beam through the medium and beam geometry, as well as other effects originating outside the laser itself and related to the servo-system. The magnitude of these influences remains compatible with the limits indicated by the uncertainty (one standard deviation) provided that the conditions of operation lie within the domain of the ensemble of those of the measurements referred to below.

1. *Radiations of stabilized lasers*

1.1 *Absorbing molecule* CH_4, *transition* ν_3, P (7), *component* $F_2^{(2)}$ ($\lambda \approx 3{,}39$ μm)

1.1.1 Hyperfine structure resolved

Absolute frequency determinations, f_{CH_4} = 88 376 181 000 kHz + x

Year	Laser	Frequency chain	CCDM Document/	x/kHz
1991	Lebedev Phys. Inst.	PTB	92-8*a*	600,29
1985-1986	Lebedev Phys. Inst.	VNIIFTRI	92-9*a*	599,9
1989-1992	Lebedev Phys. Inst.	VNIIFTRI	92-9*a*	600,11
1989	PTB	VNIIFTRI	92-9*a*	600,18
1992	PTB	PTB	92-14*a*	600,16
1988-1991	Inst. Laser Phys. (IPL), Novosibirsk	IPL	92-23*a*	600,44

Unweighted mean f_{CH_4} = 88 376 181 600,180 kHz.

Measurements whose uncertainties were larger than 200 Hz have not been taken into account in the calculation of this mean. The relative standard uncertainty of one realization of 2,9 $\times$ 10^{-12} was estimated using the maximum deviation from the mean and rounded to 3 $\times$ 10^{-12}.

Adopted value*:

f_{CH_4} = 88 376 181 600,18 kHz
standard uncertainty 0,27 kHz
relative standard uncertainty 3 $\times$ 10^{-12}.

From which:

λ_{CH_4} = 3 392 231 397,327 fm
standard uncertainty 0,010 fm
relative standard uncertainty 3 $\times$ 10^{-12}.

1.1.2 Hyperfine structure unresolved

Absolute frequency determinations, f_{CH_4} = 88 376 181 000 kHz + x

Year	Institute	Device	References	x/kHz
1983	Inst. Laser Phys.** (Novosibirsk)	Stationary device	CCDM/92-23*a* also 1.1.2-1,2,3	602,9
1985	NRC (Ottawa)	Portable laser 2	CCDM/92-4*a* also 1.1.2-4	601,48
Mean value 1986/89/90/91	NRC (Ottawa)	Portable laser 3	CCDM/92-4*a* also 1.1.2-4	599,33
Mean value 1988/1990	NRLM (Tsukuba)	Portable laser 1	1.1.2-4	596,82
Mean value 1987/1989	PTB (Braunschweig)	CH_4 beam	1.1.2-5,6 also 1.1.2-4	601,52
Mean value over 7 years	VNIIFTRI (Moscow)	Portable laser M101	CCDM/92-9*a* also 1.1.2-4	601,77
Mean value 1985/86/88	VNIIFTRI (Moscow)	Portable laser P1	CCDM/92-9*a* also 1.1.2-4	600,12
1986	VNIIFTRI (Moscow)	Portable laser PL	CCDM/92-9*a*	598,5
Mean value over 7 years	BIPM (Sèvres)	Portable laser B.3	1.1.2-4	600,96
Mean value 1988/89/91	BIPM (Sèvres)	Portable laser VB	1.1.2-4	601,33
1991	BIPM (Sèvres)	Portable laser VNIBI	CCDM/92-20*a* also 1.1.2-4	600,3

Unweighted mean f_{CH_4} = 88 376 181 600,46 kHz.

* This and subsequent adopted values are based upon the weighted or unweighted means but rounded taking into account the size of the uncertainties.

** Two other values from this laboratory, obtained in 1991, were communicated to the BIPM as private communications. If these two additional values are taken into account the unweighted mean changes by only + 0,14 kHz.

The standard deviation of a determination is 1,7 kHz. This is equivalent to a relative uncertainty of $1{,}92 \times 10^{-11}$, increased by the CCDM to $2{,}3 \times 10^{-11}$ to give an uncertainty of 2 kHz.

Adopted value:

$f_{\mathrm{CH_4}}$ =	88 376 181 600,5 kHz
standard uncertainty	2 kHz
relative standard uncertainty	$2{,}3 \times 10^{-11}$.

From which:

$\lambda_{\mathrm{CH_4}}$ =	3 392 231 397,31 fm
standard uncertainty	0,08 fm
relative standard uncertainty	$2{,}3 \times 10^{-11}$.

In 1983 [1.1.2-7], the value adopted by the CIPM was $f_{\mathrm{CH_4}}$ = 88 376 181 608 kHz with an estimated overall relative uncertainty of $1{,}3 \times 10^{-10}$ (equivalent to three times the relative standard uncertainty).

1.2 *Absorbing atom* ^{40}Ca, *transition* $^3P_1 - {}^1S_0$; $\Delta m_J = 0$ ($\lambda \approx 657$ nm)

The following values have been obtained for the ratio of the frequency f_{Ca} of this transition to the frequency f_{i} (Section 1.4):

PTB	1989 [1.2-1]	$f_{\mathrm{Ca}}/f_{\mathrm{i}}$ = 0,962 783 953 46 $(1 \pm 7 \times 10^{-11})$
NRLM***	1991 [1.2-2]	$f_{\mathrm{Ca}}/f_{\mathrm{i}}$ = 0,962 783 952 8 $(1 \pm 1 \times 10^{-9})$
Weighted mean		$f_{\mathrm{Ca}}/f_{\mathrm{i}}$ = 0,962 783 953 45.

Taking into account the recommended value of f_{i} = 473 612 214 705 kHz (Section 1.4) the following value of f_{Ca} is obtained:

$$f_{\mathrm{Ca}} = 455\,986\,240\,477 \text{ kHz.}$$

Given the large difference in the two uncertainty estimates, the CCDM considered it prudent to assume a relative standard uncertainty of $4{,}5 \times 10^{-10}$, the same as that determined for comparable measurements in Section 1.3.

Adopted value:

f_{Ca} =	455 986 240,5 MHz
standard uncertainty	0,2 MHz
relative standard uncertainty	$4{,}5 \times 10^{-10}$.

From which:

λ_{Ca} =	657 459 439,3 fm
standard uncertainty	0,3 fm
relative standard uncertainty	$4{,}5 \times 10^{-10}$.

*** A value obtained from subsequent measurements agreed with that of the PTB to within its relative uncertainty of 2 parts in 10^{10}.

1.3 *Absorbing molecule* $^{127}I_2$, *transition* 8-5, P(10), *component* a_9 (*or* g) ($\lambda \approx$ 640 nm)

The following values have been obtained for the frequency f_{a_9} of this transition:

NPL	1984	[1.3-1]	$f_{a_9} = 468\,218\,332\,412\ (1 \pm 1{,}0 \times 10^{-10})$ kHz
NIM-CSMU-PTB	1985	[1.3-2]	$f_{a_9} = 468\,218\,332\,303\ (1 \pm 1{,}2 \times 10^{-10})$ kHz
IMGC-BIPM	1985	[1.3-3]	$f_{a_9} = 468\,218\,332\,062\ (1 \pm 4{,}6 \times 10^{-10})$ kHz

Weighted mean f_{a_9} = 468 218 332 358 kHz.

Given the small number of determinations, the CCDM considered it prudent to assume a relative standard uncertainty of 4,5 × 10^{-10}.

Adopted value:

f_{a_9} =	468 218 332,4 MHz
standard uncertainty	0,2 MHz
relative standard uncertainty	4,5 × 10^{-10}.

From which:

λ_{a_9} =	640 283 468,7 fm
standard uncertainty	0,3 fm
relative standard uncertainty	4,5 × 10^{-10}.

1.4 *Absorbing molecule* $^{127}I_2$, *transition* 11-5, R(127), *component* a_{13} (*or* i) ($\lambda \approx$ 633 nm)

The recommended frequency or wavelength values are based on a phase-coherent frequency measurement at the LPTF [CCDM/92-19*a*] using a laser of the INM stabilized to component f.

LPTF/ETCA/INM 1992 [1.4-1] $f_i = 473\,612\,214\,705{,}4\ (1 \pm 2{,}5 \times 10^{-11})$ kHz.

Adopted value:

f_i =	473 612 214 705 kHz
standard uncertainty	12 kHz
relative standard uncertainty	2,5 × 10^{-11}.

From which:

λ_i =	632 991 398,22 fm
standard uncertainty	0,02 fm
relative standard uncertainty	2,5 × 10^{-11}.

For applications where relaxed tolerances and the resultant wider uncertainty range are acceptable, the coefficients detailed in the Annotated bibliography [1.4-1] would lead to a standard uncertainty of about 50 kHz (or a relative standard uncertainty of 1 × 10^{-10}) for a laser operated under the conditions recommended in 1983 [1.1.2-7].

In 1983, the value adopted by the CIPM was f_i = 473 612 214,8 MHz with an estimated overall relative uncertainty of 1×10^{-9} (equivalent to three times the relative standard uncertainty).

1.5 *Absorbing molecule* $^{127}I_2$, *transition* 9-2, R(47), *component* a_7 (*or* o) ($\lambda \approx$ 612 nm)

The following values have been obtained for the frequency f_{a_7} of this transition:

NPL	1982 [1.5-1]	f_{a_7} = 489 880 354 972 $(1 \pm 1 \times 10^{-10})$ kHz
BIPM	1982 [1.5-1]	f_{a_7} = 489 880 354 721 $(1 \pm 2{,}1 \times 10^{-10})$ kHz
PTB/BIPM	1986 [1.5-2]	f_{a_7} = 489 880 355 019 $(1 \pm 8{,}4 \times 10^{-11})$ kHz
VNIIM	1989 [1.5-3]	f_{a_7} = 489 880 355 055 $(1 \pm 3{,}0 \times 10^{-10})$ kHz
INM	1991 [1.5-4]	f_{a_7} = 489 880 354 841 $(1 \pm 8{,}4 \times 10^{-11})$ kHz

Unweighted mean f_{a_7} = 489 880 354 922 kHz.

Other available values having relative standard uncertainties higher than 3×10^{-10} have not been used. The relative standard deviation calculated from the dispersion of these five values is $2{,}8 \times 10^{-10}$. This value is rounded to 3×10^{-10} as the relative standard uncertainty.

Adopted value:

f_{a_7} =	489 880 354,9 MHz
standard uncertainty	0,15 MHz
relative standard uncertainty	3×10^{-10}.

From which:

λ_{a_7} =	611 970 770,0 fm
standard uncertainty	0,18 fm
relative standard uncertainty	3×10^{-10}.

In 1983, the value adopted by the CIPM was f_{a_7} = 489 880 355,1 MHz with an estimated overall relative uncertainty of $1{,}1 \times 10^{-9}$ (equivalent to three times the relative standard uncertainty).

1.6 *Absorbing molecule* $^{127}I_2$, *transition* 17-1, P(62), *component* a_1 (*or* o) ($\lambda \approx$ 576 nm)

The following values have been obtained for the frequency f_{a_1} of this transition:

NBS 1982 [1.6-1]	f_{a_1} = 520 206 808 491 $(1 \pm 1{,}5 \times 10^{-10})$ kHz
NPL 1984 [1.6-2]	f_{a_1} = 520 206 808 272 $(1 \pm 1 \times 10^{-10})$ kHz

Unweighted mean f_{a_1} = 520 206 808 382 kHz.

With this mean based on only two determinations, the CCDM considered it prudent to assume an estimated relative standard uncertainty of 4×10^{-10}, closely equivalent to the difference between the two values.

Adopted value:

f_{a_1} =	520 206 808,4 MHz
standard uncertainty	0,2 MHz
relative standard uncertainty	4×10^{-10}.

From which:

λ_{a_1} =	576 294 760,4 fm
standard uncertainty	0,2 fm
relative standard uncertainty	4×10^{-10}.

In 1983, the value adopted by the CIPM was f_{a_1} = 520 206 808,51 MHz with an estimated overall relative uncertainty of 6×10^{-10} (equivalent to three times the relative standard uncertainty).

1.7 *Absorbing molecule* $^{127}I_2$, *transition* 26-0, R(12), *component* a_9 ($\lambda \approx 543,5$ nm)

The following values have been obtained for the frequency f_{a_9} of this transition:

PTB 1991 [1.7-1]	f_{a_9} = 551 579 483 029 $(1 \pm 8,4 \times 10^{-11})$ kHz
NPL 1992 [1.7-2]	f_{a_9} = 551 579 482 900 $(1 \pm 13 \times 10^{-11})$ kHz

Unweighted mean f_{a_9} = 551 579 482 964 kHz.

With this mean based on only two determinations, linked by the same reference frequency, the CCDM considered it prudent to assume an estimated relative standard uncertainty of $2,5 \times 10^{-10}$ closely equivalent to the difference between the two values.

Adopted value:

f_{a_9} =	551 579 482,96 MHz
standard uncertainty	0,14 MHz
relative standard uncertainty	$2,5 \times 10^{-10}$.

From which:

λ_{a_9} =	543 516 333,1 fm
standard uncertainty	0,14 fm
relative standard uncertainty	$2,5 \times 10^{-10}$.

1.8 *Absorbing molecule* $^{127}I_2$, *transition* 43-0, P(13), *component* a_3 (*or* s) ($\lambda \approx$ 515 nm)

The following values have been obtained for the ratio of the frequency f_{a_3} of this transition to the frequency f_i (Section 1.4):

NPL	1982 [1.8-1]	f_{a_3}/f_i = 1,229 889 316 88 $(1 \pm 1 \times 10^{-10})$
BIPM	1982 [1.8-1]	f_{a_3}/f_i = 1,229 889 316 88 $(1 \pm 2{,}5 \times 10^{-10})$
PTB	1989 [1.8-2]	f_{a_3}/f_i = 1,229 889 317 33 $(1 \pm 7 \times 10^{-11})$
PTB	1985 [1.8-3]	f_{a_3}/f_i = 1,229 889 317 44 $(1 \pm 7 \times 10^{-11})$
PTB	1986 [1.8-4]	f_{a_3}/f_i = 1,229 889 317 36 $(1 \pm 8 \times 10^{-11})$
PTB	1991 [1.8-5]	f_{a_3}/f_i = 1,229 889 317 45 $(1 \pm 8 \times 10^{-11})$

Unweighted mean f_{a_3}/f_i = 1,229 889 317 22.

Other available values having relative uncertainties higher than $2{,}5 \times 10^{-10}$ have not been used.

Taking the recommended value f_i = 473 612 214 705 kHz (Section 1.4), the following value for f_{a_3} is obtained:

f_{a_3} = 582 490 603 371 kHz.

The relative standard uncertainty calculated from the dispersion of the six values is $2{,}2 \times 10^{-10}$, which the CCDM preferred to round up to $2{,}5 \times 10^{-10}$.

Adopted value:

f_{a_3} =	582 490 603,37 MHz
standard uncertainty	0,15 MHz
relative standard uncertainty	$2{,}5 \times 10^{-10}$.

From which:

λ_{a_3} =	514 673 466,4 fm
standard uncertainty	0,13 fm
relative standard uncertainty	$2{,}5 \times 10^{-10}$.

In 1983, the value adopted by the CIPM was f_{a_3} = 582 490 603,6 MHz with an estimated overall relative uncertainty of $1{,}3 \times 10^{-9}$ (equivalent to three times the relative standard uncertainty).

2. *Radiations of spectral lamps*

2.1 *Radiation corresponding to the transition between the levels* $2p_{10}$ *and* $5d_5$ *of the atom of* ^{86}Kr ($\lambda \approx$ 606 nm)

The following value was obtained from $(\lambda_i)_{Kr} \times (1/\lambda_{Kr})$:

[2.1-1] f_{Kr}/f_i = 1,044 919 242 05.

Taking the recommended value of f_i = 473 612 214 705 kHz (Section 1.4) and using the relative standard uncertainty as given in [2.1-1] of $1{,}3 \times 10^{-9}$, the following value for f_{Kr} is obtained:

f_{Kr} = 494 886 516 415 kHz.

Adopted value:

f_{Kr} =	494 886 516,4 MHz
standard uncertainty	0,6 MHz
relative standard uncertainty	$1,3 \times 10^{-9}$.

From which:

λ_{Kr} =	605 780 210,3 fm
standard uncertainty	0,8 fm
relative standard uncertainty	$1,3 \times 10^{-9}$.

In 1983, the value adopted by the CIPM was λ_{Kr} = 605 780 210 fm with an estimated overall relative uncertainty of 4×10^{-9} (equivalent to three times the relative standard uncertainty).

