

Bureau International des Poids et Mesures

Consultative Committee for Length (CCL)

10th Meeting (September 2001)

Note on the use of the English text

To make its work more widely accessible the Comité International des Poids et Mesures publishes an English version of its 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.

TABLE OF CONTENTS

| | |
|--|-----------|
| Photograph of participants attending the 10th meeting of the Consultative Committee for Length | 2 |
| Member States of the Metre Convention and Associates of the General Conference | 75 |
| The BIPM and the Metre Convention | 77 |
| List of members of the Consultative Committee for Length | 81 |

Report to the International Committee for Weights and Measures, by A. Sacconi and A. Lewis **83**

| | |
|--|------------|
| Agenda | 84 |
| 1 Opening of the meeting; appointment of the rapporteur; approval of the agenda | 85 |
| 2 Report on the implementation of the Mutual Recognition Arrangement by the Director | 86 |
| 3 Examination of replies to the BIPM questionnaire | 88 |
| 4 Presentations of new results related to items in the questionnaire | 89 |
| 5 Report of the Working Group on Dimensional Metrology (progress in the key comparisons) | 89 |
| 6 Report of the Working Group on the <i>Mise en Pratique</i> | 95 |
| 7 Modifications to the 1997 <i>Mise en Pratique</i> of the definition of the metre, including proposals for new recommended radiations | 97 |
| 8 Identification of new key comparisons | 99 |
| 9 Work at the BIPM | 99 |
| 9.1 BIPM ongoing key comparison at 633 nm | 99 |
| 9.2 Other international comparisons of stabilized lasers | 100 |
| 9.3 Research and introduction of new techniques | 101 |
| 9.4 Nanometrology | 101 |
| 9.5 Collaboration with national laboratories | 101 |
| 10 CCL working groups: composition and terms of reference | 102 |
| 11 Recommendations to the CIPM | 103 |
| 12 Other business | 103 |
| 13 Next meeting of the CCL | 104 |

Recommendations submitted to the International Committee for Weights and Measures

- CCL 1 (2001). Scope of the *mise en pratique* **107**
- CCL 2 (2001). Development of optical comb technology **108**
- CCL 3 (2001). Revision of recommended radiations **109**
- CCL 4 (2001). Radiations of spectral lamps and other sources **110**

Recommendation adopted by the International Committee for Weights and Measures

- 1 (CI-2002). Revision of the practical realization of the definition of the metre **113**

Appendices

- L 1. Working documents submitted to the CCDDM at its 10th meeting **125**
- L 2. Source data for the list of recommended radiations, 2001 **127**
- L 3. Absolute frequency of the other transitions related to those adopted as recommended and frequency intervals between transitions and hyperfine components **149**
- L 4. References **189**

List of acronyms used in the present volume 205

**MEMBER STATES OF THE METRE CONVENTION AND
ASSOCIATES OF THE GENERAL CONFERENCE**

as of 19 September 2001

Member States of the Metre Convention

| | |
|------------------------|-------------------------------|
| Argentina | Korea (Dem. People's Rep. of) |
| Australia | Korea (Rep. of) |
| Austria | Malaysia |
| Belgium | Mexico |
| Brazil | Netherlands |
| Bulgaria | New Zealand |
| Cameroon | Norway |
| Canada | Pakistan |
| Chile | Poland |
| China | Portugal |
| Czech Republic | Romania |
| Denmark | Russian Federation |
| Dominican Republic | Singapore |
| Egypt | Slovakia |
| Finland | South Africa |
| France | Spain |
| Germany | Sweden |
| Greece | Switzerland |
| Hungary | Thailand |
| India | Turkey |
| Indonesia | United Kingdom |
| Iran (Islamic Rep. of) | United States |
| Ireland | Uruguay |
| Israel | Venezuela |
| Italy | Yugoslavia |
| Japan | |

Associates of the General Conference

| | |
|------------------|-----------|
| Cuba | Latvia |
| Ecuador | Lithuania |
| Hong Kong, China | Malta |

THE BIPM AND THE METRE CONVENTION

The International Bureau of Weights and Measures (BIPM) was set up by the Metre Convention 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.

The BIPM has its headquarters near Paris, in the grounds (43 520 m²) 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 Metre Convention.

The task of the BIPM is to ensure worldwide unification of physical measurements; its function is thus to:

- establish fundamental standards and scales for the measurement of the principal physical quantities and maintain the international prototypes;
- carry out comparisons of national and international standards;
- ensure the coordination of corresponding measurement techniques;
- carry out and coordinate measurements of the fundamental physical constants relevant to these activities.

The BIPM operates under the exclusive supervision of the International Committee for Weights and Measures (CIPM) which itself comes under the authority of the General Conference on Weights and Measures (CGPM) and reports to it on the work accomplished by the BIPM.

Delegates from all Member States of the Metre Convention attend the General Conference which, at present, meets every four years. The function of these meetings is to:

- discuss and initiate 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;
- confirm the results of new fundamental metrological determinations and various scientific resolutions of international scope;
- take all major decisions concerning the finance, organization and development of the BIPM.

The CIPM has eighteen members each from a different State: at present, it meets every year. The officers of this committee present an annual report on the administrative and financial position of the BIPM to the Governments of

the Member States of the Metre Convention. The principal task of the CIPM is to ensure worldwide uniformity in units of measurement. It does this by direct action or by submitting proposals to the CGPM.

The activities of the BIPM, which in the beginning were limited to 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 and radiometry (1937), ionizing radiation (1960), time scales (1988) and to chemistry (2000). 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 for a library and offices. In 2001 a new building for the workshop, offices and meeting rooms was opened.

Some forty-five physicists and technicians work in the BIPM laboratories. They mainly conduct metrological research, international comparisons of realizations of units and calibrations of standards. An annual report, the *Director's Report on the Activity and Management of the International Bureau of Weights and Measures*, gives details of the work in progress.

Following the extension of the work entrusted to the BIPM in 1927, the CIPM has set up bodies, known as Consultative Committees, whose function is to provide it with information on matters that it refers to them for study and advice. These Consultative Committees, which may form temporary or permanent working groups to study special topics, are responsible for coordinating the international work carried out in their respective fields and for proposing recommendations to the CIPM concerning units.

The Consultative Committees have common regulations (*BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1963, **31**, 97). They meet at irregular intervals. The president of each Consultative Committee is designated by the CIPM and is normally a member of the CIPM. The members of the Consultative Committees are metrology laboratories and specialized institutes, agreed by the CIPM, which send delegates of their choice. In addition, there are individual members appointed by the CIPM, and a representative of the BIPM (Criteria for membership of Consultative Committees, *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1996, **64**, 124). At present, there are ten such committees:

- 1 the Consultative Committee for Electricity and Magnetism (CCEM), new name given in 1997 to the Consultative Committee for Electricity (CCE) set up in 1927;
- 2 the Consultative Committee for Photometry and Radiometry (CCPR),

new name given in 1971 to the Consultative Committee for Photometry (CCP) set up in 1933 (between 1930 and 1933 the CCE dealt with matters concerning photometry);

- 3 the Consultative Committee for Thermometry (CCT), set up in 1937;
- 4 the Consultative Committee for Length (CCL), new name given in 1997 to the Consultative Committee for the Definition of the Metre (CCDM), set up in 1952;
- 5 the Consultative Committee for Time and Frequency (CCTF), new name given in 1997 to the Consultative Committee for the Definition of the Second (CCDS) set up in 1956;
- 6 the Consultative Committee for Ionizing Radiation (CCRI), new name given in 1997 to the Consultative Committee for Standards of Ionizing Radiation (CCEMRI) set up in 1958 (in 1969 this committee established four sections: Section I (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 Consultative Committee for Units (CCU), set up in 1964 (this committee replaced the “Commission for the System of Units” set up by the CIPM in 1954);
- 8 the Consultative Committee for Mass and Related Quantities (CCM), set up in 1980;
- 9 the Consultative Committee for Amount of Substance: metrology in chemistry (CCQM), set up in 1993;
- 10 the Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV), set up in 1998.

The proceedings of the General Conference, the CIPM and the Consultative Committees are published by the BIPM in the following series:

- *Report of the meetings of the General Conference on Weights and Measures;*
- *Reports of the meetings of the International Committee for Weights and Measures;*
- *Reports of the meetings of Consultative Committees.*

The BIPM also publishes monographs on special metrological subjects and, under the title *The International System of Units (SI)*, a brochure, periodically updated, in which are collected all the decisions and recommendations concerning units.

The collection of the *Travaux et Mémoires du Bureau International des Poids et Mesures* (22 volumes published between 1881 and 1966) and the *Recueil de Travaux du Bureau International des Poids et Mesures* (11 volumes published between 1966 and 1988) ceased by a decision of the CIPM.

The scientific work of the BIPM is published in the open scientific literature and an annual list of publications appears in the *Director's Report on the Activity and Management of the International Bureau of Weights and Measures*.

Since 1965 *Metrologia*, an international journal published under the auspices of the CIPM, has printed articles dealing with scientific metrology, improvements in methods of measurement, work on standards and units, as well as reports concerning the activities, decisions and recommendations of the various bodies created under the Metre Convention.

LIST OF MEMBERS OF THE CONSULTATIVE COMMITTEE FOR LENGTH

as of 19 September 2001

President

Chung Myung Sai, member of the International Committee for Weights and Measures, Korea Research Council of Fundamental Science and Technology, Seoul.

Executive Secretary

J.-M. Chartier, International Bureau of Weights and Measures [BIPM], Sèvres.

Members

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

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

Centro Nacional de Metrología [CENAM], Querétaro.

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

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

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

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

National Institute of Metrology [NIM], Beijing.

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

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

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

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

National Physical Laboratory [NPL], Teddington.

National Research Council of Canada [NRC], Ottawa.

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

Physikalisch-Technische Bundesanstalt [PTB], Braunschweig.

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

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

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

Observers

Centro Español de Metrología [CEM], Madrid.

CSIR, Division of Production Technology [CSIR-NML], Pretoria.

Standards, Productivity and Innovation Board [SPRING], Singapore.

Consultative Committee for Length

Report of the 10th meeting

(19-20 September 2001)

to the International Committee for Weights and Measures

Agenda

- 1 Opening of the meeting; appointment of the rapporteur; approval of the agenda.
- 2 Report on the implementation of the Mutual Recognition Arrangement by the Director.
- 3 Examination of replies to the BIPM questionnaire.
- 4 Presentations of new results related to items in the questionnaire.
- 5 Report of the Working Group on Dimensional Metrology (progress in the key comparisons).
- 6 Report of the Working Group on the *Mise en Pratique*.
- 7 Modifications to the 1997 *Mise en Pratique* of the definition of the metre, including proposals for new recommended radiations.
- 8 Identification of new key comparisons.
- 9 Work at the BIPM:
 - 9.1 BIPM ongoing key comparison at 633 nm;
 - 9.2 Other international comparisons of stabilized lasers;
 - 9.3 Research and introduction of new techniques;
 - 9.4 Nanometrology;
 - 9.5 Collaboration with national laboratories.
- 10 CCL working groups: composition and terms of reference.
- 11 Recommendations to the CIPM.
- 12 Other business.
- 13 Next meeting of the CCL.

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

The Consultative Committee for Length (CCL) held its 10th meeting at the International Bureau of Weights and Measures (BIPM), Sèvres, on Wednesday 19 and Thursday 20 September 2001. Four sessions were held.

The following delegates were present: O. Acef (BNM-LPTF), P. Balling (CMI), R. Bergmans (NMI VSL), F. Bertinotto (IMGC-CNR), M.S. Chung (President of the CCL), C.I. Eom (KRISS), R. Fira (SMU), P. Gill (NPL), J.L. Hall (NIST/JILA), J. Helmcke (PTB), L. Hollberg (NIST), E. Jaatinen (NML CSIRO), P. Juncar (BNM-INM), A.N. Korolev (VNIIM), T. Kurosawa (NMIJ/AIST), A. Lassila (MIKES), E. Latysheva (VNIIM), A. Lewis (NPL), A. Madej (NRC), H. Matsumoto (NMIJ/AIST), J. Pekelsky (NRC), T.J. Quinn (Director of the BIPM), A. Sacconi (IMGC-CNR), H. Schnatz (PTB), S. Shen (NIM), R. Thalmann (METAS), M. Viliesid (CENAM), T. Yandayan (UME), T. Yoon (KRISS).

Observers: E. Prieto (CEM), S. Tan (SPRING).

Guests: Y.S. Domnin (VNIIFTRI), A.J. Wallard (NPL).

Also present: P. Giacomo (Director Emeritus of the BIPM); J.-M. Chartier, R. Felder, L.-S. Ma, S. Picard, L. Robertsson, C. Thomas, L.F. Vitushkin (BIPM).

Dr Chung welcomed the delegates, observers and guests to the 10th meeting of the CCL. The original plan had been to hold a meeting in the year 2000, however the date of the meeting had been postponed to await the results of interesting research in the field of femtosecond lasers and comb technology, and to await results from some of the first round of CCL key comparisons and expected progress in calibration and measurement capability (CMC) matters. It had therefore been decided to hold the 10th meeting of the CCL in late 2001.

Dr Quinn then welcomed the meeting, which was being held in the new building at BIPM, the “Pavillon du Mail”. He spoke briefly regarding the recent terrorist acts in the United States and suggested that it would be fitting to show a sign of respect for those who had died and express the meeting's sympathy and solidarity with the international community.

The meeting observed a moment of silence.

The president proposed the appointment of Dr Sacconi and Dr Lewis as Rapporteurs. This was agreed.

It was suggested that agenda item 5 be taken after item 7, so that the final version of the report of the Working Group on Dimensional Metrology (WGDM) to the meeting could be completed. This would also allow discussion of the outcomes of the Working Group on the *Mise en Pratique* (MePWG) directly before the agenda item pertaining to modifications to the current *Mise en Pratique*. This was accepted and the agenda was otherwise approved. Within these minutes the items will nevertheless be reported in the original sequence.

2 REPORT ON THE IMPLEMENTATION OF THE MUTUAL RECOGNITION ARRANGEMENT BY THE DIRECTOR

Dr Quinn informed the meeting that much had happened regarding the Mutual Recognition Arrangement (MRA) since the last meeting of the then Consultative Committee for the Definition of the Metre (CCDM) in 1997. The MRA had been signed and the CCL had formally approved the first set of CCL key comparisons, which had since been started. The fact that the MRA had progressed so far was due to the enormous amount of work being performed by the national metrology institutes (NMIs), both in submitting and reviewing the CMCs and in taking part in the various key, supplementary, and regional comparisons. Now the workload for the NMIs is still in the initial peak, but hopefully there would be some lessening of the burden on the work of the NMIs.

The BIPM key comparison database (KCDB) had been opened since the year 2000, and populated with CMC data. Key comparison CCL-K1 on short gauge block measurements by interferometry was now completed and the results and report had been entered into the KCDB.

The flow of CMCs is overseen by the Joint Committee of the Regional Metrology Organizations and the BIPM (JCRB), which meets every six months. The JCRB had praised the work of the Technical Committee (TC) chairmen of the regional metrology organizations (RMOs) for their hard work and cooperation in getting the MRA operational. Dr Quinn noted that it

was very important that these TC and RMO chairmen were well chosen as the process of the MRA relied on the work of these people.

Because the KCDB was now available on the World Wide Web, the next important stage was to ensure that the availability of the database was publicized as widely as possible. This would encourage industrial users to visit the database and become more familiar with the data it offers.

Dr Thomas gave a short presentation on the KCDB, using a computer linked to the database via the network. The list of comparisons in length was shown; it includes also the regional key comparisons (KCs) corresponding to the CCL-KCs. Appendix B of the database contained details of key comparisons and some previous comparisons which had been organized by the EUROMET and which were being used for provisional equivalence. During the meeting of the WGDM on the previous two days, several similar comparisons organized by other RMOs had been examined and were to be entered into the database.

The meeting was shown the results of the CCL-K1 key comparison including the tables and graphs of equivalence, the data reported by the participants, graphs of the results and an explanation of the calculation of the key comparison reference values and the degrees of equivalence. In this comparison, the expert group responsible (WGDM) had decided not to produce long, detailed tables of mutual equivalence values for the whole set of gauge blocks used in the comparison, as they thought that this would be confusing and misleading. This was explained in the report.