Annotated bibliography

1. *BIPM Com. Cons. Déf. Mètre*, 1982, **7**, M53-M64.

1.1.2-1 Zakharyash V. F., Klementyev V. M., Nikitin M. V., Timchenko B. A., Chebotayev V. P., Absolute Measurement of the Frequency of the E-line of Methane, *Sov. Phys. Tech. Phys.*, 1983, **23**, 11, 1374-1375.

1.1.2-2 Chebotayev V. P., Klementyev V. M., Nikitin M. V., Timchenko B. A., Zakharyash V. F., Comparison of Frequency Stabilities of the Rb Standard and of the He-Ne/CH_4 Laser Stabilized to the E Line in Methane, *Appl. Phys.*, 1985, **B36**, 59-61.

1.1.2-3 Bagayev S. N., Borisov B. D., Gol'dort V. G., Gusev A. Yu. *et al*, An Optical Standard of Time, *Avtometrya*, 1983, **3**, 37-58.

1.1.2-4 Felder R., A Decade of Work on the Determination of the Frequency of the F_2^2 Methane Transition at λ = 3,39 µm, *Rapport BIPM*-92/8.

1.1.2-5 Weiss C. O., Kramer G., Lipphardt B., Garcia E., Frequency Measurement of a CH_4 Hyperfine Line at 88 THz/"Optical Clock", *IEEE J. Quant. Electron.*, 1988, **24**, 10, 1970-1972.

1.1.2-6 Felder R., Robertsson L., Report on the 1989 PTB Experiment, *Rapport BIPM*-92/7.

1.1.2-7 *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1983, **51**, 25-28 and Documents Concerning the New Definition of the Metre, *Metrologia*, 1984, **19**, 165-166.

1.2-1 Bönsch G., Nicolaus A., Brand U., Wellenlängenbestimmung der Ca-Interkombinationslinie mit dem Michelson-Interferometer der PTB, *PTB Mitteilungen*, 1989, **99**, 329-334 [Document CCDM/92-14*i*].
This paper gives:
$\lambda_{\mathrm{Ca}}/\lambda_{\mathrm{i}}$ = 1,038 654 618 63 $(1 \pm 7 \times 10^{-11})$.

One calculates:

$f_{\mathrm{Ca}}/f_{\mathrm{i}}$ = 0,962 783 953 46 (1 ± 7 × 10^{-11}).

1.2-2 ITO N., ISHIKAWA J., MORINAGA A., Frequency Locking a Dye Laser to the Central Optical Ramsey Fringe in a Ca Atomic Beam and Wavelength Measurement, *J. Opt. Soc. Am.*, 1991, **B8**, 1388-1390 [Document CCDM/92-13*d*].

This paper gives:

λ_{Ca} = 657,459 439 6 (1 ± 1 × 10^{-9}) nm.

With the value adopted by the CIPM in 1983 [1] of:

f_{i} = 473 612 214,8 (1 ± 3,4 × 10^{-10}) MHz,

one can calculate:

$f_{\mathrm{Ca}}/f_{\mathrm{i}}$ = 0,962 783 952 8 (1 ± 1 × 10^{-9}).

1.3-1 BENNETT S. J., MILLS-BAKER P., Iodine Stabilized 640 nm Helium-neon Laser, *Opt. Commun.*, 1984, **51**, 322-324 [Document CCDM/92-12*d*].

From this paper, the ratio $f_{\mathrm{g}}/f_{\mathrm{i}}$ has been calculated [Document CCDM/92-12*a*]. The value is:

$f_{\mathrm{g}}/f_{\mathrm{i}}$ = 0,988 611 184 191 (1 ± 1 × 10^{-10}) (1 standard deviation).

With the recommended value of f_{i} = 473 612 214 705 (1 ± 2,5 × 10^{-11}) kHz (Section 1.4), one calculates f_{g} = 468 218 332 427 (1 ± 1,03 × 10^{-10}) kHz at an iodine pressure of 16 Pa (or a cold finger reference temperature of 14,3 °C) and a modulation width of 7 MHz. For a reference temperature of 16 °C and a modulation width of 6 MHz, peak to peak, corrections of – 23 kHz and + 8 kHz have to be applied to this value assuming a pressure dependent frequency shift of – 7,8 kHz/Pa and modulation dependent shift of – 7,6 kHz/MHz, similar to that reported in [1.3-2], giving:

f_{a_9} = 468 218 332 412 (1 ± 1,0 × 10^{-10}) kHz.

1.3-2 ZHAO K. G., BLABLA J., HELMCKE J., $^{127}I_2$-stabilized ^{3}He-^{22}Ne Laser at 640 nm Wavelength, *IEEE Trans. Instrum. Meas.*, 1985, **IM-34**, 252-256 [Document CCDM/92-10.2*c*].

This paper gives:

λ_{a_9} = 640,283 468 8 (1 ± 1,1 × 10^{-9}) nm (3 standard deviations).

BÖNSCH G., Simultaneous Wavelength Comparison of Iodine-stabilized Lasers at 515 nm, 633 nm and 640 nm, *IEEE Trans. Instrum. Meas.*, 1985, **IM-34**, 248-251.

This paper gives:

$\lambda_{\mathrm{i}}/\lambda_{\mathrm{a}_9}$ = 0,988 611 183 86 (1 ± 12 × 10^{-11}) (1 standard deviation) [Document CCDM/92-14*a*].

With the recommended value of f_{i} = 473 612 214 705 (1 ± 2,5 × 10^{-11}) kHz (Section 1.4) one calculates f_{a_9} = 468 218 332 270 (1 ± 1,23 × 10^{-10}) kHz at a cold finger temperature of 18 °C (iodine pressure = 22,6 Pa). For a reference temperature of 16 °C (iodine pressure = 18,9 Pa) a correction of

+ 29 kHz (using – 7,8 kHz/Pa) has to be applied to this value. To account for the modulation width of 6,5 MHz, peak to peak, and a modulation dependence of – 7,6 kHz/MHz, an additional correction of + 4 kHz has to be applied, giving:

f_{a_9} = 468 218 332 303 (1 ± 1,2 × 10^{-10}) kHz.

1.3-3 Document CCDM/92-6*a* and Document CCDM/92-20*a*.
These papers give:

λ_{a_9} (17 °C)/$\lambda_{a_{17}}$ (20 °C) = 1,011 520 341 04 (1 ± 4,6 × 10^{-10}).

With the recommended value of f_i = 473 612 214 705 (1 ± 2,5 × 10^{-11}) kHz (Section 1.4) one calculates f_{a_9} = 468 218 332 048 (1 ± 4,6 × 10^{-10}) kHz at a cold finger temperature of 17 °C (iodine pressure = 20,7 Pa). For a reference temperature of 16 °C (iodine pressure = 18,9 Pa) a correction of + 14 kHz has to be applied to this value, giving:

f_{a_9} = 468 218 332 062 (1 ± 4,6 × 10^{-10}) kHz.

1.4-1 Acef O., Zondy J. J., Abed M., Rovera D. G., Gérard A. H., Clairon A., Laurent Ph., Millerioux Y., Juncar P., A CO_2 to Visible Optical Frequency Synthesis Chain: Accurate Measurement of the 473 THz He-Ne/I_2 Laser, *Opt. Commun.*, 1993, **97**, 29-34 and document CCDM/92-19*a*.
These papers give:

f_f (INM) = (473 612 353 586 ± 3,4) kHz.

Taking into account the frequency difference $f_f - f_i$ = (138 892 ± 5) kHz between the components f and i [Appendix M 3, Table 12], the frequency of component i of the INM laser is f_i (INM) = 473 612 214 694,0 kHz.
Document CCDM/92-20*a*.
This paper gives:

$f_{INM12} - f_{BIPM4}$ = – (11,4 ± 1,5) kHz.

Chartier J.-M., Robertsson L., Fredin-Picard S., Recent Activities at BIPM in the Field of Stabilized Lasers — Radiations Recommended for the Definition of the Meter, *IEEE Trans. Instrum. Meas.*, 1991, **40**, 181-184 [Document CCDM/92-20*p*].
Chartier J.-M., Robertsson L., Sommer M. et al., International Comparison of Iodine-stabilized Helium-neon Lasers at λ = 633 nm Involving Seven Laboratories, *Metrologia*, 1991, **28**, 19-25 [Document CCDM/92-20*q*].
Chartier J.-M., Darnedde H., Frennberg M. et al., Intercomparison of Northern European $^{127}I_2$ Stabilized He-Ne Lasers at λ = 633 nm, *Metrologia*, 1992, **29**, 331-339. [Document CCDM/92-20*y*].
These papers show that the frequency of laser BIPM4 is very close to the mean. It was agreed that the CCDM should adopt an international value close to this average.

By applying the corresponding frequency difference (Document CCDM/92-20*a*) f_i (BIPM) – f_i (INM) = 11,4 kHz, the value is f_i = 473 612 214 705,4 kHz.

The standard uncertainty was derived from the uncertainty of the frequency chain and uncertainties resulting from variations in operational parameters listed below:

Iodine cell	
cell-wall temperature (25 ± 5) °C	
[coefficient 0,5 kHz/°C]	2,5 kHz
cold finger temperature (15 ± 0,2) °C	
[coefficient – 15 kHz/°C]	3,0 kHz
uncertainty of the iodine purity	5,0 kHz
Frequency modulation width, peak to peak,	
(6 ± 0,3) MHz [coefficient – 10 kHz/MHz]	3,0 kHz
One-way intracavity beam power,	
(10 ± 5) mW [absolute value of the	
coefficient ⩽ 1,4 kHz/mW]	7,0 kHz
Uncertainty of the interval $f_f - f_i$	5,0 kHz
Uncertainty of the frequency difference	
$f_{INM} - f_{BIPM}$	1,5 kHz
Uncertainty of the LPTF/ETCA/INM	
frequency measurement	3,4 kHz
Combined standard uncertainty	11,7 kHz
Relative standard uncertainty	$2,5 \times 10^{-11}$

1.5-1 *BIPM Com. Cons. Déf. Mètre*, 1982, **7**, M57 and Documents Concerning the New Definition of the Metre, *Metrologia*, 1984, **19**, 167.
These papers give:
NPL 1982 [12] f_o/f_i = 1,034 349 072 43 ($1 \pm 1 \times 10^{-10}$)
BIPM 1982 [24] f_o/f_i = 1,034 349 071 90 ($1 \pm 2,1 \times 10^{-10}$).
Measurements whose relative uncertainties were larger than 3×10^{-10} have not been taken into account.
From the values of these ratios and with the recommended value of f_i = 473 612 214 705 ($1 \pm 2,5 \times 10^{-11}$) kHz (Section 1.4), one calculates:
NPL 1982 f_o or f_{a_7} = 489 880 354 972 ($1 \pm 1 \times 10^{-10}$) kHz
BIPM 1982 f_o or f_{a_7} = 489 880 354 721 ($1 \pm 2,1 \times 10^{-10}$) kHz.

1.5-2 Bönsch G., Gläser M., Spieweck F., Bestimmung der Wellenlängenverhältnisse von drei $^{127}I_2$-stabilisierten Lasern bei 515 nm, 612 nm und 633 nm, *PTB Jahresbericht*, 1986, 161 [Document CCDM/92-14*n*] and Document CCDM/92-14*a*.

These papers give:

$\lambda_{b_{15}}/\lambda_i$ = 0,966 791 921 43 (1 ± 8 × 10^{-11}).

With the recommended value of f_i = 473 612 214 705 (1 ± 2,5 × 10^{-11}) kHz (Section 1.4), one calculates:

$f_{b_{15}}$ = 489 880 194 701 (1 ± 8,4 × 10^{-11}) kHz.

Using the frequency difference $f_{b_{15}} - f_{a_7}$ = (– 160 318 ± 3) kHz [Appendix M 3, Table 8], one calculates:

f_{a_7} = 489 880 355 019 (1 ± 8,4 × 10^{-11}) kHz.

1.5-3 VITUSHKIN L. F., ZAKHARENKO Yu. G., YVANOV I. V., LEIBENGARDT G. I., SHUR V. L., Measurements of Wavelength of High-stabilized He-Ne/I_2 Laser at 612 nm, *Opt. Spektr.*, 1990, **68**, 705-707.

This paper gives:

λ_d/λ_o = 1,034 348 712 (1 ± 3 × 10^{-10}).

With the recommended value of f_i = 473 612 214 705 (1 ± 2,5 × 10^{-11}) kHz (Section 1.4) and using the frequency difference $f_d - f_i$ = (165 116 ± 5) kHz between the components d and i [Appendix M 3, Table 12], one calculates:

f_d = 473 612 379 821 (1 ± 2,7 × 10^{-11}) kHz and

f_o or f_{a_7} = 489 880 355 055 (1 ± 3,0 × 10^{-10}) kHz.

1.5-4 HIMBERT M., BOUCHAREINE P., HACHOUR A., JUNCAR P., MILLERIOUX Y., RAZET A., Measurements of Optical Wavelength Ratios Using a Compensated Field Sigmameter, *IEEE Trans. Instrum. Meas.*, 1991, **40**, 200-203 [Document CCDM/92-19*g*] and Document CCDM/92-19*a*.

These papers give:

f_i or $f_{a_{13}}$ = (489 880 604 541 ± 88) kHz.

With the values adopted by the CIPM in 1983 [1] of f_i = 473 612 214,8 MHz and the frequency difference $f_e - f_i$ = (152 255 ± 5) kHz [Appendix M 3, Table 12], one obtains:

f_e = 473 612 367 055 kHz and

$f_{a_{13}}/f_e$ = 1,034 349 267.

With the recommended value of f_i = 473 612 214 705 (1 ± 2,5 × 10^{-11}) kHz (Section 1.4) and the frequency difference $f_e - f_i$, one calculates:

f_e = 473 612 366 960 kHz and

$f_{a_{13}}$ = 489 880 604 443 kHz

using the uncertainty on the ratio $f_{a_{13}}/f_e$ given in document CCDM/92-19*g* of ± 8 × 10^{-11} one obtains:

$f_{a_{13}}$ = 489 880 604 443 (1 ± 8,4 × 10^{-11}) kHz.

Using the frequency difference $f_{a_7} - f_{a_{13}}$ = (– 249 602 ± 10) kHz between the components a_7 and a_{13} [Appendix M 3, Table 7] one calculates:

f_{a_7} = 489 880 354 841 (1 ± 8,4 × 10^{-11}) kHz.

1.6-1 NBS measurement of frequencies in the visible and near IR [Document CCDM/82-30].
This document gave the value 520 206 808 547 $(1 \pm 1{,}5 \times 10^{-10})$ kHz, which was reduced by 12 kHz at the request of the delegate at the 7th meeting of the CCDM. The value must now also be multiplied by the ratio (88 376 181 600,5/88 376 181 608) to account for the 1992 respecification of the methane frequency (Section 1.1.2), giving:
f_{a_1} = 520 206 808 491 $(1 \pm 1{,}5 \times 10^{-10})$ kHz.

1.6-2 Barwood G. P., Rowley W. R. C., Characteristics of a $^{127}I_2$-Stabilized Dye Laser at 576 nm, *Metrologia*, 1984, **20,** 19-23 [Document CCDM/92-12*c*].
This publication supersedes Document CCDM/82-34.
This paper gives:
$f_{a_1}/f_{a_{13}}$ = 1,098 381 317 29 $(1 \pm 1 \times 10^{-10})$.
With the recommended value of $f_{a_{13}}$ = 473 612 214 705 $(1 \pm 2{,}5 \times 10^{-11})$ kHz (Section 1.4) one calculates f_{a_1} = 520 206 808 272 $(1 \pm 1 \times 10^{-10})$ kHz.

1.7-1 Documents CCDM/92-14*a*, CCDM/92-14*l* and Brand U., Ein iodstabilisiertes He-Ne Laser-Wellenlängennormal grüner Strahlung, *PTB Bericht*, 1991, **Opt. 34**, 1-109 [Document CCDM/92-14*j*].
These papers give:
λ_{a_9}/λ_i = 0,858 647 265 30 $(1 \pm 8 \times 10^{-11})$ (1 standard deviation).
With the recommended value of f_i = 473 612 214 705 $(1 \pm 2{,}5 \times 10^{-11})$ kHz (Section 1.4) one calculates: f_{a_9} = 551 579 483 03 $(1 \pm 8{,}4 \times 10^{-11})$ kHz at a cold finger temperature of – 10 °C (iodine pressure = 1,4 Pa). For a reference temperature of 0 °C (iodine pressure = 4,1 Pa), a correction of – 8 kHz has to be applied to this value with the pressure dependence of – 3,0 kHz/Pa (Document CCDM/92-14*j*, 44), giving:
f_{a_9} = 551 579 483 029 $(1 \pm 8{,}4 \times 10^{-11})$ kHz.