Regarding Appendix C, the first sets of CMCs had been entered into the database in December 2000. These included about 300 CMCs in the field of length metrology. There were now approximately 10 000 CMCs in the database, following the addition of many CMCs from the fields of electricity and magnetism and of chemical metrology. More CMCs, including a large number from length, were about to be submitted for approval by the JCRB in October 2001.

Dr Thomas gave a demonstration of searching Appendix C for CMC entries, using both “vertical” (branch, field, sub-field) and “horizontal” (direct search of a sub-field in the list) selections through the data. Searches could be performed using a range of criteria, including country, metrology area, sub-field, NMI, etc. The formatting of the data which was presented as the result of such searches had been chosen to make comparisons between the uncertainties offered by different entrants easy to make. The lists of services had been classified using terminology agreed upon and adopted by the

RMOs. In the area of length, this terminology was known by the name “DimVIM” and had been produced by the WGDM. This approach had been followed in other Consultative Committees.

3 EXAMINATION OF REPLIES TO THE BIPM QUESTIONNAIRE

Mr Chartier gave a presentation of the results of the BIPM survey which had been sent to participants prior to the meeting. [The received responses are listed in Appendix L 1]. Overall twenty-two answers had been received (including that from the BIPM). This time the survey had been performed by e-mail rather than by post, and it had been considerably easier to send out the questionnaires and collate the returned data. A summary of the responses had been prepared [CCL/01-01b]. Five laboratories had made absolute frequency or wavelength measurements of radiations not included in the *Mise en Pratique*. Four of these five laboratories thought that these new frequencies/wavelengths should be included in the *Mise en Pratique* (the BIPM abstained).

Ten laboratories were working on new standards or comb generators. Five laboratories had noted errors or omissions in the 1997 list of recommended radiations, and six laboratories wished to make changes to values of frequency, wavelength or uncertainty given in the current *Mise en Pratique*. A total of eleven laboratories thought it desirable to bring out a revised *Mise en Pratique* in 2001.

Since the last meeting of the CCL, seventeen laboratories had participated in international comparisons involving stabilized lasers and twenty-one of the twenty-two respondents had participated in international comparisons involving dimensional metrology.

On the issue of creating a new working group for the subject of nanometrology (or any other field), even if the responses were mixed, with nine laboratories being in favour and eight against such a new working group, it was noted that the presence of this subject inside the WGDM is working well.

Finally, Mr Chartier anticipated a provisional list of recommended radiations.

4 PRESENTATIONS OF NEW RESULTS RELATED TO ITEMS IN THE QUESTIONNAIRE

The latest results had been presented at, and debated during, the meeting of the Working Group on the *Mise en Pratique* the previous day. As such, the details were to be presented in the working group presentation to the CCL (item 6).

5 REPORT OF THE WORKING GROUP ON DIMENSIONAL METROLOGY (PROGRESS IN THE KEY COMPARISONS)

Dr Pekelsky presented a report from the Working Group on Dimensional Metrology [CCL/WGDM/01-43]. He noted that all the documents from the WGDM would be made available on the WGDM website at the BIPM. The CCL Working Group on Dimensional Metrology is an advisory committee in this subject area that makes recommendations on the needs and priorities for CCL key comparisons, that acts as a focus for information exchange on international comparisons and related matters, and which maintains links with RMOs to ensure involvement of BIPM and member NMIs of the CCL in major comparisons, thereby providing the means for assuring worldwide traceability of dimensional measurements at the highest levels of accuracy. Much work had been performed by the WGDM since the last meeting of the CCL. The WGDM had met each year since the last CCL meeting and had set up seven discussion groups (whose reach extended outside the CCL NMIs) to consider and debate the topics of the planned and future CCL key comparisons. These discussion groups were:

DG2 – gauge blocks;

DG3 – long gauge blocks;

DG4 – angle;

DG5 – diameter;

DG6 – CMM artefacts;

DG7 – nanometrology;

DG8 – thermal expansivity.

Dr Pekelsky reported on the progress in the CCL key comparisons. The CCL had approved six key comparisons in 1997, and these were either still running, or, in the case of CCL-K1, just completed. The original plan for these comparisons was as follows:

| No. | Artefact | Pilot | Start | Duration |
|--------|--------------------|----------------------|---------|-----------|
| CCL-K1 | gauge blocks | METAS (Switzerland) | 03-1998 | 1.5 years |
| CCL-K2 | long gauge blocks | NPL (United Kingdom) | 10-1999 | 1.5 years |
| CCL-K3 | angle standards | CSIR (South Africa) | 07-1998 | 1.5 years |
| CCL-K4 | diameter standards | NIST (United States) | 09-1998 | 2 years |
| CCL-K5 | 1-D CMM artefacts | PTB (Germany) | 03-1998 | 2 years |
| CCL-K6 | 2-D CMM artefacts | CENAM (Mexico) | 01-2000 | 2 years |

Each pilot laboratory, in some cases teamed with one or two experts from other NMIs, produced a technical protocol that has been approved by the participants and by WGDM, and these are available on the BIPM website. Except for CCL-K1, there had been delays to the start and/or duration of the comparisons. The approval, by the CCL, of the final report for CCL-K1 and of the expression of the results using the nominal sizes of gauge blocks as the reference values, had been by correspondence. During most of the key comparisons it had been very difficult to keep to the schedule, as some participants suffered equipment problems during their turn, or there were extraordinary delays with transport, notably with customs processing. The only CCL key comparison to have been completed and entered into the database, CCL-K1, had taken four years from start to database entry – over twice the planned timescale. If other key comparisons follow similar timescales, the initial set of CCL key comparisons may not be all completed until well into 2004.

Dr Pekelsky presented a chart detailing the progress in CCL key comparisons:

| | CCL-K1 | CCL-K2 | CCL-K3 | CCL-K4 | CCL-K5 | CCL-K6 |
|-------------------|---------|---------|---------|---------|---------|---------|
| Planning start | 09-1997 | 10-1997 | 01-1999 | 01-1999 | 01-1998 | 04-2000 |
| Circulation start | 03-1998 | 09-1999 | 07-2000 | 11-2000 | 04-1999 | 01-2001 |
| Circulation end | 09-1999 | 08-2001 | 07-2002 | 04-2002 | 11-2001 | 12-2002 |
| Draft A report | 09-1999 | 09-2001 | – | – | – | – |
| Draft B report | 01-2001 | – | – | – | – | – |
| App. B listed | 08-2001 | 09-2003 | 07-2004 | 04-2004 | 11-2003 | 12-2004 |

Dr Pekelsky then described the current situation of the CCL key comparisons, the DG7 nanotechnology studies and the work in DG8.

CCL-K1. Short gauge blocks, ten steel and ten tungsten carbide, ranging from 0.5 mm to 100 mm. The results were in Appendix B and the pilot had submitted a report to *Metrologia* for publication. It was noted that start to finish was about two years for the technical work and two years for analysis, approval and publication in Appendix B.

CCL-K2. Four steel gauge blocks, of lengths 175 mm, 500 mm, 500 mm and 900 mm. The circulation was finished, and draft A results had just been discussed with some participants present at the 6th WGDM meeting. This project had significant problems with customs in one country. Technical performance of the participants was generally excellent, perhaps bolstered because the uncertainty estimated by the pilot laboratory for the thermal expansivity was small (not typical of client calibrations). The WGDM now recommends that manufacturers' nominal properties be provided (not better), after checking that the actual value is within normal tolerance range.

CCL-K3. A twelve-face polygon and four angle blocks of 5", 30", 5' and 5°. This comparison had been delayed while locating suitable artefacts, and also by communication shortfalls between the pilot and participants. There had also been some damage to the polygon during transit between participants, when a clamp bolt came free in the case and rattled against the polygon faces while travelling; the damage was deemed minor, and the circulation continues. Regarding other problems, the WGDM has recommended tightening the communication channels, and also adjusting the schedule to place the COOMET loop at the end, after a pilot measurement.