1.7-2 Document CCDM/92-12*a*.
This paper gives:
$f_{b_{10}}$ (0 °C)/f_i = 1,164 624 021 92 $(1 \pm 12 \times 10^{-11})$.
With the recommended value of f_i = 473 612 214 705 $(1 \pm 2{,}5 \times 10^{-11})$ kHz (Section 1.4) one calculates $f_{b_{10}}$ = 551 580 162 320 $(1 \pm 12{,}3 \times 10^{-11})$ kHz at a cold finger temperature of 0 °C (iodine pressure = 4,1 Pa). From the measured value of $f_{b_{10}} - f_{a_9}$ = (679 420 ± 15) kHz (standard uncertainty) [Appendix M 3, Table 5], one calculates:
f_{a_9} = 551 579 482 900 $(1 \pm 13 \times 10^{-11})$ kHz.

1.8-1 *BIPM Com. Cons. Déf. Mètre*, 1982, **7**, M57 and Documents Concerning the New Definition of the Metre, *Metrologia*, 1984,

19, 168.
These papers give:
NPL 1982 [12] f_{a_3}/f_i = 1,229 889 316 88 (1 ± 1 × 10^{-10})
BIPM 1982 [27] f_{a_3}/f_i = 1,229 889 316 88 (1 ± 2,5 × 10^{-10}).
Measurements whose relative uncertainties were larger than 2,5 × 10^{-10} have not been taken into account.

1.8-2 BÖNSCH G., NICOLAUS A., BRAND U., Wellenlängenbestimmung der Ca-Interkombinationslinie mit dem Michelson-Interferometer der PTB, *PTB Mitteilungen*, 1989, **99**, 329-334 [Document CCDM/92-14*i*].
This paper gives:
f_i/f_{a_3} = 0,813 081 295 94 (1 ± 7 × 10^{-11});
one calculates:
f_{a_3}/f_i = 1,229 889 317 33 (1 ± 7 × 10^{-11}).

1.8-3 BÖNSCH G., Simultaneous Wavelength Comparison of Iodine-stabilized Lasers at 515 nm, 633 nm and 640 nm, *IEEE Trans. Instrum. Meas.*, 1985, **IM-34**, 248-251.
This paper gives:
f_i/f_{a_3} = 0,813 081 295 87 (1 ± 7 × 10^{-11});
one calculates:
f_{a_3}/f_i = 1,229 889 317 44 (1 ± 7 × 10^{-11}).

1.8-4 BÖNSCH G., GLÄSER M., SPIEWECK F., Bestimmung der Wellenlängenverhältnisse von drei $^{127}I_2$-stabilisierten Lasern bei 515 nm, 612 nm und 633 nm, *PTB Jahresbericht*, 1986, 161 [Document CCDM/92-14*n*].
This paper gives:
f_i/f_{a_3} = 0,813 081 295 92 (1 ± 8 × 10^{-11});
one calculates:
f_{a_3}/f_i = 1,229 889 317 36 (1 ± 8 × 10^{-11}).

1.8-5 BÖNSCH G., NICOLAUS A., BRAND U., Wellenlängenbestimmung für den I_2-stabilisierten He-Ne-Laser bei 544 nm, *PTB Jahresbericht*, 1991, 173-174 [Document CCDM/92-14*l*].
This paper gives:
f_i/f_{a_3} = 0,813 081 295 86 (1 ± 8 × 10^{-11});
one calculates:
f_{a_3}/f_i = 1,229 889 317 45 (1 ± 8 × 10^{-11}).

2.1-1 *BIPM Com. Cons. Déf. Mètre*, 1982, **7**, M58 and Documents Concerning the New Definition of the Metre, *Metrologia*, 1984, **19**, 168.
f_{Kr}/f_i = 1,044 919 242 05 (1 ± 1,3 × 10^{-9}).

APPENDIX M 3

Frequency intervals between hyperfine components of absorption lines of iodine

These tables replace those published in *BIPM Com. Cons. Déf. Mètre*, 1982, **7**, M65-M75 and *Metrologia*, 1984, **19**, 170-178.

The notation for the hyperfine components is that used in the bibliography.

The values adopted for the frequency intervals are the weighted means of the values given in the bibliography.

For the uncertainties, account has been taken of:

the uncertainties given by the authors;

the spread in the different determinations of a single component;

the effect of any perturbing components;

the difference between the calculated and the measured values.

TABLE 1

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 515$ nm; $^{127}I_2$, transition 43-0, P(13)

Reference: component a_3 (or s), f = 582 490 603,37 MHz [1]

Component	$f(a_n) - f(a_3)$	s	Component	$f(a_n) - f(a_3)$	s
a_1	– 131,770	0,001	a_{11}	393,962	0,002
a_2	– 59,905	0,001	a_{12}	435,599	0,003
a_3	0	–	a_{13}	499,712	0,005
a_4	76,049	0,002	a_{14}	518	1
a_5	203,229	0,005	a_{15}	587,396	0,002
a_6	240,774	0,005	a_{16}	616,756	0,005
a_7	255,005	0,001	a_{17}	660,932	0,005
a_8	338,699	0,005	a_{18}	740	1
a_9	349,717	0,005	a_{19}	742	1
a_{10}	369	1	a_{20}	757,631	0,010
			a_{21}	817,337	0,005

Ref. [2-5]

TABLE 2

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 515$ nm; $^{127}I_2$, transition 43-0, R(15)

References
- component a_3, 43-0, P(13), $^{127}I_2$, f = 582 490 603,37 MHz [1]
- $f(a_1) - f(a_3)$ = [– 131,770 ± 0,001] MHz, (Table 1)
- $f(b_1) - f(a_1)$ = [283,835 ± 0,005] MHz [3, 6]

Component	$f(b_n) - f(b_1)$	*s*	Component	$f(b_n) - f(b_1)$	*s*
b_1	0	0,005	b_{11}	525,207	0,005
b_2	69,739	0,005	b_{12}	566,287	0,005
b_3	129,155	0,005	b_{13}	630,782	0,005
b_4	217	1	b_{14}	658,178	0,005
b_5	335,828	0,005	b_{15}	725,166	0,005
b_6	368	1	b_{16}	739,394	0,005
b_7	396,442	0,005	b_{17}	791,673	0,005
b_8	471	1	b_{18}	865,523	0,005
b_9	472	1	b_{19}	874,840	0,005
b_{10}	500,627	0,005	b_{20}	892,895	0,010
			b_{21}	947,278	0,010

Ref. [3, 4, 6]

TABLE 3

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 515$ nm; $^{127}I_2$, transition 58-1, R(98)

References
- component a_3, 43-0, P(13), $^{127}I_2$, f = 582 490 603,37 MHz [1]
- $f(d_6) - f(a_3)$ = [– 2100 ± 1] MHz [7]

Component		$f(d_n) - f(d_6)$	*s*	Component		$f(d_n) - f(d_6)$	*s*
d_1	1	– 413,488	0,005	d_8	8	200,478	0,005
d_2	2	– 359,553	0,005	d_9	9	225,980	0,005
d_3	3	– 194,521	0,005	d_{10}	10	253	1
d_4	4	– 159,158	0,005	d_{11}	11	254	1
d_5	5	– 105,769	0,005	d_{12}	12	314,131	0,005
d_6	6	0	–	d_{13}	13	426,691	0,005
d_7	7	172,200	0,005	d_{14}	14	481,574	0,005
				d_{15}	15	510,246	0,005

Ref. [4, 6, 7]

TABLE 4

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx$ 543,5 nm ; $^{127}I_2$, transition 26-0, R(12)					
Reference: component a_9, f = 551 579 482,96 MHz [1]					
Component	$f(a_n) - f(a_9)$	s	Component	$f(a_n) - f(a_9)$	s
a_1	– 482,822	0,015	a_9	0	–
a_2	– 230,450	0,015	a_{10}	83,283	0,015
a_3	– 220,688	0,028	a_{11}	193,769	0,033
a_4	– 173,917	0,015	a_{12}	203,037	0,030
a_5	– 168,710	0,015	a_{13}	256,166	0,023
a_6	– 116,493	0,015	a_{14}	269,370	0,017
a_7	– 72,983	0,015	a_{15}	373,511	0,015
a_8	– 53,724	0,015			

Ref. [8-13]

TABLE 5

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx$ 543,5 nm ; $^{127}I_2$, transition 28-0, R(106)					
Reference: component a_9, 26-0, R(12), $^{127}I_2$, f = 551 579 482,96 MHz [1]					
Component	$f(b_n) - f(a_9)$	s	Component	$f(b_n) - f(a_9)$	s
b_1	105,637	0,016	b_9	564,849	0,015
b_2	358,943	0,015	b_{10}	679,420	0,015
b_3	387,823	0,016	b_{11}	804,246	0,020
b_4	397,265	0,015	b_{12}	811,724	0,020
b_5	425,741	0,020	b_{13}	833,939	0,020
b_6	506,727	0,015	b_{14}	842,064	0,020
b_7	519,996	0,017	b_{15}	966,655	0,021
b_8	551,661	0,021			

Ref. [8-13]

TABLE 6

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx$ 576 nm ; $^{127}I_2$, transition 17-1, P(62)							
Reference: component a_1 (or o), f = 520 206 808,4 MHz [1]							
Component		$f(a_n) - f(a_1)$	s	Component		$f(a_n) - f(a_1)$	s
a_1	o	0	–	a_7	i	428,51	0,02
a_2	n	275,03	0,02	a_8	h	440,17	0,02
a_3	m	287,05	0,02	a_9	g	452,30	0,02
a_4	l	292,57	0,02	a_{10}	f	579,43	0,03
a_5	k	304,26	0,02	–	–	–	–
a_6	j	416,67	0,02	a_{15}	a	869,53	0,03

Ref. [14, 15]

TABLE 7

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx$ 612 nm ; $^{127}I_2$, transition 9-2, R(47)							
Reference: component a_7 (or o), f = 489 880 354,9 MHz [1]							
Component		$f(a_n) - f(a_7)$	s	Component		$f(a_n) - f(a_7)$	s
a_1	u	– 357,16	0,02	a_{11}	k	119,045	0,006
a_2	t	– 333,97	0,01	a_{12}	j	219,602	0,006
a_3	s	– 312,46	0,02	a_{13}	i	249,602	0,01
a_4	r	– 86,168	0,007	a_{14}	h	284,304	0,01
a_5	q	– 47,274	0,004	a_{15}	g	358,37	0,03
a_6	p	– 36,773	0,003	a_{16}	f	384,66	0,01
a_7	o	0	–	a_{17}	e	403,764	0,02
a_8	n	81,452	0,003	a_{18}	d	429,993	0,02
a_9	m	99,103	0,003	a_{19}	c	527,165	0,02
a_{10}	l	107,463	0,005	a_{20}	b	539,222	0,02
				a_{21}	a	555,093	0,02

Ref. [16, 18, 19, 21, 24]

TABLE 8

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx$ 612 nm ; $^{127}I_2$, transition 11-3, P(48)					
Reference: component a_7, 9-2, R(47), $^{127}I_2$, f = 489 880 354,9 MHz [1]					
Component	$f(b_n) - f(a_7, {}^{127}I_2)$	s	Component	$f(b_n) - f(a_7, {}^{127}I_2)$	s
b_1	– 1034,75	0,07	b_9	– 579,91	0,01
b_2	– 755,86	0,05	b_{10}	– 452,163	0,005
b_3	– 748,28	0,03	b_{11}	– 316,6	0,4
b_4	– 738,35	0,04	b_{12}	– 315,8	0,4
b_5	– 731,396	0,006	b_{13}	– 297,42	0,03
b_6	– 616,01	0,03	b_{14}	– 294,72	0,03
b_7	– 602,42	0,03	b_{15}	– 160,318	0,003
b_8	– 593,98	0,01			

Ref. [16, 18, 19, 21, 24]

TABLE 9

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx$ 612 nm ; $^{127}I_2$, transition 15-5, R(48)		
Reference: component a_7, 9-2, R(47), $^{127}I_2$, f = 489 880 354,9 MHz [1]		
Component	$f(c_n) - f(a_7, {}^{127}I_2)$	s
c_1	– 513,83	0,03
c_2	– 237,40	0,03
c_3	– 228,08	0,03
c_4	– 218,78	0,03
c_5	– 209,96	0,03
c_6	– 97,74	0,03
c_8	– 73,92	0,03
c_9	– 59,30	0,03

Ref. [16]

TABLE 10

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 612$ nm ; $^{129}I_2$, transition 10-2, P(110)							
Reference: component a_7, 9-2, R(47), $^{127}I_2$, f = 489 880 354,9 MHz [1]							
Component		$f(a_n) - f(a_7, {}^{127}I_2)$	s	Component		$f(a_n) - f(a_7, {}^{127}I_2)$	s
a_1	b′	– 376,29	0,05	a_{15}	n	1,61	0,20
a_2	a′	– 244,76	0,10	a_{16}	m	10,63	0,15
a_3	z	– 230,79	0,20	a_{17}	l	15,82	0,20
a_4	y	– 229,40	0,20	a_{18}	k	25,32	0,10
a_5	x	– 216,10	0,05	a_{19}	j	49,44	0,15
a_6	w	– 149,37	0,10	a_{20}	i	54,66	0,20
a_7	v	– 134,68	0,10	a_{21}	h	69,02	0,10
a_8	u	– 130,98	0,10	a_{22}	g	74,47	0,15
a_9	t	– 116,67	0,05	a_{23}	f	110,60	0,10
a_{10}	s	– 96,26	0,20	a_{24}	e	153,09	0,20
a_{11}	r	– 90,70	0,20	a_{25}	d	154,70	0,20
a_{12}	q	– 84,12	0,20	a_{26}	c	163,98	0,20
a_{13}	p	– 77,79	0,20	a_{27}	b	166,22	0,20
a_{14}	o	– 72,70	0,20	a_{28}	a	208,29	0,10

Ref. [22, 25, 26]

TABLE 11

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 612$ nm ; $^{129}I_2$, transition 14-4, R(113)							
Reference: component a_7, 9-2, R(47), $^{127}I_2$, f = 489 880 354,9 MHz [1]							
Component		$f(b_n) - f(a_7, {}^{127}I_2)$	s	Component		$f(b_n) - f(a_7, {}^{127}I_2)$	s
b_{19}	r	– 410,4	0,3	b_{28}	i	– 289,4	0,5
b_{20}	q	– 390,0	0,3	b_{29}	h	– 273,1	0,3
b_{21}	p	– 383,9	0,5	b_{30}	g	– 255,7	0,5
b_{22}	o	– 362,8	0,3	b_{31}	f	– 247	5
b_{23}	n	– 352,9	0,3	b_{32}	e	– 237	5
b_{24}	m	– 346,4	0,3	b_{33}	d	– 223	5
b_{25}	l	– 330,0	0,3	b_{34}	c	– 198,6	0,3
b_{26}	k	– 324,9	0,3	b_{35}	b	– 193,1	0,3
b_{27}	j	– 304,7	0,3	b_{36}	a	– 187,0	0,3

Ref. [25, 26]

TABLE 12

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 633$ nm ; $^{127}I_2$, transition 11-5, R(127)							
Reference: component a_{13} (or i), f = 473 612 214,705 MHz [1]							
Component		$f(a_n) - f(a_{13})$	s	Component		$f(a_n) - f(a_{13})$	s
a_2	t	– 582,9	0,5	a_{12}	j	– 21,565	0,005
a_3	s	– 558,9	0,5	a_{13}	i	0	–
a_4	r	– 320,73	0,01	a_{14}	h	21,939	0,005
a_5	q	– 292,69	0,05	a_{15}	g	125,694	0,005
a_6	p	– 290,29	0,05	a_{16}	f	138,892	0,005
a_7	o	– 263,20	0,01	a_{17}	e	152,255	0,005
a_8	n	– 162,814	0,005	a_{18}	d	165,116	0,005
a_9	m	– 153,801	0,005	a_{19}	c	283,006	0,005
a_{10}	l	– 137,994	0,005	a_{20}	b	291,100	0,005
a_{11}	k	– 129,950	0,005	a_{21}	a	299,931	0,005

Ref. [27-39]

TABLE 13

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 633$ nm ; $^{127}I_2$, transition 6-3, P(33)							
References	● component a_{13}, 11-5, R(127), $^{127}I_2$, f = 473 612 214,705 MHz [1] ● $f(b_{21}) - f(a_{13}$, 11-5, R(127)) = [– 393,53 ± 0,02] MHz [40]						
Component		$f(b_n) - f(b_{21})$	s	Component		$f(b_n) - f(b_{21})$	s
b_1	u	– 922,57	0,02	b_{11}	k	– 439,02	0,02
b_2	t	– 895,06	0,02	b_{12}	j	– 347,36	0,02
b_3	s	– 869,68	0,02	b_{13}	i	– 310,28	0,02
b_4	r	– 660,52	0,02	b_{14}	h	– 263,60	0,02
b_5	q	– 610,71	0,02	b_{15}	g	– 214,56	0,02
b_6	p	– 594,01	0,02	b_{16}	f	– 179,30	0,02
b_7	o	– 547,42	0,02	b_{17}	e	– 153,94	0,02
b_8	n	– 487,08	0,02	b_{18}	d	– 118,22	0,02
b_9	m	– 461,27	0,02	b_{19}	c	– 36,72	0,02
b_{10}	l	– 453,23	0,02	b_{20}	b	– 21,98	0,02
				b_{21}	a	0	–

Ref. [35, 40, 41, 42]

TABLE 14

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 633$ nm ; $^{129}I_2$, transition 8-4, P(54)

References:
- ● component a_{13}, 11-5, R(127), $^{127}I_2$, f = 473 612 214,705 MHz [1]
- ● f (a_{28}, 8-4, P(54)) – f (a_{13}, 11-5, R(127)) = [95,90 ± 0,04] MHz [43, 44, 45]

Component		$f(a_n) - f(a_{28})$	s	Component		$f(a_n) - f(a_{28})$	s
a_2	z′	– 449	2	a_{15}	j′	– 206,05	0,2
a_3	y′	– 443	2	a_{16}	i′	– 197,73	0,08
a_4	x′	– 434	2	a_{17}	h′	– 193,23	0,08
a_5	w′	– 429	2	a_{18}	g′	– 182,74	0,03
a_6	v′	– 360,9	1	a_{19}	f′	– 162,61	0,05
a_7	u′	– 345,1	1	a_{20}	e′	– 155,72	0,05
a_8	t′	– 340,8	1	a_{21}	d′	– 138,66	0,05
a_9	s′	– 325,4	1	a_{22}	c′	– 130,46	0,05
a_{10}	r′	– 307,0	1	a_{23}	a′	– 98,22	0,03
a_{11}	q′	– 298,2	1	a_{24} / a_{25}	n_2 / n_1	– 55,6[a]	0,5
a_{12}	p′	– 293,1	1				
a_{13}	o′	– 289,7	1	a_{26}	m_2	– 43,08	0,03
a_{14}	n′	– 282,7	1	a_{27}	m_1	– 41,24	0,05
				a_{28}	k	0	–

Ref. [46-51]

[a]also component m_8 of 6-3, P(33), $^{127}I^{129}I$

TABLE 15

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 633$ nm; $^{129}I_2$, transition 12-6, P(69)

References:
- ● component a_{13}, 11-5, R(127), $^{127}I_2$, f = 473 612 214,705 MHz [1]
- ● f (a_{28}, 8-4, P(54)) – f (a_{13}, 11-5, R(127)) = [95,90 ± 0,04] MHz [43, 44, 45]

Component		$f(b_n) - f(a_{28}, {}^{129}I_2)$	*s*	Component		$f(b_n) - f(a_{28}, {}^{129}I_2)$	*s*
b_1	b‴	99,12	0,05	b_{20}	q′	507,66	0,10
b_2	a‴	116,08	0,05	b_{22}	o′	535,65	0,10
b_3	z″	132,05	0,05	b_{23}	n′	536,59	0,10
b_4	s″	234,54	0,05	b_{24}	m′	545,06	0,05
b_5	r″	256,90[a]	0,05	b_{25}	l′	560,94	0,05
b_6	q″	264,84[b]	0,05	b_{26}	k′	566,19	0,05
b_7	p″	288,06	0,05	b_{27}	j′	586,27	0,03
b_8	k″	337,75	0,1	b_{28}	i′	601,78	0,03
b_9	i''_1	358,8	0,5	b_{29}	h′	620,85	0,03
b_{10}	i''_2			b_{30}	g′	632,42	0,03
b_{11}	f″	373,80	0,05	b_{31}	f′	644,09	0,03
b_{12}	d″	387,24	0,05	b_{32}	e′	655,47	0,03
b_{13}	c″	395,3	0,2	b_{33}	d′	666,81	0,10
b_{14}	b″	402,45	0,05	b_{34}	c′	692,45	0,10
b_{15}	a″	407	4	b_{35}	b′	697,96	0,10
b_{16}	z′	412,37	0,05	b_{36}	a′	705,43	0,10
b_{17}	y′	417	4				

Ref. [46, 49, 51]

[a] also component m_{28} of 6-3, P(33), $^{127}I^{129}I$

[b] also component m_{29} of 6-3, P(33), $^{127}I^{129}I$

TABLE 16

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 633$ nm; $^{129}I_2$, transition 8-4, P(60)

References:
- ● component a_{13}, 11-5, R(127), $^{127}I_2$, f = 473 612 214,705 MHz [1]
- ● $f(a_{28}$, 8-4, P(54)) – $f(a_{13}$, 11-5, R(127)) = [95,90 ± 0,04] MHz [43, 44, 45]

Component		$f(d_n) - f(a_{28}, {}^{129}I_2)$	*s*
d_{23}	A′	– 555	5
d_{24}	N	– 511	2
d_{25}	N		
d_{26}	M	– 499	2
d_{27}	M		
d_{28}	K	– 456	2

Ref. [46]

TABLE 17

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 633$ nm; $^{129}I_2$, transition 6-3, P(33)

References:
- ● component a_{13}, 11-5, R(127), $^{127}I_2$, f = 473 612 214,705 MHz [1]
- ● $f(e_2) - f(a_{13}$, 11-5, R(127)) = [988,29 ± 0,20] MHz [52, 53, 54]

Component		$f(e_n) - f(e_2)$	*s*	Component		$f(e_n) - f(e_2)$	*s*
e_1	A	– 19,82	0,05	e_9	I	239	2
e_2	B	0	–	e_{10}	J	249	2
e_3	C	17,83	0,03	e_{11}	K	260	2
e_4	D	102,58	0,05	e_{12}	L	269	3
e_5	E	141	2	e_{13}	M	273	4
e_6	F	157	2	e_{14}	N	287	4
e_7	G	191	2	e_{15}	O	293	5
e_8	H	208	2	e_{16}	P	295	5
				e_{17}	Q	306	6

Ref. [46, 51, 52, 53]

TABLE 18

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx$ 633 nm ; $^{127}I^{129}I$, transition 6-3, P(33)

References:
- component a_{13}, 11-5, R(127), $^{127}I_2$, *f* = 473 612 214,705 MHz [1]
- *f* (a_{28}, 8-4, P(54)) – *f* (a_{13}, 11-5, R(127)) = [95,90 ± 0,04] MHz [43, 44, 45]

Component		$f(m_n) - f(a_{28}, {}^{129}I_2)$	*s*	Component		$f(m_n) - f(a_{28}, {}^{129}I_2)$	*s*
m_1	m'	– 254	3	m_{26}	u''	212,80	0,05
m_2	l'	– 233,71	0,10	m_{27}	t''	219,43	0,05
m_3	k'	– 226,14	0,10	m_{28}	r''	256,90	0,10
m_4	j'	– 207	1,5	m_{29}	q''	264,84	0,05
m_5	b'	– 117,79	0,10	m_{30}	o''	299,22	0,05
m_6	p	– 87,83	0,15	m_{31}	n''	312,43	0,05
m_7	o	– 78,2	0,5	m_{32}	m''	324,52	0,03
m_8	n	– 56[a]	1	m_{33}	l''	333,14	0,03
m_9	l	– 17,55	0,05	m_{34}, m_{35}	k''_2, k''_1	337,7	0,5
m_{10}	j	12,04	0,03				
m_{11}	i	15,60	0,03	m_{36}	j''	345,05	0,05
m_{12}	h	33,16	0,03	m_{37}	h''	362,18	0,10
m_{13}	g_2	39,9	0,2	m_{38}	g''	369,78	0,03
m_{14}	g_1	41,3	0,2	m_{39}	e''	380,37	0,03
m_{15}	f	50,72	0,03	m_{40}	d''	385	4
m_{16}	e	54,06	0,10	m_{41}	x'	431	4
m_{17}	d	69,33	0,03	m_{42}	w'	445	4
m_{18}	c	75,06	0,03	m_{43}	v'	456,7	0,5
m_{19}	b	80,00	0,03	m_{44}	u'	477,17	0,05
m_{20}	a	95,00	0,03	m_{45}	t'	486,43	0,05
m_{21}	y''	160,74	0,03	m_{46}	s'	495,16	0,05
m_{22}	x''	199,52	0,03	m_{47}	r'	503,55	0,05
m_{23}	w''	205,06	0,05	m_{48}	p'	515,11	0,05
m_{24}, m_{25}	v''_2, v''_1	207,9	0,5				

Ref. [34, 46, 49, 50, 51]

[a] also components a_{24} and a_{25} of 8-4, P(54), $^{129}I_2$

TABLE 19

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 640$ nm; $^{127}I_2$, transition 8-5, P(10)					
Reference: component a_9 (or g), f = 468 218 332,4 MHz [1]					
Component	$f(a_n) - f(a_9)$	s	Component	$f(a_n) - f(a_9)$	s
a_1	– 495,4	0,4	a_9	0	–
a_2	– 241,5	0,7	a_{10}	77,84	0,03
a_3	– 233,0	0,35	a_{11}	186,22	0,07
a_4	– 177,8	1,3	a_{12}	199,51	0,07
a_5	– 175,2	0,6	a_{13}	256,6	0,15
a_6	– 130,8	0,04	a_{14}	272,75	0,07
a_7	– 82,45	0,03	a_{15}	374,0	0,2
a_8	– 61,85	0,14			

Ref. [9, 19, 55-62]

TABLE 20

(unit: MHz; *s*: estimated standard uncertainty)

$\lambda \approx 640$ nm; $^{127}I_2$, transition 8-5, R(16)		
Reference: component a_9, 8-5, P(10), $^{127}I_2$, f = 468 218 332,4 MHz [1]		
Component	$f(b_n) - f(a_9)$	s
b_1	62,83	0,01
b_2	329,8	0,2
b_3	335,99	0,02

Ref. [9, 19, 55-62]

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APPENDIX M 4

Questionnaire sent by the BIPM to member laboratories of the CCDM

M 4A **Questionnaire**

1. Absolute frequency measurements

1.1 Have you made absolute measurements of the frequency of any of the radiations recommended in the *mise en pratique* of the definition of the metre or any other radiations? If so, please list the values obtained with their uncertainties.

1.2 Do you plan to make any absolute measurements of frequency in the visible? If so, please give a sketch of the frequency chain you intend to use.

2. Measurements of frequency ratios

2.1 Have you made measurements of the frequency ratios between radiations listed in the *mise en pratique* of the definition of the metre or between any others? If so, please list the values obtained with their uncertainties.

2.2 Do you plan to make any measurements of frequency ratios? If so, please give brief details of the instrument you expect to use and the uncertainties you hope to achieve.

3. *Mise en pratique* of the definition of the metre

3.1 Do you have proposals for changing any of the values of frequency, wavelength or uncertainty given in the *mise en pratique* of the definition of the metre? If so, please give an outline of your proposals.

3.2 Do you have proposals for additional radiations to be included in the *mise en pratique*? If so, please give a brief summary of why you think these new radiations would be useful.

3.3 Do you have any proposals for changes in the operating conditions for lasers specified in the *mise en pratique* for high-accuracy realization of the definition of the metre? Do these proposals include additional parameters that should be specified?

3.4 Which of the recommended radiations and frequencies of the *mise en pratique* do you maintain in your laboratory for the realization of the definition of the metre and what are your estimated uncertainties in the realization?

3.5 Have you developed or are you working on new methods that might allow improved frequency reproducibility among the recommended or other radiations for the definition of the metre? If so, please give a brief outline of the method and an estimate of the time scale of the work.

4. International comparisons of laser frequencies

4.1 Please list the comparisons of laser frequencies in which you have participated giving

a) the frequencies and wavelengths,

b) the participating laboratories,

c) the results or a reference to the publication containing the results.

4.2 For the future, which radiations and frequencies should be the subject of international comparisons in which you would like to participate?

5. Mechanical standards of length

5.1 What types of mechanical length standard does your laboratory calibrate (line-scales, end standards, step gauges, etc.)? What are the uncertainties given?

5.2 Is the demand for each of these types of standard calibration increasing, constant or decreasing? Are there demands for increased accuracy for these measurements?

5.3 Are there new areas of length metrology that are likely to require your attention in the future?

5.4 Are there any aspects of length metrology that require an international comparison to be carried out among national laboratories?

5.5 What means do you use to determine the refractive index of air for the comparison of wavelength standards and mechanical length standards?

M 4B **Abstract of replies***

This analysis is based upon the following documents:

CCDM/92-4*a*	NRC	(Canada)
/92-5*a*	CSIRO	(Australia)
/92-6*a*	IMGC	(Italy)
/92-7*a*	VNIIM	(Russian Federation)
/92-8*a*	LPI	(Russian Federation)
/92-9*a*	VNIIFTRI	(Russian Federation)
/92-10*a*	NIM	(People's Rep. of China)
/92-11*a*	NIST	(USA)
/92-12*a*	NPL	(United Kingdom)
/92-13*a*	NRLM	(Japan)
/92-14*a*	PTB	(Germany)
/92-15*a*	CSMU	(Czechoslovakia)
/92-16*a*	CSIR	(South Africa)
/92-17*a*	OFMET	(Switzerland)
/92-18*a*	DSIR	(New Zealand)
/92-19*a*	INM/LNE	(France)
/92-20*a*	BIPM	
/92-21*a*	KRISS	(Rep. of Korea)
/92-23*a*	IPL	(Russian Federation)
/92-24*a*	JILA/NIST	(USA)

* In their replies to the BIPM questionnaire, most laboratories expressed uncertainties in the form ± a value. Often, they did not specify whether the value given represents one standard deviation or three standard deviations.

In this report the uncertainties are shown in the ± form and it is assumed that they represent one standard deviation (1 σ).

Other laboratories, among them the BIPM, chose to express uncertainties in the recommended way. In this report these values are shown as a standard uncertainty of one standard deviation (1 σ).

1. Absolute frequency measurements

1.1 Have you made absolute measurements of the frequency of any of the radiations recommended in the *mise en pratique* of the definition of the metre or any other radiations? If so, please list the values obtained with their uncertainties.

NRC The unweighted mean and standard uncertainty of 9 separate absolute frequency measurements of helium-neon radiation locked to the $F_2^{(2)}$ component, ν_3 transition, P(7) band of the CH_4 molecule made from 1989-03-29 until 1991-05-10 are:

f = 88 376 181 599,415 kHz, with a standard uncertainty of 0,104 kHz,

(*see* Appendix A of Document CCDM/92-4*a* and Document CCDM/92-4*b*).

CSIRO No activity.

IMGC Frequency measurements have been made on two $^{14}NH_3$ transitions, namely:

$\nu_{sQ\,(7,\,7)}$ = (1 138 211,0 ± 0,5) MHz,

$\nu_{aR\,(7,\,7)}$ = (3 679 592,5 ± 0,5) MHz.

(Document CCDM/92-6*d*).

VNIIM No answer.

LPI Absolute frequency measurements using a transportable He-Ne/CH_4 laser at λ = 3,39 μm, central component (resolved magnetic hyperfine structure) of the $F_2^{(2)}$ methane line were made on the radio-optical frequency chains at the PTB (1991) and the VNIIFTRI (1992).

The following results were obtained:

PTB : f = (88 376 181 600 290 ± 35) Hz,

VNIIFTRI : f = (88 376 181 600 018 ± 100) Hz,

where the indicated uncertainty is the r.m.s. uncertainty in one series of measurements.

The r.m.s. deviation of the mean values between series for the PTB measurements (six series) and for the VNIIFTRI measurements (two series) were 5 Hz and 3 Hz respectively.

VNIIFTRI Absolute frequency measurements of He-Ne/CH_4 at λ = 3,39 μm of the methane radiation of the $F_2^{(2)}$ transition using a portable laser with optogalvanic signal stabilization, denoted M 101, from 1985 until 1992 (seven different determinations) give the following result:

f = (88 376 181 601,77 ± 0,52) kHz.