CCL-K4. Part (a) Internal diameter of four rings ranging from 5 mm to 100 mm, and **Part (b)** external diameter of five plugs ranging from 2 mm to 98.5 mm. Some NMIs had experienced equipment failures, and the schedule was to be adjusted with COOMET at the end. Corrosion had been observed on two plugs, away from the diameter measurement positions. Additional alignment marks had been added during circulation to give a better indication of the measurement position on some of the artefacts. One participant had commented that the form errors (roundness) on the gauge surfaces might prevent them from realizing their CMC uncertainty claimed in Appendix C.

CCL-K5. 1-D coordinate measuring machine (CMM) standards: three ball-bars (400 mm and 800 mm steel, and 800 mm invar) and a 1 metre step gauge (steel, with ceramic inserts). Some NMIs (CSIR, IMGC and NRC) had equipment failures or difficulties, and had asked for a bilateral remeasurement with the pilot laboratory, after the comparison. Otherwise, most of the results had been sent to the pilot laboratory, with just measurement by the VNIIMS to be arranged.

CCL-K6. 2-D CMM standards: steel ball plate with 5×5 array of 22 mm diameter ceramic balls on 83 mm centres; zerodur bore plate with a pattern of 20 mm holes on 50 mm centres. Five NMIs had completed measurements, and now the COOMET circulation will be shifted to the end of the schedule, which will introduce a small overall extension of the plan.

Nanometrology. The nearly two-dozen technical contacts in this DG had been very active during the report period, communicating mainly by e-mail correspondence, and also during a general meeting held at the BIPM (February 1999). At this meeting, five pilot study topics had been identified that challenge measurands deemed to be needed by the nanoscience and nanotechnology community:

| Name | Artefact | Pilot | No. of participants | Schedule |
|-------|--------------|----------------------|---------------------|----------------------------|
| NANO1 | linewidth | NIST (United States) | 9 | to be decided |
| NANO2 | step height | PTB (Germany) | 14 | 10-2000 – 01-2002 |
| NANO3 | line scales | PTB (Germany) | 15 | 04-2000 – 02-2002 |
| NANO4 | 1-D gratings | METAS (Switzerland) | 11 | 02-1999 – 05-2000 |
| NANO5 | 2-D grids | DFM (Denmark) | 7 | 03-2002 – to be decided |

There had been considerable progress on these projects. Project NANO4 had been finished, and the final report had been prepared. Projects NANO2 and

NANO3 were under way, with the artefact circulation of the latter recently completed. The pilot laboratories for NANO1 and NANO5 had undertaken important preparatory work to produce suitable artefacts.

Thermal expansivity. This discussion group (DG) was being moderated by the NMIJ/AIST (Japan), where a considerable facility for a broad range of thermal characterization had been developed. The interest across WGDM members was very high in this topic, but only a few labs were currently equipped to make measurements. A pilot study had been proposed by the DG moderator at the 6th WGDM meeting, suggesting that ceramic artefacts (gauge blocks) be measured over three temperature ranges: 10 °C to 30 °C, 200 °C to 800 °C, and –200 °C to 0 °C. The range spanning 20 °C (ISO standard reference temperature for dimensional metrology) was of obvious interest to the WGDM, whereas the other ranges had importance to materials science. The WGDM had recommended that the moderator discuss this proposal with the technical contacts of the DG, to work out the metrology details and level of ability of other NMIs to participate in this project.

The topic of the selection of key comparisons had been discussed at each of the four WGDM meetings. There were resource implications of beginning new key comparisons, as these would require the starting of linking RMO comparisons, necessitating participation in both comparisons for the set of linking laboratories (selected CCL members). A better alternative was to start supplementary comparisons (either RMO or CCL) because these did not need to link directly with other comparisons, thus halving the workload. A new DG1 discussion group will be formed to examine the overall issue of choosing appropriate key comparison topics.

The WGDM had discussed the use of key comparison reference values in artefact-based CCL key comparisons and of the linking of the key comparison reference value to the corresponding value from the RMO comparisons for the purposes of establishing degrees of mutual equivalence. In dimensional metrology, artefact properties can dominate a laboratory's overall performance. Thus the key comparison reference value is only applicable to the results obtained for a specific artefact, and is a poor test of the participants' ability to realize the SI unit or to transfer it to all material artefacts. Furthermore, artefact properties may cause a positive shift of a participant's results in one comparison, whereas they may experience a negative shift in another comparison. Thus trying to link the two comparisons, by shifting the results in one, based on the results in the other, may not be reliable. Each comparison could be viewed as a separate "proficiency" test, aimed to test competency rather than the realization of the

SI units. The WGDM had decided to await the publication of the first data from an RMO comparison linked to CCL-K1 before making a firm decision. The data from a EUROMET comparison on short gauge blocks was expected within a few days.

Although not the direct business of the WGDM, the Appendix C listing of services (CMCs) had been discussed at the WGDM meetings because representatives of the length technical committees of most of the RMOs also attend WGDM meetings. Profit was taken of this fact and the WGDM had been instrumental in preparing a document of common terminology for the listing of length CMCs. This document had been called the “DimVIM” and length CMCs from all regions had been classified according to the DimVIM list of services. A CEM project, realized in parallel, was mentioned for a corresponding classification in Spanish to be used in national and secondary laboratories and also on a wider scale. Other Consultative Committees had seen the benefits of this approach and had produced their own CMC classification documents. Additionally, the WGDM had prepared guidance documents for use in preparing and formatting the CMC entries. This helped ensure harmonization of the CMCs throughout the different regions, facilitating the inter-regional review. The net outcome of this work, was that the CMCs submitted by the length technical committees were the very first to be entered into the BIPM key comparison database.

Dr Pekelsky summarized his report and tabled two recommendations from the WGDM to the CCL:

CCL-WGDM-1: Customs formalities for CCL key comparison artefacts

The WGDM recommends to the CCL that each CCL member, when replying to an invitation to participate in the key comparison, shall provide all the information about the formalities necessary for customs clearance to the WGDM chairman and to the pilot laboratories, together with details about the contact person at each NMI for customs questions. Communication to this person must be assured!

CCL-WGDM-2: Nano4 (grating pitch) study to provisional Appendix B

Given that the WGDM has previewed and approved the preliminary results of the NANO4 study on grating pitch, the WGDM recommends to the CCL that, when the final report is ready, the results of NANO4 be officially approved and submitted to the provisional BIPM key comparison database (Appendix B), provided that the participants all agree to such publication.

The meeting unanimously accepted these two recommendations.

In order for the nanometrology pilot studies to be entered into Appendix B to support the claimed uncertainties in CMCs, they would have to be re-classified as CCL supplementary comparisons. This would need to be discussed by the participants, because it placed a different emphasis on the data which they had reported during these studies. Although the studies had been performed in accordance with the Appendix F guidelines for CIPM key comparisons, the data had been confidential. Publication in Appendix B meant that the data would be public, and this required approval by participants.

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

Dr Gill gave an introduction to the ideas debated at the previous day's discussion of the Working Group on the *Mise en Pratique* (the MePWG) and presented the agenda for the group meeting. The discussions had followed the themes of draft proposals for new frequencies for inclusion in the *Mise en Pratique*: the use of new technology including femtosecond lasers and comb generators; and the likely direction of future BIPM work in laser frequencies. Since the previous CCDM/CCL meeting, there had been a step change in optical frequency and wavelength measurements. This has resulted for two main reasons:

First, cold-atom and trapped-ion frequency standards had now begun to demonstrate experimental line-Qs approaching their theoretical expectations, and this research would clearly be the basis for the next generation of frequency/wavelength standards.

Secondly, absolute frequency measurement of these standards has been readily demonstrated by new wide-span comb techniques. These involve the use of femtosecond laser systems with repetition rates stabilized to give highly reproducible mode spacings in the frequency domain. The femtosecond comb extended across a few tens of nanometres for the basic laser, but was extended to many hundreds of nm by the use of microstructure fibre. Widespan combs from 400 nm to beyond 1200 nm are now in use or under development in several standards laboratories, including the BIPM. It was the view of the MePWG that this technology was a major way forward

in the measurement and comparison of optical frequency standards and their relation to other regions of the spectrum, in particular, the caesium microwave standard realizing the SI second.