Proposed values based on measurements using the VNIIFTRI frequency chain are:
central component frequency (LPI and PTB)
f = (88 376 181 600,04 ± 0,45) kHz,
unresolved transition (BIPM, VNIIFTRI, NRLM)
f = (88 378 181 600,0 ± 6,6) kHz.
The two last given uncertainties are three times the standard uncertainty. All measurements cover 1985-1992.

NIM No answer.

NIST No.

NPL No.

NRLM Measurements of the radiation from a He-Ne/CH_4 laser at λ = 3,39 µm give:
f = (88 376 181,73 ± 0,20) MHz.

PTB Absolute frequency measurements of the central hfs component of the ν_3 transition, P(7) component $F_2^{(2)}$, of CH_4 at λ = 3,39 µm have been made using linear Ramsey excitation in a molecular beam.
The measured value is:
f = (88 376 181 600,16 ± 0,20) kHz.
(Document CCDM/92-14*d*).

CSMU No.

CSIR No.

OFMET No.

DSIR No.

INM 1. In September 1986, at the LPTF (Paris), measurements of radiation from He-Ne/CH_4 lasers at λ = 3,39 µm;
Laser M101 (VNIIFTRI, Russian Federation):
f = (88 376 181 601,94 ± 0,15) kHz,
Laser B.3 (BIPM):
f_c = (88 376 181 597,52 ± 0,64) kHz,
$f_{t\,(B.3)} - f_{c\,(B.3)}$ = (3,23 ± 0,61) kHz,
(Document CCDM/92-19*e*).

The indices c and t denote, respectively, that the servo-control system was placed at the frequency-cell (c) or frequency-tube (t) end of the laser.

2. In 1983, at the LPTF (Villetaneuse), measurements of radiation from a CO_2/OsO_4 laser at λ = 10 µm:
   f_{CO_2} R(10)/OsO_4 = (29 054 057 446,66 ± 0,05) kHz,
   (Document CCDM/92-19*c*).

3. In 1986, at the LPTF (Paris), measurements of radiation from a CO_2/OsO_4 laser at λ = 10 µm:
   f_{CO_2} R(12)/OsO_4 = (29 096 274 952,34 ± 0,07) kHz,
   (Document CCDM/92-19*e*).

4. In 1989, measurements of radiation from a CO_2/OsO_4 laser at λ = 10 µm:
   f_{CO_2} R(10)/OsO_4 = (29 054 072 700,965 ± 0,050) kHz.

5. In 1991, measurements of radiation from a CO_2/OsO_4 laser at λ = 10 µm:
   f_{CO_2} R(26)/OsO_4 = (29 370 814 078,41 ± 0,08) kHz,
   (Document CCDM/92-19*b*).

6. In 1992, at the LPTF (Paris), measurements of radiation from a He-Ne/$^{127}I_2$ laser at λ = 633 nm: component f of the R(127) 11-5:
   f_f = 473 612 353 586 kHz, with a standard uncertainty of 3,4 kHz,
   as $f_i - f_f$ = 138 892 kHz, with a standard uncertainty of 5 kHz,
   f_i = 473 612 214 694 kHz, with a standard uncertainty of 6 kHz.

BIPM

1. In September 1986 at the LPTF (Paris), measurements of the radiation from a He-Ne/CH_4 laser at λ = 3,39 µm; BIPM laser B.3:
   $f_{t\,(B.3)}$ = 88 376 181 600,75 kHz, with a standard uncertainty of 0,24 kHz,
   (Document CCDM/92-19*c*).

The index t denotes that the servo-control system was placed at the frequency-tube end of the laser.

2. In December 1988 at the NRC (Ottawa), measurements with the BIPM laser VB:
   f_{VB} = 88 376 181 603,17 kHz, with a standard uncertainty of 1,0 kHz,
   (Document CCDM/92-20*i*).

3. In 1992 at the LPTF (Paris), measurements of the radiation from He-Ne/$^{127}I_2$ lasers at λ = 633 nm, component f, R(127) 11-6, of the INM laser, INM12, and of the BIPM laser, BIPM4:

   f_{INM12_f} = 473 612 353 586 kHz, with a standard uncertainty of 3,4 kHz,

   (Document CCDM/92-19*a*);

   $f_{INM12_f} - f_{BIPM4}$ = – 11,4 kHz, with a standard uncertainty of 1,5 kHz,

   f_{BIPM4_f} = 473 612 353 597 kHz, with a standard uncertainty of 3,7 kHz,

   (Document CCDM/92-20*a*).

KRISS None.

IPL Since the beginning of 1981, the Institute of Laser Physics of the Siberian Branch of the Russian Academy of Sciences has made the following absolute measurements of the $F_2^{(2)}$ and E absorption lines of methane at λ = 3,39 μm:

f_{CH_4} ($F_2^{(2)}$) = (88 376 181 603 ± 3) kHz (1981);
f_{CH_4} ($F_2^{(2)}$) = (88 376 181 602,9 ± 1,2) kHz (1983);
f_{CH_4} ($F_2^{(2)}$) = (88 376 181 600,7 ± 0,5) kHz (1987)**;
f_{CH_4} ($F_2^{(2)}$) = (88 376 181 600,47 ± 0,1) kHz (1988)**;
f_{CH_4} ($F_2^{(2)}$) = (88 376 181 600,46 ± 0,1) kHz (1989)**;
f_{CH_4} ($F_2^{(2)}$) = (88 376 181 600,4 ± 0,1) kHz (1991)**;
f_{CH_4} (E) = (88 373 149 031,2 ± 1,2) kHz (1985).

JILA No answer.

1.2 Do you plan to make any absolute measurements of frequency in the visible? If so, please give a sketch of the frequency chain you intend to use.

NRC The NRC seriously plans to measure:
the frequency of the radiation at 474 THz from a He-Ne/I_2 laser,
the frequency of the radiation at 520 THz stabilized on I_2 obtained from frequency doubled He-Ne,
the 445 THz clock transition of the Sr^+ ion (available within 1 year).
The frequency chain is sketched in Document CCDM/92-4*a*.

** Absolute frequency of the (7-6) transition of the magnetic hyperfine structure of $F_2^{(2)}$ P(7)ν3 methane line. Measurements were made with the resolved magnetic hyperfine structure of $F_2^{(2)}$ absorption line of methane.

CSIRO No activity in this field.

IMGC Not presently.

VNIIM No answer.

LPI No activity is planned in the visible spectrum, but the transportable He-Ne/CH_4 hfs resolved laser system could substitute the low-frequency part in radio-optical chains without loss of accuracy (reproducibility of 3 parts in 10^{13}, approximately the same as for Cs standards).
The frequency chain is sketched in Document CCDM/92-8*a*.

VNIIFTRI No answer.

NIM No answer.

NIST The NIST is interested in measuring the transition laser frequency of a Hg ion (532 375,92 GHz) that is being developed as frequency/length standard.

NPL Yes. Target wavelengths at present are 674 nm (narrow linewidth transition in cold Sr^+ ions), 411 nm, and 467 nm (narrow transitions in cold Yb^+ ions).

NRLM The NRLM plans to make absolute frequency measurements of a Ca-stabilized dye laser. Absolute frequency measurement in the 1,5 μm region has been chosen as useful reference point.

PTB Absolute frequency measurement of the transition frequency of the intercombination line $^3P_1$-$^1S_0$ of ^{40}Ca at λ = 657 nm is in preparation, starting from the CO_2 laser frequency.
(Document CCDM/92-14*g*).

CSMU No.

CSIR No.

OFMET No.

DSIR No.

INM A sketch of the frequency chain of the LPTF is given in Document CCDM/92-19*a*.

BIPM No answer.

KRISS No.

IPL In 1993-1994 we plan further absolute frequency measurements of the transition (7-6) $F_2^{(2)}$ P(7) ν_3 in methane with higher accuracy.

JILA No answer.

2. Measurements of frequency ratios

2.1 Have you made measurements of the frequency ratios between radiations listed in the *mise en pratique* of the definition of the metre or between any others? If so, please list the values obtained with their uncertainties.

NRC No, not since 1973.

CSIRO No activity in this field.

IMGC The IMGC has made four series of measurements on frequency ratios:

1. CO_2 lasers at 10,6 μm and He-Ne lasers at 3,39 μm:
   $f_{CO_2R(32)}$ = (29 477 160 862 ± 12) kHz.
   (Document CCDM/92-6*e*);
2. He-Ne lasers at 612 nm, 640 nm and 633 nm (IMGC and BIPM, Nov. 1985). Results are listed in Document CCDM/92-6*a*;
3. RuO_4 and CO_2 transitions;
4. $^{188}OsO_4$ and CO_2 transitions.
   (Documents CCDM/92-6*f*, *h* and *i*).

VNIIM The VNIIM has measured frequency ratios between the radiations of He-Ne lasers at 3,39 μm and 633 nm; and 633 nm and 612 nm.
The results are listed in Document CCDM/92-7*a*.
[Vitushkin L. F., Zakharenko Yu. G., Korotkov V. I., Leibengardt G. I., Mel'nikov N. A., Shur V. L., Measurement of the Emission Wavelength of He-Ne/I_2 Laser of the State Primary Length-unit Standard (in Russian), *Optika i Spektroskopia*, 1988, **65**, 1186-1188, translated into English in *Optics and Spectroscopy*, 1988, **65**, 699-700].
[Vitushkin L. F., Zakharenko Yu. G., Ivanov I. V., Leibengardt G. I., Shur V. L., Measurement of the

Wavelength of Highly Stable He-Ne/I_2 Laser at 612 nm (in Russian), *Optika i Spektroskopia*, 1990, **68**, 705-707, translated into English in *Optics and Spectroscopy*, 1990, **68**, 412-413].

LPI No answer.

VNIIFTRI No answer.

NIM The NIM has measured frequency ratios between stabilized He-Ne lasers at 3,39 μm and 633 nm. Obtained frequency ratios R(i) and R(f) between the i and the f components of the R(127) 11-5 transition in the B-X system of $^{127}I_2$ and the $F_2^{(2)}$ component of the ν_3 P(7) transition in CH_4 are:

$R_{(i)}$ = 5,359 048 177, with an uncertainty of 2,3 parts in 10^9,

$R_{(f)}$ = 5,359 049 762, with an uncertainty of 2,3 parts in 10^9,

(Document CCDM/92-10-1*j*).

NIST No answer.

NPL The NPL has measured five series of frequency ratios:

1. He-Ne/$^{127}I_2$ laser at λ = 543 nm (components b_{10} and b_{15} of R(106) 28-0) and He-Ne/$^{127}I_2$ laser at λ = 633 nm (component i of R(127) 11-5):

   $f_{b_{10}}$ (0 °C)/f_i = 1,164 624 021 92,

   $f_{b_{15}}$ (0 °C)/f_i = 1,164 624 628 62.

   The relative standard uncertainty of each ratio is 1,2 parts in 10^{10} (Document CCDM/92-12*a*);

2. Dye-laser/$^{127}I_2$ at λ = 576 nm (component o of P(62) 17-1). The result differs by only 3 parts in 10^{11} from that given in the *mise en pratique*;

3. He-Ne/$^{127}I_2$ at λ = 640 nm (component g of P(1) 8-5):

   f_g/f_i = 0,988 611 184 191.

   The relative uncertainty of the ratio is 1 part in 10^{10};

4. Rb-stabilized laser diode at λ = 780 nm and λ = 795 nm;

5. Hyperfine components of molecular tellurium (Te_2) near 486 nm.

(Documents CCDM/92-12*c*, *d*, *e*, *f* and *g*).

NRLM Frequency ratios measured give a value for the absorption line in Ca of:

f = (455 986 240,28 ± 0,46) MHz.

Frequency ratios measured between a 1,52 μm Lamb-dip stabilized He-Ne laser and a 633 nm iodine-stabilized He-Ne laser give frequencies for ^{20}Ne and ^{22}Ne.

[SASADA H., KUBOTA O., Frequency of Lamb-Dip-Stabilized 1.52 μm He-Ne Lasers, *Appl. Phys.*, 1992, **B55**, 186-188].

PTB Four series of frequency ratios have been measured using an iodine stabilized He-Ne laser at λ = 633 nm and an iodine stabilized Ar^+ laser at λ = 515 nm as reference lasers. The following results with their relative standard uncertainties are listed in Document CCDM/92-14*a*.

1. For the dye laser/ ^{40}Ca at λ = 657 nm (line $^3P_1 - {}^1S_0$):
   $\lambda_{657}/\lambda_{633,\mathrm{i}}$ = 1,038 654 618 63 (1 ± 7 × 10^{-11}),
   $\lambda_{515\mathrm{a}_3}/\lambda_{657}$ = 0,782 821 624 59 (1 ± 5 × 10^{-11}),
   $\lambda_{515\mathrm{a}_3}/\lambda_{633,\mathrm{i}}$ = 0,813 081 295 94 (1 ± 7 × 10^{-11}).

2. For the He-Ne/$^{127}I_2$ at λ = 543 nm (component a_9 of R(12) 26-0):
   $\lambda_{543\mathrm{a}_9}/\lambda_{633,\mathrm{i}}$ = 0,858 647 265 30 (1 ± 8 × 10^{-11}),
   $\lambda_{543\mathrm{a}_9}/\lambda_{515\mathrm{a}_3}$ = 1,056 041 099 06 (1 ± 6 × 10^{-11}).

3. For the He-Ne/$^{127}I_2$ at λ = 640 nm (component a_9 of P(10) 8-5):
   $\lambda_{515\mathrm{a}_3}/\lambda_{640\mathrm{a}_9}$ = 0,803 821 262 49 (1 ± 11 × 10^{-11}),
   $\lambda_{633\mathrm{i}}/\lambda_{640\mathrm{a}_9}$ = 0,988 611 183 86 (1 ± 12 × 10^{-11}).

4. For the He-Ne/$^{127}I_2$ at λ = 612 nm (component b_{15} of P(48) 11-3):
   $\lambda_{515\mathrm{a}_3}/\lambda_{612\mathrm{b}_{15}}$ = 0,841 009 609 10 (1 ± 7 × 10^{-11}),
   $\lambda_{612\mathrm{b}_{15}}/\lambda_{633,\mathrm{i}}$ = 0,966 791 921 43 (1 ± 8 × 10^{-11}),
   $\lambda_{515\mathrm{a}_3}/\lambda_{633,\mathrm{i}}$ = 0,813 081 295 92 (1 ± 8 × 10^{-11}).

The relative uncertainties of the measured wavelength ratios were in the range of several parts in 10^{11}: they almost approach the frequency reproducibility of the I_2-stabilized He-Ne laser operating at λ = 633 nm, which is more than an order of magnitude better than the uncertainty of its recommended wavelength value. A precise frequency measurement of any of the six frequencies involved would thereby also improve the uncertainty of all other frequencies.

CSMU No.

CSIR No.

OFMET No.

DSIR No.

INM Measurements at the INM give:
for a He-Ne/$^{127}I_2$ laser at λ = 612 nm:
f_{a_7} = (489 880 354 939 ± 88) kHz;
for a He-Ne/$^{127}I_2$ laser at λ = 543 nm, the results are listed in Document CCDM/92-19*a*, *h*, and *i*.

BIPM The BIPM has made three series of measurements:
1. He-Ne lasers at 612 nm, 633 nm and 515 nm at the PTB;
2. He-Ne lasers at 612 nm, 640 nm and 633 nm with the IMGC;
3. He-Ne/$^{127}I_2$ lasers at λ = 543 nm (component a_{13} of R(12) 26-0):
   $\lambda_{a_{13}}$ = 543 516 085 fm, with a standard uncertainty of 4 fm.

All the results are listed in Document CCDM/92-20*a*.

KRISS None.

IPL No answer.

JILA We are in the middle of frequency synthesis experiments based on the Hänsch ‘Divide and Conquer’ strategy. We use a stable Nd laser (λ = 1,064 µm) and its doubled frequency, stabilized on an iodine line, and sum these frequencies in a crystal of LiO_3. The frequency of the sum is close to double the frequency of a sapphire/titanium laser (λ = 709 nm) for which the LiO_3 output serves as reference. The plan is to control the frequency of a diode laser (λ = 851 nm) to the median of the frequencies of the λ = 1,064 µm and λ = 709 nm radiations. The three wavelengths thus controlled are in simple ratios and should reveal possible systematic errors in measurements for wavelengths (lambdameter).

2.2 Do you plan to make any measurements of frequency ratios? If so, please give brief details of the instrument you expect to use and the uncertainties you hope to achieve.

NRC No frequency ratio measurements are planned.

CSIRO No activity in this field.

IMGC Not presently.

VNIIM We plan to make measurements of frequency ratios 633 nm and 3,39 μm; 633 nm and 543 nm; 633 nm and 640 nm. Our interferometric installations will use Fabry-Perot interferometers, of lengths up to 1800 mm, and heterodyning techniques. We hope to achieve uncertainties of about 2 parts in 10^{10} (IR/visible) and 8 parts in 10^{11} (visible/visible).

LPI No answer.

VNIIFTRI No answer.

NIM No answer.

NIST No answer.

NPL No answer.

NRLM We plan to make measurements of frequency ratios as described in 2.1.

PTB No answer.

CSMU No answer.

CSIR No.

OFMET No.

DSIR Yes; instrument details not yet known.

INM No answer.

BIPM We plan to measure more precisely the wavelengths of some components of the He-Ne laser at λ = 543 nm.

KRISS None.

IPL No answer.

JILA No answer.

3. *Mise en pratique* of the definition of the metre

3.1 Do you have proposals for changing any of the values of frequency, wavelength or uncertainty given in the *mise en pratique* of the definition of the metre? If so, please give an outline of your proposals.

NRC The recommended value for the $F_2^{(2)}$ component, ν_3 transition, P(7) band of the CH_4 molecule and its standard deviation should be changed. The BIPM recommended value 88 376 181 608 kHz is about 7 kHz higher than averaged measurements. The recommended wavelength should be adjusted accordingly. New values obtained at the NRC, and some of the values obtained in other laboratories are given in Document CCDM/92-4*a* (Appendix A).
A change of the BIPM recommended value for the 474 THz frequency, which at the moment is based upon knowledge of the 88 THz frequency, is probably not justified due to the small gain in uncertainty.

CSIRO No proposals.

IMGC The recommendation for the radiation at 612 nm is at present based upon the a_7 component of the $^{127}I_2$ transition R(47)9-2. Two different transitions are used at the IMGC as frequency references:
P(48) 11-3, reproducibility better than 10 kHz;
R(34) 17-6, component e_{15}.
(Documents CCDM/92-6*k* and *c*).

VNIIM The estimated relative uncertainty for radiations of laser stabilized by saturated absorption in iodine vapour (component i of the transition R(127) 11-5) may be reduced to at least ± 3 parts in 10^{10} by applying the conditions in 1.3 (Recommendation 1 (CI-1983)).

LPI No answer.

VNIIFTRI No answer.

NIM No answer.

NIST No answer.

NPL *See* enclosed note by Dr B. W. Petley (Document CCDM/92-12*b*).

NRLM We do not have our own proposal.

PTB The frequency of the He-Ne/CH_4 stabilized laser (88 THz) has been measured by several groups with and without the hfs resolved.
We propose to adjust this value to the recent measurements and to decrease the quoted uncertainty. For simple laser setups it may be advisable to specify operational conditions together with wavelength values and larger uncertainties.

CSMU We have no proposals.

CSIR No.

OFMET No.

DSIR No.

INM The INM proposes a new value for the frequency of the He-Ne/$^{127}I_2$ stabilized laser at λ = 633 nm (component f of the transition R(127) 11-5) (Document CCDM/92-19*a*).

BIPM The BIPM proposes an adjustment of the frequency values of the He-Ne/CH_4 stabilized laser at λ = 3,39 μm close to:
f = 88 376 181 600 kHz,
and of the He-Ne/$^{127}I_2$ stabilized laser at λ = 633 nm close to:
f_f = 473 612 353 597 kHz, with a standard uncertainty of 11 kHz,
or f_i = 473 612 214 705 kHz, with a standard uncertainty of 11 kHz.
See Document CCDM/92-20*a* for the BIPM proposals concerning the frequency intervals between the components (Tables 5 to 14).

KRISS None.

IPL No answer.

JILA No answer.

3.2 Do you have proposals for additional radiations to be included in the *mise en pratique*? If so, please give a brief summary of why you think these new radiations would be useful.

NRC We have no proposals for additional radiations to be included in the *mise en pratique*.

CSIRO Diode lasers at 780 nm, 795 nm and 850 nm are used for the calibration of gauge blocks and length bars. At present we rely on published wavelengths for lasers stabilized on Rb, H_2O or Cs. These and other diode sources would benefit from direct frequency measurements if these were available.

IMGC Additional radiation in the visible may be useful in order to extend the choice between laser sources and allow the use of the most convenient wavelength for a particular application. In recent years two radiations have been studied:
^{3}He-^{22}Ne/$^{127}I_2$ lasers at λ = 640 nm, transition P(10) 8-5,
He-Ne/$^{127}I_2$ lasers at λ = 543 nm, transitions R(12) 26-0 and R(106) 28-0.

VNIIM No answer.

LPI No answer.

VNIIFTRI No answer.

NIM We suggest that the $^{127}I_2$ stabilized 640 nm ^{3}He-^{22}Ne laser may be used as the radiation realizing the definition of the metre. The a_9 component of the P(10) 8-5 transition of $^{127}I_2$ has been selected as a suitable reference frequency because it is well isolated from other disturbing lines.

NIST No answer.

NPL The radiation studied at the NPL and considered most appropriate for inclusion in the list of recommended radiations is that at 543 nm (551 THz) He-Ne/I_2. It is convenient, and is routinely used for the calibration of the two-mode-intensity-stabilized lasers, which in turn are used for measuring the lengths of gauge blocks.
Radiation at 640 nm from He-Ne/I_2 is also potentially suitable for inclusion as a standard.
The rubidium lines (780 nm, 795 nm) also have potential, but the need for their adoption is not clear.

NRLM We propose to add the Ca stabilized dye laser as a new radiation. Preliminary measurements show a frequency stability of 2 parts in 10^{13} (100 s), and a reproducibility of 6 parts in 10^{12}. Improvements are expected.
(Documents CCDM/92-13*e*, *f* and *g*).

PTB The PTB proposes as additional radiations to be included in the *mise en pratique* the radiations of a Ca-stabilized laser at λ = 657 nm, and two I_2-stabilized He-Ne lasers of λ = 543 nm and λ = 640 nm. The wavelengths of these radiations have been measured at the PTB (Document CCDM/92-14*a*).

CSMU Jointly with the NIM (Beijing) we propose to extend the list of recommended radiations by adding the P(10) 8-5 transition of $^{127}I_2$. Experimental results show that this transition is very useful for the stabilization of He-^{22}Ne lasers at a wavelength of 640 nm.

CSIR No.

OFMET The OFMET proposes He-Ne/I_2 radiation at λ = 543 nm, using the R(12) 26-0 and R(106) 28-0 transitions. The green He-Ne laser line is being used more frequently in metrology, in particular in two-wavelength interferometry.

DSIR No.

INM The INM proposes the transition P(33) 6-3 of $^{127}I_2$ at λ = 633 nm.

BIPM The BIPM proposes the inclusion of radiations from He-Ne/$^{127}I_2$ stabilized lasers at λ = 543 nm and CO_2/OsO_4 stabilized lasers at λ = 10,6 µm.

KRISS None.

IPL No answer.

JILA We believe that the green region around 534 nm offers a useful additional optical frequency reference with desirable properties: the diode-pumped Nd lasers can be very simple and stable, and the green second harmonic is readily obtained with powers up to some milliwatts.

3.3 Do you have any proposals for changes in the operating conditions for lasers specified in the *mise en pratique* for high-accuracy realization of the definition of the metre? Do these proposals include additional parameters that should be specified?

NRC We have no proposals for changes in the operating conditions for lasers.

CSIRO No proposals.

IMGC For the lasers at 633 nm the present recommended operating conditions are adequate to ensure an uncertainty of 3,4 parts in 10^{10}, but not to assure a reproducibility of 20 kHz.

VNIIM No answer.

LPI No answer.

VNIIFTRI No answer.

NIM We suggest that the CCDM recommend a final design which corresponds with that of the iodine-stabilized He-Ne lasers in current use at the national institutes.

NIST No answer.

NPL Results have shown that the power shift of iodine-stabilized 633 nm lasers depends upon parameters not specified in the *mise en pratique*. The relevant factors do not yet seem to be sufficiently understood to be included in the specification. Better agreement between laboratories is obtained at beam powers lower than those currently specified.
We propose that the one-way intracavity beam power specification be amended from 20 mW ± 5 mW to 7 mW ± 3 mW.

NRLM The NRLM supports a proposal to modify the conditions specified for operation of the absorption cell in the iodine-stabilized He-Ne laser at λ = 633 nm.

PTB No answer.

CSMU No.

CSIR No.

OFMET No.

DSIR No.

INM No answer.

BIPM The BIPM has six proposals.
For the He-Ne/CH_4 at λ = 3,39 μm, it proposes that:
1. the photodetector be placed in front of the tube end of the resonator;
2. the capillary diameter of the laser tube should be greater than 5 times that of the beam (2 w);
3. intracavity laser losses be minimized;

For the He-Ne/$^{127}I_2$ laser at λ = 633 nm, it proposes that:
4. the one way intracavity power be (7 ± 3) mW (also proposed by the NPL);
5. the frequency modulation be (6 ± 0,2) MHz, peak to peak;
6. the cold finger temperature of the iodine cell be (15 ± 0,1) °C.

KRISS The DC offset voltage of the phase sensitive detector in the servo control should be specified.

IPL No answer.

JILA No answer.

3.4 Which of the recommended radiations and frequencies of the *mise en pratique* do you maintain in your laboratory for the realization of the definition of the metre and what are your estimated uncertainties in the realization?

NRC Recommended radiations maintained at the NRC and their relative uncertainties equivalent to three times the standard deviation:
1. Lasers:
λ = 3,39 μm (88,4 THz); $\pm 3,6 \times 10^{-12}$;
λ = 633 nm (474 THz); $\pm 1,0 \times 10^{-9}$;
λ = 576 nm (520 THz); $\pm 1,0 \times 10^{-9}$;

2. Spectral lamps:
^{86}Kr; $\pm 1,4 \times 10^{-8}$;
^{198}Hg; $\pm 3,0 \times 10^{-8}$;
^{114}Cd; $\pm 6,0 \times 10^{-8}$.

CSIRO Recommended radiations maintained at CSIRO are:
λ = 633 nm (474 THz), with an uncertainty of 1 part in 10^{10};
λ = 612 nm (490 THz);
spectral radiations: ^{86}Kr, ^{198}Hg, ^{114}Cd, to CIPM specifications.

IMGC Recommended (and other) radiations maintained are:

1. Ever-ready radiations:
   λ = 633 nm (474 THz), with an estimated relative standard uncertainty of 3,4 parts in 10^{10};
   λ = 612 nm (490 THz)/$^{127}I_2$ P(48) 11-3, with an estimated uncertainty of 3,7 parts in 10^{10};

2. One day to one week ready radiations:
   λ = 3,39 μm (88 THz), with an estimated overall relative uncertainty of 1,3 parts in 10^{10};
   λ = 640 nm (467 THz)/$^{127}I_2$ P(10) 8-5, with an estimated relative standard uncertainty of 5,7 parts in 10^{10};
   λ = 612 nm (490 THz)/$^{127}I_2$ R(34) 17-6 or R(47) 9-2, with an estimated relative standard uncertainty of 3,7 parts in 10^{10};
   λ = 605 nm (494 THz)/$^{127}I_2$ P(62) 11-2;
   CO_2 lasers, stabilized on CO_2, with an estimated overall relative uncertainty of 1 part in 10^9;
   CO_2 lasers stabilized on OsO_4, with an estimated overall relative uncertainty of 1 part in 10^{10};

3. Radiations whose development is in progress:
   He-Ne 543 nm — FM spectroscopy;
   He-Ne 514 nm — FM spectroscopy;
   laser diode 1,5 μm — FM spectroscopy;
   CO_2 laser — thermal molecular beam OsO_4.

VNIIM Radiations maintained at the VNIIM are:
λ = 633 nm (474 THz), with an overall relative uncertainty of 3 parts in 10^{10};
λ = 612 nm (490 THz), with an overall relative uncertainty of 3,5 parts in 10^{10};
λ = 640 nm.

LPI No answer.

VNIIFTRI No answer.

NIM Radiations maintained at the NIM are:
λ = 3,39 μm (88 THz), with an overall relative uncertainty of 1,3 parts in 10^{10};
λ = 633 nm (474 THz), with an overall relative uncertainty of 1 part in 10^9;

λ = 612 nm (490 THz), with an overall relative uncertainty of 1,1 parts in 10^9;
λ = 515 nm (582 THz), with an overall relative uncertainty of 1,3 parts in 10^9;
λ = 576 nm under research;
λ = 640 nm (467 THz), with a relative standard uncertainty of 3,6 parts in 10^{10}.

NIST — The NIST maintains the recommended frequency reference at λ = 633 nm (474 THz) with a relative standard uncertainty of 3,4 parts in 10^{10}.

NPL — Recommended radiation maintained at the NPL is:
λ = 633 nm (474 THz), with a reproducibility within a standard deviation of 5 kHz (1 part in 10^{11}).
There is a capability to realize 612 nm (490 THz), 576 nm (519 THz) and 515 nm (582 THz), although they are not in regular use.

NRLM — Recommended radiations maintained at the NRLM are:
λ = 633 nm (474 THz);
λ = 612 nm (490 THz);
λ = 3,39 μm (88 THz).

PTB — Recommended radiations maintained at the PTB are:
λ = 633 nm (474 THz);
λ = 612 nm (490 THz);
λ = 3,39 μm (88 THz);
λ = 515 nm (582 THz);
λ = 543 nm (552 THz);
λ = 657 nm (456 THz).

CSMU — The recommended radiation at λ = 633 nm (474 THz) is maintained at the CSMU. For the uncertainties, *see* Document CCDM/92-15*a*.

CSIR — The recommended radiation at λ = 633 nm (474 THz) is maintained at the CSIR. The relative standard uncertainty is better than 5 parts in 10^{11} following recent comparisons with the BIPM.

OFMET — The recommended radiation at λ = 633 nm (474 THz) is maintained at the OFMET. The mean frequency difference, compared to the BIPM laser, is 2,7 kHz with a standard uncertainty of 1,8 kHz.

DSIR The recommended radiation at λ = 633 nm (474 THz) is maintained at the DSIR. International comparisons show this to be in agreement with all participating lasers to within ± 40 kHz.

INM Recommended radiations maintained at the INM are:
λ = 633 nm (474 THz);
λ = 612 nm (490 THz);
λ = 576 nm (520 THz), dye laser.

BIPM Recommended radiations maintained at the BIPM are:
λ = 3,39 μm (88 THz), with an estimated standard uncertainty of 1 kHz (1 part in 10^{11});
λ = 515 nm (582 THz);
λ = 543 nm (552 THz), with an estimated standard uncertainty of 15 kHz (3 parts in 10^{11});
λ = 633 nm (474 THz), with an estimated standard uncertainty of 10 kHz (2 parts in 10^{11});
λ = 612 nm (490 THz), with an estimated standard uncertainty: internal cell some parts in 10^{10}, external cell less than 5 kHz (< 1 part in 10^{11}).

KRISS The recommended radiation at λ = 633 nm (474 THz) is maintained at the KRISS, with an estimated standard uncertainty of 4,9 kHz (1 part in 10^{11}).

IPL Recommended radiations maintained at the IPL are:
λ = 515 nm (582 THz);
λ = 3,39 μm (88 THz);
λ = 10,6 μm (29 THz).

JILA Recommended radiations maintained at the JILA are:
λ = 633 nm (474 THz);
λ = 612 nm (490 THz);
using internal and external iodine cell systems respectively.

3.5 Have you developed or are you working on new methods that might allow improved frequency reproducibility among the recommended or other radiations for the definition of the metre? If so, please give a brief outline of the method and an estimate of the time scale of the work.

NRC Work is under way to develop frequency and wavelength standards based on single trapped ions:
1. Work on Ba^+ (24 THz) is well advanced, and high accuracy measurements of the ion frequency will be made in the summer of 1992;

2. Work on the Sr^+ ion will have greater significance for length metrology due to its clock frequency in the visible close to 474 THz He-Ne/I_2. This work is not as far advanced. We expect maintain trapped and cooled ions during 1993.

CSIRO No proposals.

IMGC Two new methods are under development at the IMGC:

1. CO_2 laser stabilized using a thermal molecular beam. (Document CCDM/92-6*m*).

2. FM (Frequency-phase Modulation) spectroscopy is widely used at the IMGC.

VNIIM The VNIIM is working on five projects in this field:

1. Iodine stabilized laser at $\lambda = 633$ nm with increased modulation frequency;

2. Development of a portable He-Ne/I_2 laser;

3. Improvement of He-Ne/I_2 lasers at $\lambda = 640$ nm;

4. Development of a He-Ne/I_2 laser at $\lambda = 543$ nm;

5. Study of a new type of super narrow resonance in the spectra of two and three levels systems in a strong laser polyharmonic field and possibilities for their use in frequency stabilization of laser systems.