Because of the wide span available from the femtocomb, it is now possible to frequency double the infrared part of the comb to compare with the green part of the comb spectrum, and by so doing, unequivocally fix the optical comb envelope relative to the basic intermode spacing. One can then use this optical ruler to measure any frequency within the visible to mid-infrared. Comparisons between combs are already demonstrating measurement capabilities at an uncertainty level of a few parts in 10^{15} . Comparisons with other frequency chains are fully supporting these observations, albeit at a slightly lower accuracy, limited in the main by the alternative chain measurement method, or the optical standard stability or reproducibility. Further, just recently, the combination of an optical frequency standard based on a single cold ion together with a widespan comb stabilized to the optical standard rather than a microwave standard, has allowed the demonstration of an optical clock referenced to a cold-ion optical transition and delivering a range of visible-to-infrared frequencies plus a microwave output frequency. It is envisaged that simple demonstrations of comb systems, perhaps referenced by GPS-based standards, can play a role in dimensional metrology. Further, it should be possible to use combs in interferometry, as pseudo-white light sources.

Dr Hall gave a short presentation entitled, "Realizing the metre, today, tomorrow...". This compared and contrasted the previous realization of the metre using krypton, with current realizations using He-Ne lasers, and future standards using comb systems based on honeycomb microstructure optical fibres. It was noted that noise in the latest optical frequency standards was now less than in the microwave frequency standards. Dr Chung expressed his congratulations for Dr Hall's presentation.

7 MODIFICATIONS TO THE 1997 *MISE EN PRATIQUE* OF THE DEFINITION OF THE METRE, INCLUDING PROPOSALS FOR NEW RECOMMENDED RADIATIONS

Initially, six proposals were tabled, concerning modifications to the current *Mise en Pratique*. These concerned:

- CCL 1: a change of the title of the *Mise en Pratique* to better reflect a wider range of applications, and including its use for secondary representations of the second;
- CCL 2: recommendations on the use of comb technologies;
- CCL 3: recommendations on use of new and revised radiations;
- CCL 4: details of revised values (frequency and uncertainty);
- CCL 5: details of new recommended radiations;
- CCL 6: transfer of some radiations to the secondary list.

These proposals were then discussed by the meeting.

The first proposal was clearly related to the work on the second and would require consultation with the CCTF. This led to a proposal for a joint working group between the CCL and the CCTF. There was some discussion of the actual text of proposals CCL 2 through CCL 4 and of which lists needed updating.

Regarding CCL 4, Dr Quinn recommended to reword this proposal as a statement of intent. He noted that the revision process has to go back to the MePWG for the complete documentation. The refinement of values takes a lot of time to be fully documented. Dr Gill fully supported this remark by saying that CCL 4 is meant as information for the CIPM, but the formal revision of the list has to be prepared with all the necessary documentation. Dr Quinn remarked that new results are accepted only when published and now the situation is rapidly changing with a number of new results.

Proposal CCL 6 recommended the move to the secondary list (spectral lamps and other sources) of certain frequency standards which had frequency values that were unlikely to be further improved. These included the iodine-stabilized references at 640 nm, 612 nm, 515 nm and 543 nm. As some of these were important sources for use in dimensional metrology (e.g. the 543 nm radiation is used extensively in gauge-block metrology) or could still be subject to research (e.g. work on measuring the zero vibration level lines at 515 nm), movement to the secondary list did not mean that the radiations

were no longer important. The move to the secondary list could have a benefit in that because there would be no updates to the value, they could still be used as recommended realizations of the metre, without the need to check for updated values. It was agreed that this proposal is based on the present situation and nothing prevents the presentation of new data. If necessary, one or more of these standards could be returned to the primary list if results of future work required this.

Discussion of proposals CCL 4 through CCL 6 indicated there was still a consensus to be reached that would require more time than was available at the meeting. It was therefore decided that proposals CCL 1 through CCL 3 would be drafted as recommendations to the CIPM, and proposals CCL 4 through CCL 6 would form the basis of a provisional working document to be submitted by the CCL to the CIPM for outline approval, but allowing further discussion within the MePWG to check and confirm final details. The issue of when to draw the line regarding data for inclusion in the next version of the *Mise en Pratique* was discussed along with the values of the frequencies and uncertainties to be presented in the working document. The texts of proposals CCL 4 through CCL 6 were combined into a new proposal, CCL 4 with parts CCL 4-1 through CCL 4-3. These were then discussed again by members of the MePWG.

After a long and partly controversial discussion, the conclusions were as follows:

- regarding CCL 4, the information was to be regarded as provisional, for transmission in outline to the CIPM;
- agreement was reached on all values and uncertainties detailed in CCL 4-1 and CCL 4-2 the MePWG would, within the next few months, update the data relating to CCL 4-1 and CCL 4-2;
- other than the values given in CCL 4, no new radiations would be accepted for the next issue of the *Mise en Pratique*;
- new data received within the next few months would not be accepted for inclusion in the *Mise en Pratique*. If such data arising brought significant doubt to any value recommended for publication, this position would be so highlighted in the revised *Mise en Pratique*.

The recommendations to the CIPM are discussed under item 11 of these minutes.

8 IDENTIFICATION OF NEW KEY COMPARISONS

As stated in their report, the WGDM had not identified any more CCL key comparisons in the field of dimensional metrology which it thought should be started at this time. The WGDM had decided to wait until the current set of comparisons was finished before deciding on any further comparisons. This was accepted and agreed.

The MePWG confirmed its request for the CCL to delegate to them the authority to decide whether or not to start a key comparison of iodine-stabilized Nd:YAG lasers operating at 532 nm wavelength. This was because the start of such a key comparison, if the comparison was deemed necessary, would likely be before the next meeting of the CCL. The meeting accepted and approved the proposal.

9 WORK AT THE BIPM

9.1 BIPM ongoing key comparison at 633 nm

The ongoing key comparison at 633 nm, known as BIPM.L-K10, was discussed. This comparison posed some interesting questions as to the statement of degrees of equivalence for the BIPM key comparison database. Generally, as the comparison progressed, lasers which took part were adjusted, taking into account the data being analyzed, and at the end of the comparison most lasers were in a better state than they were at the start. This was a peculiarity of this comparison, in contrast to dimensional metrology comparisons where the traveling standard usually becomes more degraded with each measurement. However, both sets of data (pre- and post-adjustment) were presented in the *Metrologia* reports so this could be analysed by those who were interested.

Dr Picard presented the current draft of the report which was being prepared for entry into the BIPM key comparison database. The format used was the same as for other key comparisons. The data included a list of participants, dates of measurement, references to publications in *Metrologia*, individual results, summaries of results (tables and graphs) and tables of degrees of

equivalence, based on laser BIPM-4 as the reference laser. This data and the interpretation of the degrees of equivalence were discussed.

What was important was the stability of the NMIs' lasers, not the initial offset from the BIPM-4 reference value. Many NMIs have several reference lasers, all with different offsets from the BIPM-4 frequency, but these lasers were very stable and so knowledge of the offset allowed use of the lasers for measuring the frequency of test lasers. The frequencies of lasers of most NMIs agreed with that of the reference laser BIPM-4 within two standard deviations. There was no evidence for drift of any laser with respect to any other(s) so the conclusion was that the lasers were stable and were considered equivalent. For future comparisons, Mr Chartier suggested to report the difference from the value of the definition (*Mise en Pratique*) rather than from the value of BIPM-4.

A discussion was then started on the question of how to distinguish between the technology transfer role of BIPM and the key comparison exercise. Mr Chartier pointed out that since 1993 the same procedure had been applied as described in paragraph 3.2 of *Metrologia*, 1997, **34**, 297-300, and that in each measurement report both the first and final results are given.

In conclusion, it was proposed that the results of BIPM.L-K10 be published in the BIPM key comparison database in the manner in which they had been presented to the CCL, but with the following changes: the large table of degrees of mutual equivalence would be deleted; the value of the BIPM-4 laser would be used as the key comparison reference value; and a statement would be added to the results emphasizing that there is no significance attached to any difference from the reference value within a range of 2 sigma. This proposal was accepted.