LPI The LPI is working on four projects in this field:

1. We have developed a double-mode method of sub-Doppler spectroscopy which allows one to register narrow resonances of saturated dispersion with improved signal to noise ratio and to reduce the influence of systematic offsets characteristic of sub-Doppler spectroscopy (like the gas-lens effect for example);

2. On the basis of the method described above, stabilized 88 THz methane He-Ne lasers have been created. The relative frequency reproducibility of the transportable double-mode He-Ne/CH_4 lasers is estimated as 3 parts in 10^{13};

3. During 1992-1994 comparisons and investigations of these double-mode lasers will be made. We hope to obtain a relative frequency reproducibility of about 3 parts in 10^{14};

4. Work on methane stabilized colour-centre lasers can increase the accuracy to 1 part in 10^{15}. Estimated time for this project: 1992-2002.

VNIIFTRI No answer.

NIM No answer.

NIST The NIST/Boulder is working on several potential new frequency/length standards with greater accuracy than present standards: Hg ion, 657 nm Ca, Sr and Cs transitions are also under consideration. This work has a time scale of one to five years with the goal of improving portable and high-accuracy laboratory standards.

NPL Research and development into new optical frequency standards based upon cooled single ions in radio-frequency traps.

NRLM We have a plan to develop a frequency-stabilized dye laser by using an absorption line of trapped and cooled Ca atoms.

PTB No answer.

CSMU The CSMU has developed iodine stabilized He-Ne lasers using a fifth-harmonic locking technique. It has obtained a relative standard uncertainty of 1 part in 10^{11}. The CSMU recommends more effort on experimental work to develop fifth harmonic locking techniques, and to realize international comparisons of such lasers.
It has developed a new technique for measurement of modulation depth of frequency modulated lasers. The use of this method simplifies the measuring process and omits the use of expensive broadband spectral analyzers.
[Ziegler M., Balling P., Smydke J., Blabla J., *CPEM'92* (short communication)].
[Balling P., Ziegler M., *Report CSMU-KM*-24/92 (in English)].

CSIR No.

OFMET No.

DSIR No.

INM No answer.

BIPM We have begun studies on external CH_4 cells in a Fabry-Perot interferometer at λ = 3,39 μm and on the stabilization of a 515 nm Ar^+ laser using the FM sideband technique.

KRISS None.

IPL We are developing new methods for obtaining ultra-narrow optical resonances with absolute frequencies of 1 Hz to 10 Hz with a view to creating a new generation of laser time and frequency standards with long-term relative frequency stability and reproducibility at the level of 10^{-16}-10^{-17} for stationary systems and at the level of 10^{-15}-10^{-16} for transportable standards.

JILA In collaboration with the BIPM and the East China Normal University, we are developing an attractive system at λ = 612 nm which uses absorbing cells in an external ring resonator.

4. International comparisons of laser frequencies

4.1 Please list the comparisons of laser frequencies in which you have participated giving

a) the frequencies and wavelengths,

b) the participating laboratories,

c) the results or a reference to the publication containing the results.

NRC The NRC has taken part in three comparisons:

1. λ = 633 nm (474 THz), d, e, f, g, h, i, j components; NRC (Canada), NML/CSIRO (Australia), March 1984:
   $f_{NRC} - f_{NML} = -38{,}1$ kHz (8 parts in 10^{11}).
   (Document CCDM/92-18*b*);

2. λ = 3,39 μm (88 THz), $F_2^{(2)}$ component, ν_3 transition, P(7) band; between the NRC (Canada) and the VNIIFTRI (ex-USSR), Nov.-Dec. 1988.

Results obtained for the portable M 101 laser:
$f = (88\,376\,181\,601{,}48 \pm 0{,}1)$ kHz; VNIIFTRI frequency chain,
$f = (88\,376\,181\,601{,}29 \pm 0{,}1)$ kHz; NRC frequency chain,
$f = (88\,376\,181\,601{,}46 \pm 0{,}1)$ kHz; VNIIFTRI frequency chain;

3. λ = 3,39 µm (88 THz), $F_2^{(2)}$ component, ν_3 transition, P(7) band; between the NRC (Canada), the VNIIFTRI (ex-USSR), and the BIPM, Dec. 1988.

Results obtained for the BIPM VB laser with 200 kHz modulation width:

f = (88 376 181 603,98 ± 0,2) kHz against M101 laser; VNIIFTRI chain,

f = (88 376 181 603,29 ± 1,0) kHz against NRC CsV clock; NRC frequency chain.

CSIRO — The CSIRO has taken part in four comparisons:

1. λ = 633 nm (474 THz) d, e, f, g, h, i, j components; CSIRO (Australia), PEL (New Zealand), May 1984. (Document CCDM/92-18*b*);

2. λ = 633 nm (474 THz); between the CSIRO (Australia) and the NPL (United Kingdom). Checking of iodine cell by the Hanle effect, June 1985: no contamination;

3. λ = 633 nm (474 THz) d, e, f, g components; between the CSIRO (Australia) and the NRLM (Japan), Dec. 1989:
   $f_{\text{NRLM (NN-6)}} - f_{\text{CSIRO}}$ = 3,2 kHz, with a standard uncertainty of 2,1 kHz;

4. λ = 633 nm (474 THz) d, e, f, g components; between the CSIRO (Australia) and the BIPM, 1991. Checking of iodine cell:
   $f_{\text{CSIRO-1}} - f_{\text{BIPM}}$ = 1,6 kHz, with a standard uncertainty of 2,7 kHz.

IMGC — The IMGC took part in a comparison with the LMM (Spain) in June 1991 using λ = 633 nm (474 THz), d, e, f, g, h components:

a_{15}: $f_{\text{LMM}} - f_{\text{IMGC}}$ = (– 0,31 ± 1,74) kHz;
a_{16}: $f_{\text{LMM}} - f_{\text{IMGC}}$ = (– 0,40 ± 0,44) kHz;
a_{17}: $f_{\text{LMM}} - f_{\text{IMGC}}$ = (– 3,30 ± 1,39) kHz;
a_{18}: $f_{\text{LMM}} - f_{\text{IMGC}}$ = (– 14,68 ± 1,77) kHz.

VNIIM — The VNIIM has taken part in two comparisons:

1. λ = 633 nm (474 THz); in Bratislava, Sept. 1988:
   $f_{\text{VNIIM (L1)}} - f_{\text{BIPM4}}$ = (8,8 ± 12) kHz
   [*Metrologia*, 1991, **28**, 19-25];

2. λ = 633 nm (474 THz); in Helsinki, Jan. 1991:
   $f_{\text{VNIIM (L1)}} - f_{\text{TTK}}$ = (2,8 ± 3,4) kHz.

LPI — No answer.

VNIIFTRI No answer.

NIM The NIM took part in four comparisons:

1. λ = 633 nm (474 THz) d, e, f, g components; international comparison, Apr. 1984.
(Document CCDM/92-18*b*);

2. λ = 633 nm (474 THz) d, e, f, g, h components; between the NIM (PRC) and the PTB (FRG), July 1988:
$f_{NIM(1)} - f_{PTB}$ = (1,77 ± 1,07) kHz,
$f_{NIM(2)} - f_{PTB}$ = (– 4,97 ± 1,17) kHz;

3. λ = 612 nm (490 THz) k, l, m, n, o, p, q, r, s components; between the NIM (PRC) and the PTB (FRG), May 1990: the standard deviation for 25 groups of 10 s measurements was better than 4,2 parts in 10^{12} (Document CCDM/92-10*a*);

4. International comparison of $^{127}I_2$ absorption cell organized by the BIPM.

NIST The NIST took part in an international comparison at λ = 633 nm (474 THz).
(Document CCDM/92-18*b*).

NPL The NPL took part in an international comparison at λ = 633 nm (474 THz).
(Document CCDM/92-18*b*).

NRLM The NRLM took part in five comparisons:

1. International comparison of $^{127}I_2$ absorption cells organized by the BIPM, 1990;

2. λ = 633 nm (474 THz); between the NRLM (Japan) and the BIPM, 1988:
$f_{NRLM} - f_{BIPM}$ = (0,9 ± 2,6) kHz;

3. λ = 633 nm (474 THz); between the NRLM (Japan) and the CSIRO (Australia), 1986:
$f_{NRLM} - f_{CSIRO}$ = (3,16 ± 2,1) kHz.
(Document CCDM/92-18*b*);

4. λ = 3,39 µm (88 THz); between the NRLM (Japan) and the BIPM, 1988:
$f_{NRLM} - f_{BIPM}$ = (– 4,21 ± 0,23) kHz;

5. λ = 3,39 µm (88 THz); between the NRLM (Japan) and the VNIIFTRI (ex-USSR), 1988:
$f_{NRLM} - f_{VNIIFTRI}$ = (– 4,93 ± 0,14) kHz.

PTB The PTB has taken part in six comparisons:

1. λ = 633 nm (474 THz); PTB (FRG) participating with PEL (New Zealand), NML/CSIRO (Australia), NPLI (India), NRC (Canada), NBS (USA), NIM (PRC), NPL (United Kingdom), NRLM (Japan) and KSRI (Rep. of Korea). International comparison, 1984.
(Document CCDM/92-18*b*);

2. λ = 633 nm (474 THz); between the PTB (FRG) and the UPT (CSSR), 1987.
(Document CCDM/92-14*r*);

3. λ = 633 nm (474 THz); ASMW (DRG) participating with the BIPM, CSMU (CSSR), CSAV (CSSR), OMH (Hungary), VNIIM (ex-USSR), 1988.
(Document CCDM/92-20*q*);

4. λ = 633 nm (474 THz); PTB (FRG) participating with the BIPM, SP (Sweden), DFM (Denmark), MRI (Finland), University of Helsinki (Finland) and Århus University (Denmark), 1990:
$f_{\mathrm{PTB}} - f_{\mathrm{BIPM}} < 10$ kHz.
(Document CCDM/92-20*y*);

5. λ = 3,39 µm (88 THz); between the PTB (FRG), the BIPM, and the VNIIFTRI (ex-USSR), May 1989: the results were evaluated by the BIPM;

6. λ = 3,39 µm (88 THz); between the PTB (Germany) and the Russian Academy of Sciences, Nov. 1991:
a) Lebedev Institute of Physics, Moscow;
b) Institute of Laser Physics, Novosibirsk.

The results from *a*) were presented by M. A. Gubin at the CPEM'92. The results from *b*) will be published later.

CSMU The CSMU has taken part in eight comparisons:

1. λ = 633 nm (474 THz); between the CSMU (CSSR) and the ASMW (DRG), June 1983:
$f_{\mathrm{ASMW}} - f_{\mathrm{CSMU}} = (-\,0{,}19 \pm 2{,}17)$ kHz;

2. λ = 633 nm (474 THz); between the CSMU (CSSR) and the VNIIM (ex-USSR), Aug. 1983:
$f_{\mathrm{CSMU}} - f_{\mathrm{VNIIM}} = (43 \pm 5)$ kHz;

3. λ = 633 nm (474 THz); between the CSMU (CSSR) and the VNIIM (ex-USSR), Dec. 1984:
$f_{\mathrm{VNIIM}} - f_{\mathrm{CSMU}} = (38{,}5 \pm 4{,}4)$ kHz;

4. λ = 633 nm (474 THz); international comparison.
(Document CCDM/92-20*q*);

5. λ = 633 nm (474 THz); between the CSMU (CSSR) and the OMH (Hungary), Nov. 1989:
   $f_{CSMU} - f_{OMH}$ = (13,2 ± 2,4) kHz;

Lasers stabilized by other methods:

6. λ = 633 nm (474 THz), frequency comparison of lasers stabilized on the Lamb-dip; between the CSMU (Czechoslovakia) and the INM (Romania), Dec. 1985;

7. λ = 633 nm (474 THz), frequency comparison of lasers stabilized on iodine and on two orthogonal modes; between the CSMU (Czechoslovakia) and the VNIIM (ex-USSR), Dec. 1989;

8. comparison of iodine cells in cooperation with ASMW (ex-DRG), 1989-1990 (Document CCDM/92-15*a*).

CSIR — The CSIR took part, with the BIPM, in a comparison at λ = 633 nm (474 THz).
(Document CCDM/92-20*a*).

OFMET — The OFMET took part, with the BIPM, in a comparison at λ = 633 nm (474 THz), Dec. 1991:
$f_{OFMET} - f_{BIPM}$ = 2,7 kHz, with a standard uncertainty of 1,8 kHz,
(Document CCDM/92-20*a*).

DSIR — The DSIR took part in an international comparison at λ = 633 nm (474 THz), d, e, f, g, h, i, j components.
(Document CCDM/92-18*b*).

INM — *See* Document CCDM/92-20*a*.

BIPM — *See* Figure 1 (page M 199) and Document CCDM/92-20*a*.

KRISS — The KRISS has taken part in two international comparisons:

1. In 1984, at λ = 633 nm (474 THz).
   (Document CCDM/92-18*b*);

2. In 1991, bilateral comparison between the KRISS and the BIPM:
   $f_{KRISS} - f_{BIPM4}$ = 6,7 kHz, with a standard uncertainty of 3,1 kHz, n = 18,
   (Document CCDM/92-20*a*).

IPL — In 1991, the first comparisons of the frequency scales of our institute with those of the PTB were made with the help of our He-Ne/CH_4 (λ = 3,39 μm) transportable laser. Coincidence between the two frequency chains: 200 Hz.

Fig. 1. — Comparisons of He-Ne lasers at $\lambda = 633$ nm in which the BIPM was involved; * and $^{+}$ respectively indicate that:
* the laser was stabilized using the fifth harmonic signal,
$^{+}$ the absolute frequency of laser INM12 was determined at the LPTF (Paris) between the two measurements.

JILA No answer.

4.2 For the future, which radiations and frequencies should be the subject of international comparisons in which you would like to participate?

NRC Iodine-stabilized He-Ne lasers at λ = 633 nm (474 THz), R(127), 11-5, components d, e, f, g, h, i, j.

CSIRO No answer.

IMGC We consider useful the recent comparison between iodine cells. We would like to discuss comparisons with other laboratories but 633 nm and 543 nm are important; in future, attention should be paid to frequency-stabilized laser diodes.

VNIIM The VNIIM would like to participate in comparisons of iodine stabilized He-Ne lasers at λ = 543 nm, 612 nm and 633 nm and in comparisons of iodine cells.

LPI The LPI would like to participate in comparisons of He-Ne/CH_4 lasers. We would like to compare, and also to measure, our frequency with the reference lasers of the most accurate radio-optical frequency chains: PTB (FRG), NRC (Canada) and LPTF (France).

VNIIFTRI No answer.

NIM No answer.

NIST No answer.

NPL The NPL would be interested in a comparison of iodine-stabilized green He-Ne lasers at λ = 543 nm.

NRLM A comparison of CO_2 lasers; this radiation is important for practical use.

PTB An international comparison at λ = 543 nm is planned with the BIPM;
An international comparison of the ^{40}Ca intercombination line $^1S_0$-$^3P_1$ is planned with the NRLM;
An international comparison is planned at λ = 3,39 μm with the Institute of Laser Physics, Novosibirsk.

CSMU The CSMU would like to take part in comparisons of iodine-stabilized He-Ne lasers at λ = 640 nm, 633 nm, 612 nm, 543 nm, and of diode lasers in the visible and IR region.

CSIR We do not anticipate arranging any international comparisons in the near future but we consider taking part in a comparison arranged by another laboratory depending on the circumstances.

OFMET No proposition.

DSIR No answer.

INM We would like to participate in the international comparison at λ = 515 nm, 612 nm, and 543 nm.

BIPM No answer.

KRISS We would like to participate in an international comparison at λ = 612 nm He-Ne/$^{127}I_2$.

IPL No answer.

JILA The Ca intercombination line at 657 nm is very narrow and can be reached with diode laser excitation as shown by Hollberg's work at the NIST (Boulder).

5. Mechanical standards of length

5.1 What types of mechanical length standards does your laboratory calibrate (line-scales, end standards, step gauges, etc.)? What are the uncertainties given?

NRC The NRC laboratories for calibrating mechanical standards of length are currently being renovated and several new instruments await installation.