9.2 Other international comparisons of stabilized lasers

The MePWG had noted that the only key comparison in stabilized lasers was BIPM.L-K10 at 633 nm. The planned retirement of Mr Chartier early in 2002 represented a loss of a considerable experience for the performance of laser comparisons. This would need to be taken into account when planning any future comparisons of lasers. Provision of facilities at the BIPM would also be important, and it would be necessary to make full use of the latest technology, such as comb generators, to work towards the BIPM maintaining a suitable capability for laser comparisons in the future.

It was thought that the ongoing comparison at 633 nm would be the mainstay of the work, but with work on the 532 nm Nd:YAG laser becoming more

prevalent. It was thought that the comparisons at 633 nm and 532 nm would continue via the BIPM. It was proposed that the decision on whether or not to instigate a CCL (or CIPM) key comparison at 532 nm would be delegated to the MePWG. This proposal was accepted.

It was proposed that, for all future key comparisons of laser frequencies, a strict protocol document would be prepared in advance, and participants would be asked to measure the frequency of an unknown laser. Prior to taking part, participants could undertake any bilateral or other comparisons in order to establish their frequency offsets and uncertainties (for example, using two lasers at each NMI). This proposal was accepted.

9.3 Research and introduction of new techniques

It was quite clear that research into using frequency-comb technologies would be of great importance for future frequency comparisons. The BIPM has a femtosecond comb which it was researching with help from the JILA. It would soon have the ability to measure frequencies of 633 nm and 532 nm radiations using the comb. Whether this would involve a travelling comb, or a travelling laser, with a fixed comb at the BIPM, was unclear. However, Mr Chartier thought that measurements using the BIPM comb at an NMI would probably be limited to operation at 633 nm.

9.4 Nanometrology

Dr Vitushkin presented an overview of the WGDM DG7 work in nanometrology. A detailed presentation had taken place in the WGDM meeting of the previous two days and interested parties were directed to examine the reports which would be placed on the WGDM web pages on the BIPM web server.

9.5 Collaboration with national laboratories

It was thought that combs could be of benefit to smaller NMIs in each region, rather than the larger ones – a good comb system could be a useful resource for a region. Femtosecond comb measurements at 633 nm may be easier than direct frequency comparison of stabilized lasers.

The comb work at the BIPM was also important for the comparison of CCTF frequency standards. The fountain clocks were now working at an accuracy of less than 10^{-15} , whereas the uncertainty associated with satellite-based frequency comparisons was of the order of 10^{-15} . Portable optical frequency

standards could be the reference for short-term stability and may therefore be beneficial for performing these frequency comparisons.

10 CCL WORKING GROUPS: COMPOSITION AND TERMS OF REFERENCE

Dr Pekelsky asked whether or not the terms of reference of the WGDM ought to be amended to include the work it performs, on behalf of the CCL, concerning the CMC submission and review. However, this would require a formal tabling before the CCL, and unless there was an urgent need for this, it could be left until the next CCL. The duration of chairmanship of the working groups was discussed. Dr Quinn reminded the meeting that as the two working groups of the CCL were advisory groups, the chairmanship of each group was for the period between the meetings of the CCL. As such, it was necessary to nominate and approve chairmen for the two groups for the period up to the next CCL meeting. The president of the CCL asked if there were any nominations for new chairmen of the two working groups. None were proposed. The two current chairmen, Dr Gill and Dr Pekelsky, were asked if they were willing to continue on as chairmen; they both agreed. The meeting agreed that Dr Gill should continue as chairman of the MePWG, and Dr Pekelsky should continue as the chairman of the WGDM.

Membership of the two working groups was discussed. Full members of the working groups must be CCL members or observers. Other members are guests. There were formal lists of membership of the two working groups, authorized by the CCL. The lists were updated. There were no requests to leave the membership of the WGDM, and the UME (Turkey) asked to join. There were no requests to leave the MePWG, and requests to join were made by the CENAM (Mexico), CMI (Czech Republic), IMGC-CNR (Italy), MIKES (Finland), NMi VSL (The Netherlands), and the UME (Turkey). The amendments to the membership lists of the two working groups were approved.

There was discussion as to whether or not a joint working group between the CCL and CCTF would be beneficial, due to the common work of the two Consultative Committees. It was felt that, with the CCTF producing a list of secondary frequencies for the realization of the second, there could be

potential disagreement between the frequencies of the CCTF list and the frequencies in the *Mise en Pratique*. A way of avoiding this situation would be to establish a new working group, drawing members from both committees. The meeting unanimously agreed to the formation of such a working group and requested Dr Quinn to contact the appropriate persons in the CCTF.

11 RECOMMENDATIONS TO THE CIPM

The CCL presented four recommendations.

Recommendation CCL 1 (2001) on the scope of the *Mise en Pratique* was adopted.

Recommendation CCL 2 (2001) on the development of optical comb technology was adopted.

Recommendation CCL 3 (2001) on the revision of recommended radiations was adopted.

Recommendations CCL 4 (2001) on the radiations of spectral lamps and other sources was adopted.

Provisional values for the frequencies of stabilized lasers were discussed.

12 OTHER BUSINESS

Before the meeting was concluded, Dr Quinn addressed the meeting and spoke of the work of Mr Chartier, who was to retire from the BIPM early in 2002. Dr Quinn thanked Mr Chartier, on behalf of all those at the meeting, for all of his work over many years in the Length section at the BIPM, and also for the kind help given by Mr Chartier to all the representatives of so many NMIs with whom he had worked during his time at the BIPM. The meeting warmly applauded Mr Chartier.

Dr Quinn informed the meeting that when Mr Chartier leaves the BIPM, Dr Andrew Wallard, from NPL, will take over as the head of the BIPM Length section, as well as becoming the Deputy Director and Director designate of the BIPM.

13 NEXT MEETING OF THE CCL

The WGDM felt that the meetings of the CCL should be more frequent than every four years, in order to progress the work of the MRA, particularly to discuss and approve the results of the CCL key comparisons. For the next few years, it may be more appropriate for the CCL to meet every two years. The individual working groups could meet more frequently if necessary.

However, it would be beneficial to try to set up a joint committee of the CCL and CCTF before the next meeting of either of these two Consultative Committees.

Bearing in mind these discussions, and considering the need to set a provisional date, it was decided that the date of the next CCL would be provisionally set as September 2003, with confirmation of the exact date to be made after discussions within the working groups, including the new joint CCL-CCTF working group. It would be beneficial if the WGDM, and if necessary the MePWG, could meet for two days immediately prior to the CCL meeting.

The president expressed his gratitude to all those present for a lively and fruitful meeting.

The meeting was closed.

Dr A. Sacconi and Dr A. Lewis, Rapporteurs

February 2002

revised December 2002

**Recommendations of the
Consultative Committee for Length**

**submitted to the
International Committee for Weights and Measures**

RECOMMENDATION CCL 1 (2001):**Scope of the *mise en pratique***

The Consultative Committee for Length,

considering that

- there is an increasing move towards optical frequencies for time-related activities;
- there continues to be a general widening of the scope of application of the recommended radiations of the *Mise en Pratique* to cover not only dimensional metrology and the realization of the metre, but also high-resolution spectroscopy, atomic and molecular physics, fundamental constants and telecommunications;

taking note of the Consultative Committee for Time and Frequency request for a list of radiations suitable for secondary representations of the second;

proposes a more encompassing title for the *Mise en Pratique*, such as “Recommended radiations for the realization of the definition of the metre and other optical frequency standards, including secondary representations of the second”.

RECOMMENDATION CCL 2 (2001):
Development of optical comb technology

The Consultative Committee for Length,

considering that

- new femtosecond comb techniques have clear significance for relating the frequency of high-stability optical frequency standards to that of the frequency standard realizing the SI second;
- these techniques represent a convenient measurement technique for providing traceability to the International System of Units (SI);
- comb technology can also provide frequency sources as well as a measurement technique;

recognizes these techniques as timely and appropriate, and

recommends further research to fully investigate the capability of the techniques;

welcomes validations now being made by comparison with other frequency-chain techniques;

urges national metrology institutes and other laboratories to pursue this technology to the highest level of accuracy achievable and also to seek simplicity so as to encourage widespread application.