End standards:
gauges up to 50 mm: ± 50 nm,
gauges over 50 mm: $\pm 1 \times 10^{-6}$ L***;

*** L denotes the length of the standard.

Line standards:
static mode: ± 20 nm,
scanning mode: ± 100 nm;
Survey and engineering tapes:
tapes up to 50 m: ± 5 μm to ± 0,3 μm;
Diameter standards:
50 mm to 150 mm rings: ± 0,5 μm to ± 0,7 μm;
Angle standards:
± 0,1" is typical calibration accuracy for best-quality gauges;
Flatness standards:
optical flats up to 150 mm diameter: ± 25 nm.

Under development are: general dimensional metrology, roundness standards, surface roughness standards and flatness standards.

CSIRO Line standards scales up to 1 m:
scales with lines 2 μm to 5 μm wide:
$0,1\ \mu m + 0,1 \times 10^{-6}\ L$,
scales with lines 100 μm to 200 μm wide:
$0,5\ \mu m + 0,5 \times 10^{-6}\ L$;
Survey tapes up to 60 m:
invar tapes: 1 part in 10^6,
steel tapes: 2,5 parts in 10^6;
Stage micrometers up to 10 mm: 0,2 μm to 0,5 μm;
End standards (by interferometry):
up to 100 mm: 0,032 μm to 0,077 μm,
100 mm to 400 mm: 0,2 μm to 0,6 μm;
End standards (by comparison):
up to 100 mm: 0,08 μm to 0,12 μm,
100 mm to 400 mm: 0,3 μm to 0,7 μm,
400 mm to 1000 mm: 1,2 μm to 2,0 μm;
Step gauges and end standards (by CMM):
$0,2\ \mu m + 1,3 \times 10^{-6}\ L$;
Reference standards for dimensional metrology (ring gauges, spheres, cylindrical standards, etc.) to conventional uncertainties.

IMGC Gauge blocks:
0,1 mm to 100 mm: $0,02\ \mu m + 0,3 \times 10^{-6}\ L$,
100 mm to 1000 mm: $0,03\ \mu m + 0,1 \times 10^{-6}\ L$;
Line standards:
100 mm to 1000 mm: $0,15\ \mu m + 0,2 \times 10^{-6}\ L$;
Diameter standards:
rings and plugs from 3 mm to 250 mm:
$0,15\ \mu m + 0,2 \times 10^{-6}\ L$;

	Step gauges up to 1 m: 0,3 µm + 1 × 10^{-6} *L*; Roundness: diameters from 4 mm to 150 mm: 20 nm, Indexing tables/optical polygons 360 °: 0,2"; Angle gauges: 0,5"; Autocollimators: 0,2"; Pentaprisms: 1".
VNIIM	Line scales up to 1000 mm: 0,03 µm; End standards up to 1000 mm: 0,03 µm; Incremental line scales up to 1000 mm: 0,02 µm; Laser interferometers up to 1000 mm: 0,01 µm; Submillimetre line scales 0,8 µm to 100 µm: 0,01 µm.
LPI	No answer.
VNIIFTRI	No answer.
NIM	Gauge blocks < 1000 mm: 0,05 µm + 0,5 × 10^{-6} *L*; Linear scales < 1000 mm: invar: 0,2 µm, steel: 0,1 µm + 0,4 × 10^{-6} *L*; Surveying tapes < 24 m: 1 × 10^{-6} *L*; Coefficient of thermal expansion 24 m: 0,03 × 10^{-6}/K; Indexing table 360; 720; 1440 teeth: 0,2"; Small angle measurement < 10°: 0,05"; Involute master: 1,5 µm; Flatness < 150 mm: λ/100; Ring gauge < 50 mm: 0,2 µm; Taper gauge < 150 mm: 0,3 µm + 0,01 × 10^{-6} *L*; Interferometer: 0,02 µm + 1 × 10^{-7} *L*.
NIST	Gauge blocks: 0,04 µm + 4 × 10^{-7} *L*; Line scales: 0,006 µm + 1 × 10^{-7} *L*.
NPL	Gauge blocks from 0,5 mm to 100 mm: 0,02 µm + 0,2 × 10^{-6} *L*; Length bars and long series gauge blocks: 25 mm to 100 mm: 0,04 µm + 0,8 × 10^{-6} *L*, 100 mm to 1000 mm: 0,10 µm + 0,4 × 10^{-6} *L*, 1000 mm to 1500 mm: 0,15 µm + 0,4 × 10^{-6} *L*; Step gauges from 400 mm to 1000 mm: 0,5 µm + 0,6 × 10^{-6} *L*; Line scales, up to 1000 mm: 0,5 µm.

NRLM Line scales: 3 parts in 10^7;
Gauge blocks: 3 parts in 10^7;
Flexible tapes: 2 parts in 10^5.

PTB ['Mess- und Prüfmöglichkeiten der Physikalisch-Technische Bundesanstalt' (Testing and Measurement, in the Physikalisch-Technische Bundesanstalt) Braunschweig (1988/89), 30 and 33-36].

CSMU Line standards: 0,2 μm + 0,5 × 10^{-6} L;
Gauge blocks: 0,02 μm + 0,2 × 10^{-6} L.

CSIR Line scales: ± 1 μm;
End standards: < 1 part in 10^6;
Rings, plugs: ± 0,8 μm;
Invar tapes, up to 50 m: 5 parts in 10^6.

OFMET *See* listing in Document CCDM/92-17*a*.

DSIR End standards: 0,025 μm + 1 × 10^{-6} L;
Line scales: 1 μm or 1 part in 10^6;
Dimensional measurements using Leitz: 2 μm.

INM/LNE Line scale standard from zero to 3000 mm, with a standard uncertainty**** of 0,015 μm + 0,15 × 10^{-6} L;
Gauge block from 0,5 mm to 100 mm, with a standard uncertainty of 0,006 μm + 0,05 × 10^{-6} L;
Gauge block from 100 mm to 300 mm, with a standard uncertainty of 0,15 × 10^{-6} L;
Gauge block from 20 mm to 3000 mm, with a standard uncertainty of 0,17 μm + 0,15 × 10^{-6} L;
Internal diameter of ring from 1 mm to 100 mm, with a standard uncertainty of 0,05 μm + 0,1 × 10^{-6} D*****;
External diameter of plug or sphere from 1 mm to 100 mm, with a standard uncertainty of 0,05 μm + 0,1 × 10^{-6} D;
Step gauge from 5 mm to 800 mm, with a standard uncertainty of 0,15 μm + 0,5 × 10^{-6} L;
Length bar (spherical ends) from 20 mm to 3000 mm, with a standard uncertainty of 0,17 μm + 0,15 × 10^{-6} L.

BIPM Lines scales 1 m, with a standard uncertainty: type A of 10 nm; type B of 20 nm;

**** As defined in ISO/TAG 4/WG 3 in June 1992

***** where D is the diameter.

End standards from 500 mm to 1000 mm, with a standard uncertainty: type A of 10 nm; type B of $2{,}0 \times 10^{-8} L$.

KRISS Line scale 1 m: 0,12 µm;
Gauge block 250 mm: 0,05 µm;
Gauge block 1 m: 0,6 µm.

IPL No answer.

JILA No answer.

5.2 Is the demand for each of these types of standard calibration increasing, constant or decreasing? Are there demands for increased accuracy for these measurements?

NRC Generally, the demand for all types of calibration continuously exceeds our human resources. Regarding accuracy, our clients usually ask for ‘best possible’, despite the cost. Our quest for increased accuracy is usually motivated by internal requirements to improve technique and measurement capability. To meet demands when warranted, we plan to tighten the control and measurement of the laboratory environment, and to automate the fringe-fraction measurement on the end standard interferometer.

CSIRO There is little industrial demand for precision line scales. Continuing demand for line standard scales with 100 µm lines (about ten scales on a ten year cycle).
There is a continuing demand for survey tapes.
There is a constant demand for end standards. Improved facilities for interferometric calibrations of long end standards (500 mm to 2000 mm) are required and are being developed. Gap gauges are also in increasing demand.

IMGC Calibration demands are rather constant. However, in the near future, an increase in the number of requests is expected, mainly due to certification needs. More than a specific demand for increased accuracy, there is a widespread need relying upon the evolutionary reduction of uncertainty assured by the primary laboratory.

VNIIM The demand for line scales and end standards calibration is constant. The demand for laser interferometers and submillimetre (small length) line scales (gratings, line-width scales etc.) calibration is increasing.

LPI No answer.

VNIIFTRI No answer.

NIM No answer.

NIST Demand for calibration, and the required accuracy, has remained fairly constant.

NPL Gauge blocks: constant demand, constant accuracy requested;
Length bars: constant demand, increasing accuracy requested;
Step gauges: increasing demand, increasing accuracy requested;
Line scales: decreasing demand, constant accuracy requested.

NRLM Increasing demand for all types of calibration noted in 5.1.
[Matsumoto H., Report on the Round-robin Measurement of Gauge Blocks in 1990, *Bul. NRLM*, 1991, **40**, 172].

PTB The demand for gauge blocks is increasing, partly caused by the unification of Germany and partly by the increasing number of laboratories in the German calibration service (DKD).

CSMU The demand for verification (calibration) of each type of calibration is constant, as is that for accuracy.

CSIR There is a constant demand for line scales, rings, plugs, tapes. We observe a slight increase in demand for end standard measurements.

OFMET Gauge blocks: constant demand;
Line scales: decreasing demand for X-or H-shaped steel scales, increasing demand for special line scales (incremental, glass);
Step gauges: increasing demand;
Almost no demand for higher accuracy than already realized at the OFMET.

DSIR There is some increase demand for calibrations due to ISO 9000 registrations, but no demands for increased accuracy.

INM/LNE Line scales: few demands;
Gratings: increasing;
Gauge blocks: stable;
Internal and external diameters: increasing;
Large gauge blocks and step gauges: increasing.

BIPM The number of requests is increasing, but there is no call for increased accuracy in the measurements.

KRISS The demand is constant, but higher accuracy is requested.

IPL No answer.

JILA No answer.

5.3 Are there new areas of length metrology that are likely to require your attention in the future?

NRC There have been inquiries about hardness testing, complex thread and gear forms, scanning electron microscopy calibration gratings, and dimensional metrology of integrated circuit structures. Some of these are really 'new' areas. Unfortunately, until more resources are made available, our group must continue to concentrate on its current menu of fundamental services.

CSIRO Non-contact location of surfaces for use in 3D coordinate metrology (CMM).

IMGC Nanometrology;
Form measurements;
Three-coordinate measurements (CMM).

VNIIM The new areas of length metrology for our attention are dimensional measurements in a region 3 nm to 3×10^5 nm, and the calibration of laser interferometers with an uncertainty of 2 nm to 3 nm.

LPI No answer.

VNIIFTRI No answer.

NIM No answer.

NIST The decreasing size and increasing density of features on integrated circuits is expected to require further developments of high-accuracy interferometry and two-dimensional measurement techniques.

NPL	Absolute determination of the interferometric phase correction; The application of absolute interferometry to artefacts with more complex geometries.
NRLM	Length measurements from several metres to a few tens of kilometres calibrated with a relative accuracy in the range 10^{-6} to 10^{-7}; Linewidth standards for large scale integrated circuits; Precision measurements from nanometres to picometres.
PTB	The development of new technologies like scanning tunnelling microscopy or atomic force microscopy with their high 3D resolving power may lead to novel measurement probes for length metrology and surface inspection.
CSMU	Verification of measuring tapes up to 24 m length; Calibration of electronic distance meters for surveying purposes and metrological assurance for related baselines to 1 km; Coordinate measurements.
CSIR	No new areas in the international context, but new areas for South Africa include the calibration of 3D CMMs and angle standards.
OFMET	Metrology at sub-micrometre and nanometre levels, in particular calibration of line width standards, 2D mask standards, smooth surfaces, plug gauges of small diameter.
DSIR	Measurements over 5 m may require our future attention.
INM/LNE	Three domains: nanometrology, coordinate metrology, laser diode interferometry.
BIPM	No answer.
KRISS	Line width measurement of semi conductors; X ray interferometry.
IPL	No answer.
JILA	We are receiving a lot of enquiries concerning the long-term dimensional stability of materials, notably Zerodur and ULE.

5.4 Are there any aspects of length metrology that require an international comparison to be carried out among national laboratories?

NRC Gauge blocks are still our most important means of disseminating the metre to industry. Are higher accuracies required and are they being realized?
The angle standard comparison initiated in 1979 caused many laboratories to upgrade their angle calibration capabilities. It would be interesting to compare the various new systems.
Geodesic tapes are still an important class of mechanical standards of length. How do different approaches of measurement compare?

CSIRO We have not taken part in an international comparison of end standards outside the Asia/Pacific region for many years. We suggest that such an exercise for gauge blocks (to 100 mm) would be useful. Length bars (500 mm to 1000 mm) are increasingly used in the calibration of coordinate measuring machines, and recent international comparisons under the auspices of the International Institution for Production Engineering Research (CIRP) have shown very poor agreement. An international comparison is very desirable.

IMGC Aspects related to the answer to 5.3. In Europe, these needs are usually met within the framework provided by EUROMET and the Community Bureau of Reference (BCR).

VNIIM We consider that laser interference refractometers and short-length line scales should be the subjects of international comparisons.

LPI No answer.

VNIIFTRI No answer.

NIM We suggest that an international comparison of linear optical gratings should be carried out because the yield and uses of such measurements are increasing quickly with the years and linear scales tend to be replaced by these gratings. At present it would be interesting to discuss the verifying content, method, etc.

NIST International comparisons of both gauge blocks and line scales would be useful to us.

NPL Coefficients of thermal expansion of gauge blocks and length bars;
Lengths of length bars.

NRLM It may become necessary to make an international comparison of gauge blocks.

PTB International comparisons of gauge blocks are presently organized in the frame of EUROMET. It may be suitable to open these comparisons to other national laboratories situated outside Europe.

CSMU 1 m length standards;
Mechanical standards for micro-lengths (0,7 μm to 100 μm);
Special standards (artefacts), used for calibration of CMM;
Angular standards (optical polygons and auto collimators).

CSIR Current international comparisons at the Western European Calibration Cooperation (WECC) level satisfy South Africa's needs at this stage.

OFMET International comparisons should be carried out regularly, of the type already organized between European laboratories by EUROMET, BCR and others.

DSIR An international comparison of gauge blocks.

INM/LNE At the level of EUROMET, comparison of gauge blocks, large gauge blocks and line scales.

BIPM No answer.

KRISS International comparisons of line-width standards among national laboratories are requested.

IPL No answer.

JILA No answer.

5.5 What means do you use to determine the refractive index of air for the comparison of wavelength standards and mechanical length standards?

NRC At the NRC, we measure the dominant air parameters (temperature, pressure and water content) and then calculate the index of refraction using a modified version of Bengt Edlén's 1966 formula.

CSIRO We use the equation published by Edlén (Document CCDM/92-5*b*).

IMGC Up to now, refractive index determinations have been based on the modified Edlén formula and on calibrated environmental sensors. Direct refractometry is going to be used, at the IMGC, by developing both fixed and transportable air refractometers, designed to provide an accuracy of a few parts in 10^8.

VNIIM We use laser interference refractometers to determine the refractive index of air.

LPI No answer.

VNIIFTRI No answer.

NIM Using Edlén's formula, with an accuracy of 1 part in 10^7;
Measurement using a Rayleigh interferometer, with an accuracy of 8 parts in 10^8;
Measurement with a laser interferometer, with an accuracy of 8 parts in 10^8;
Measurement with a beat frequency laser interferometer, with an accuracy of 5 parts in 10^8 to 1 part in 10^7.

NIST We measure atmospheric temperature, pressure and humidity and calculate the index with a modified version of Edlén's equation.

NPL For some measurements the refractive index is calculated by Edlén's formula, for other instruments it is determined by absolute refractometry.

NRLM Edlén's formula;
Interferometer with vacuum path;
Multi-colour method.
(Document CCDM/92-13*a*).

PTB We apply Edléns formula for some measurements, measured index of refraction by a refractometer for others.

CSMU Edlén's formula.

CSIR Edlén's formula.

OFMET Edlén's formula, but a refractometer has been built.

DSIR Edlén’s formula.

INM/LNE Bengt-Edlén’s formula (*Metrologia*, 1966 and Jones, NBS, 1980). In the future, will use direct measurement of the refractive index.

BIPM Interferometric refractometer

KRISS Either a vacuum chamber or Edlén’s formula in the gauge block interferometer;
For most length measurements, Edlén’s formula;
Laser refractometer is under construction.

IPL No answer.

JILA A simple refractometer based on computer-fitting the angular fringe pattern of a stable, flat-flat Fabry-Perot interferometer ($d\lambda/\lambda \approx 10^{-8}$). Agreement with Edlén’s formula is well within 2 parts in 10^7.

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