RECOMMENDATION CCL 3 (2001):
Revision of recommended radiations

The Consultative Committee for Length,

considering that

- a number of new frequency values for radiations of high-stability cold atom and ion standards already listed on the recommended radiations list are now available;
- the frequencies of radiations of several new cold-ion species have also recently been measured;
- new and improved values for a number of optical frequency standards based on gas cells have been determined, including the wavelength region of interest to optical telecommunications;

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

- updated frequency values for cold Ca, H, and the trapped Sr^+ ion;
- frequency values for new cold-ion species including trapped Hg^+ , trapped In^+ and trapped Yb^+ ;
- updated frequency values for Rb-stabilized lasers, iodine-stabilized Nd:YAG and He-Ne lasers, methane-stabilized He-Ne lasers and OsO_4 -stabilized CO_2 lasers at 10 μm ;
- frequency values for standards relevant to the optical communications bands, including rubidium- and acetylene-stabilized lasers.

RECOMMENDATION CCL 4 (2001):
Radiations of spectral lamps and other sources

The Consultative Committee for Length,

considering that

- a significant number of new and high-accuracy frequency values for various cold atoms and ions have been recently measured, which should be added to the Consultative Committee for Length list of recommended radiations;
- new and more accurate gas-cell based standards have also been developed and measured;
- a number of existing recommended radiations such as certain iodine-stabilized laser standards have values that are unlikely to be further improved;

recognizes that these radiations (including the iodine-stabilized references at 640 nm, 612 nm, 515 nm and 543 nm) should be moved to the list for radiations of spectral lamps and other sources, but reiterates that these radiations continue to be appropriate radiations for the realization of the metre.

**Recommendation of the
Consultative Committee for Length**

**adopted by the
International Committee for Weights and Measures**

RECOMMENDATION 1 (CI-2002):
Revision of the practical realization of the definition of the metre

The International Committee for Weights and Measures,

recalling

- that in 1983 the 17th General Conference (CGPM) adopted a new definition of the metre;
- that in the same year the CGPM invited the International Committee (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 the CIPM adopted Recommendation 1 (CI-1983) (*mise en pratique* of the definition of the metre) to the effect
 - that the metre should be realized by one of the following methods:
 - (a) by means of the length l of the path travelled in vacuum by a plane electromagnetic wave in a time t ; this length is obtained from the measured time t , using the relation $l = c_0 \cdot t$ and the value of the speed of light in vacuum $c_0 = 299\,792\,458$ m/s,
 - (b) by means of the wavelength in vacuum λ of a plane electromagnetic wave of frequency f ; this wavelength is obtained from the measured frequency f using the relation $\lambda = c_0 / f$ and the value of the speed of light in vacuum $c_0 = 299\,792\,458$ m/s,
 - (c) by means of one of the radiations from the list below, whose stated wavelength in vacuum or whose stated frequency can be used with the uncertainty shown, provided that the given specifications and accepted good practice are followed;

- that in all cases any necessary corrections be applied to take account of actual conditions such as diffraction, gravitation or imperfection in the vacuum;
- that in the context of general relativity, the metre is considered a unit of proper length. Its definition, therefore, applies only within a spatial extent sufficiently small that the effects of the non-uniformity of the gravitational field can be ignored (note that, at the surface of the Earth, this effect in the vertical direction is about 1 part in 10^{16} per metre). In this case, the effects to be taken into account are those of special relativity only. The local methods for the realization of the metre recommended in (b) and (c) provide the proper metre but not necessarily that given in (a). Method (a) should therefore be restricted to lengths l which are sufficiently short for the effects predicted by general relativity to be negligible with respect to the uncertainties of realization. For advice on the interpretation of measurements in which this is not the case, see the report of the Consultative Committee for Time and Frequency (CCTF) Working Group on the Application of General Relativity to Metrology (Application of general relativity to metrology, *Metrologia*, 1997, **34**, 261-290);
- that the CIPM had already recommended a list of radiations for this purpose;

recalling also that in 1992 and in 1997 the CIPM revised the practical realization of the definition of the metre;

considering

- that science and technology continue to demand improved accuracy in the realization of the metre;
- that since 1997 work in national laboratories, in the BIPM and elsewhere has identified new radiations and methods for their realization which lead to lower uncertainties;
- that there is an increasing move towards optical frequencies for time-related activities, and that there continues to be a general widening of the scope of application of the recommended radiations of the *mise en pratique* to cover not only dimensional metrology and the realization of the metre, but also high-resolution spectroscopy, atomic and molecular physics, fundamental constants and telecommunication;
- that a number of new frequency values with reduced uncertainties for radiations of high-stability cold atom and ion standards already listed in the recommended radiations list are now available, that the frequencies of

radiations of several new cold atom and ion species have also recently been measured, and that new improved values with substantially reduced uncertainties for a number of optical frequency standards based on gas cells have been determined, including the wavelength region of interest to optical telecommunications;

- that new femtosecond comb techniques have clear significance for relating the frequency of high-stability optical frequency standards to that of the frequency standard realizing the SI second, that these techniques represent a convenient measurement technique for providing traceability to the International System of Units (SI) and that comb technology also can provide frequency sources as well as a measurement technique;

recognizes comb techniques as timely and appropriate, and recommends further research to fully investigate the capability of the techniques;

welcomes validations now being made of comb techniques by comparison with other frequency chain techniques;

urges national metrology institutes and other laboratories to pursue the comb technique to the highest level of accuracy achievable and also to seek simplicity so as to encourage widespread application;

recommends

- that the list of recommended radiations given by the CIPM in 1997 (Recommendation 1 (CI-1997)) be replaced by the list of radiations given below, including
 - updated frequency values for cold Ca atom, H atom and the trapped Sr^+ ion,
 - frequency values for new cold ion species including trapped Hg^+ ion, trapped In^+ ion and trapped Yb^+ ion,
 - updated frequency values for Rb-stabilized lasers, I_2 -stabilized Nd:YAG and He-Ne lasers, CH_4 -stabilized He-Ne lasers and OsO_4 -stabilized CO_2 lasers at 10 μm ,
 - frequency values for standards relevant to the optical communications bands, including Rb- and C_2H_2 -stabilized lasers.

CIPM list of approved radiations for the practical realization of the metre, 2002: frequencies and vacuum wavelengths

This list replaces those published in *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1983, **51**, 25-28, 1992, **60**, 141-144, 1997, **65**, 243-252 and *Metrologia*, 1984, **19**, 165-166, 1993/94, **30**, 523-525, 1999, **36**, 211-215.

In this list, the values of the frequency f and of the vacuum wavelength λ should be related exactly by the relation $\lambda \cdot f = c_0$, with $c_0 = 299\,792\,458$ 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 L 2 of the Consultative Committee for Length (CCL): Source data for the list of recommended radiations, 2001.

It should be noted that for several of the listed radiations, few independent values are available, so the estimated uncertainties may not 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. Such radiations are listed in Appendix L 3 of the CCL: Absolute frequency of the other transitions related to those adopted as recommended and frequency intervals between transitions and hyperfine components.

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 CCL⁽¹⁾ or to the BIPM.

⁽¹⁾ At its 1997 meeting, the CIPM changed the name of the Consultative Committee for the Definition of the Metre (CCDM) to that of Consultative Committee for Length (CCL).

1 Recommended radiations of stabilized lasers

1.1 Absorbing ion $^{115}\text{In}^+$, $5s^2\ ^1S_0 - 5s5p\ ^3P_0$ transition

The values $f = 1\,267\,402\,452\,899.92\text{ kHz}$

$$\lambda = 236\,540\,853.549\,75\text{ fm}$$

are associated with a relative standard uncertainty of 3.6×10^{-13} .

1.2 Absorbing atom ^1H , $1S-2S$ two-photon transition

The values $f = 1\,233\,030\,706\,593.55\text{ kHz}$

$$\lambda = 243\,134\,624.626\,04\text{ fm}$$

with a relative standard uncertainty of 2.0×10^{-13} apply to the laser frequency stabilized to the two-photon transition in a cold hydrogen beam, corrected to zero laser power, and for atoms which are effectively stationary, i.e. the values are corrected for second-order Doppler shift.

1.3 Absorbing ion $^{199}\text{Hg}^+$, $5d^{10}6s\ ^2S_{1/2} (F=0) - 5d^96s^2\ ^2D_{5/2} (F=2) \Delta m_F=0$ transition

The values $f = 1\,064\,721\,609\,899\,143\text{ Hz}$

$$\lambda = 281\,568\,867.591\,969\text{ fm}$$

with a relative standard uncertainty of 1.9×10^{-14} are corrected for the second-order Zeeman shift.

1.4 Absorbing ion $^{171}\text{Yb}^+$, $6s\ ^2S_{1/2} (F=0, m_F=0) - 5d\ ^2D_{3/2} (F=2, m_F=0)$ transition

The values $f = 688\,358\,979\,309\,312\text{ Hz}$

$$\lambda = 435\,517\,610.739\,69\text{ fm}$$

are associated with a relative standard uncertainty of 2.9×10^{-14} .

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

The values $f = 642\,121\,496\,772.6\text{ kHz}$

$$\lambda = 466\,878\,090.061\text{ fm}$$

with a relative standard uncertainty of 4.0×10^{-12} are corrected for the AC Stark shift and second-order Zeeman shift.

1.6 Absorbing molecule $^{127}\text{I}_2$, a_{10} component, R(56) 32-0 transition⁽²⁾The values $f = 563\,260\,223\,513\text{ kHz}$

$$\lambda = 532\,245\,036.104\text{ fm}$$

with a relative standard uncertainty of 8.9×10^{-12} apply to the radiation of a frequency-doubled Nd:YAG laser, stabilized with an iodine cell external to the laser, having a cold-finger temperature of $-15\text{ }^\circ\text{C}$.

1.7 Absorbing molecule $^{127}\text{I}_2$, a_{16} , or f, component, R(127) 11-5 transitionThe values $f = 473\,612\,353\,604\text{ kHz}$

$$\lambda = 632\,991\,212.58\text{ fm}$$

with a relative standard uncertainty of 2.1×10^{-11} apply to the radiation of a He-Ne laser with an internal iodine cell, stabilized using the third harmonic detection technique, subject to the conditions:

- cell-wall temperature $(25 \pm 5)\text{ }^\circ\text{C}$ ⁽³⁾;
- cold-finger temperature $(15.0 \pm 0.2)\text{ }^\circ\text{C}$;
- frequency modulation width, peak-to-peak, $(6.0 \pm 0.3)\text{ MHz}$;
- one-way intracavity beam power (i.e. the output power divided by the transmittance of the output mirror) $(10 \pm 5)\text{ mW}$ for an absolute value of the power shift coefficient $\leq 1.0\text{ kHz/mW}$.

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 L 2 of the CCL.

1.8 Absorbing atom ^{40}Ca , $^1\text{S}_0 - ^3\text{P}_1$; $\Delta m_J = 0$ transitionThe values $f = 455\,986\,240\,494\,150\text{ Hz}$

$$\lambda = 657\,459\,439.291\,67\text{ fm}$$

with a relative standard uncertainty of 1.1×10^{-13} apply to the radiation of a laser stabilized to Ca atoms. The values correspond to the mean frequency of

⁽²⁾ All transitions in I_2 refer to the $\text{B}^3\Pi\,0_u^+ - \text{X}^1\Sigma_g^+$ system from now on.

⁽³⁾ For the specification of operating conditions, such as temperature, modulation width and laser power, the symbols \pm refer to a tolerance, not an uncertainty.

the two recoil-split components for atoms which are effectively stationary, i.e. the values are corrected for the second-order Doppler shift.

1.9 Absorbing ion $^{88}\text{Sr}^+$, $5\ ^2\text{S}_{1/2} - 4\ ^2\text{D}_{5/2}$ transition

The values $f = 444\,779\,044\,095.5\text{ kHz}$

$$\lambda = 674\,025\,590.8631\text{ fm}$$

with a relative standard uncertainty of 7.9×10^{-13} apply to the radiation of a laser stabilized to the transition observed with a trapped and cooled strontium ion. The values correspond to the centre of the Zeeman multiplet.

1.10 Absorbing atom ^{85}Rb , $5\text{S}_{1/2} (F_g=3) - 5\text{D}_{5/2} (F_e=5)$ two-photon transition

The values $f = 385\,285\,142\,375\text{ kHz}$

$$\lambda = 778\,105\,421.23\text{ fm}$$

with a relative standard uncertainty of 1.3×10^{-11} apply to the radiation of a laser stabilized to the centre of the two-photon transition. The values apply to a rubidium cell at a temperature below $100\text{ }^\circ\text{C}$ and are corrected to zero laser power.

1.11 Absorbing molecule $^{13}\text{C}_2\text{H}_2$, P(16) ($\nu_1 + \nu_3$) transition

The values $f = 194\,369\,569.4\text{ MHz}$

$$\lambda = 1\,542\,383\,712\text{ fm}$$

with a provisional relative standard uncertainty of 5.2×10^{-10} apply to the radiation of a laser stabilized with an external $^{13}\text{C}_2\text{H}_2$ cell at a pressure range from 1.3 Pa to 5.3 Pa .

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

1.12.1 The values $f = 88\,376\,181\,600.18\text{ kHz}$

$$\lambda = 3\,392\,231\,397.327\text{ fm}$$

with a 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 values correspond to the mean frequency of the two recoil-split components for molecules which are effectively stationary, i.e. the values are corrected for second-order Doppler shift.

1.12.2 The values $f = 88\,376\,181\,600.5\text{ kHz}$

$$\lambda = 3\,392\,231\,397.31\text{ fm}$$

with a relative standard uncertainty of 2.3×10^{-11} apply to the radiation of a He-Ne laser stabilized to the centre of the unresolved hyperfine-structure of a methane cell, within or external to the laser, held at room temperature and subject to the following conditions:

- methane pressure $\leq 3\text{ Pa}$;
- mean one-way intracavity surface power density (i.e., the output power density divided by the transmittance of the output mirror) $\leq 10^4\text{ W m}^{-2}$;
- radius of wavefront curvature $\geq 1\text{ m}$;
- inequality of power between counter-propagating waves $\leq 5\%$;
- servo-referenced to a detector placed at the output facing the laser tube.

1.13 Absorbing molecule OsO_4 , transition in coincidence with the $^{12}\text{C}^{16}\text{O}_2$, $\text{R}(10)(00^01) - (10^00)$ laser line

The values $f = 29\,054\,057\,446\,579\text{ Hz}$

$$\lambda = 10\,318\,436\,884.460\text{ fm}$$

with a relative standard uncertainty of 1.4×10^{-13} apply to the radiation of a CO_2 laser stabilized with an external OsO_4 cell at a pressure below 0.2 Pa . This laser line is selected due to its reduced sensitivity to pressure shifts and other effects, in comparison with the previously selected $\text{R}(12)$ laser line.

2 Recommended values for radiations of spectral lamps and other sources

2.1 ^{86}Kr spectral lamp radiation, $5d_5 - 2p_{10}$ transition

The value $\lambda = 605\,780\,210.3\text{ fm}$

with a relative expanded uncertainty $U = 3.9 \times 10^{-9}$, where $U = ku_c$ ($k = 3$), u_c being the combined standard uncertainty, applies to the radiation emitted by a discharge lamp. The radiation of ^{86}Kr is obtained by means of a hot-cathode discharge lamp containing ^{86}Kr , of a purity not less than 99% , in sufficient quantity to assure the presence of solid krypton at a temperature of 64 K , this lamp having a capillary with an inner diameter from 2 mm to 4 mm and a wall thickness of about 1 mm .

It is estimated that the wavelength of the radiation emitted by the positive

column is equal, to within 1 part in 10^8 , to the wavelength corresponding to the transition between the unperturbed levels, when the following conditions are satisfied:

- the capillary is observed end-on from the side closest to the anode;
- the lower part of the lamp, including the capillary, is immersed in a cold bath maintained at a temperature within one degree of the triple point of nitrogen;
- the current density in the capillary is $(0.3 \pm 0.1) \text{ A} \cdot \text{cm}^{-2}$.

2.2 ^{86}Kr , ^{198}Hg and ^{114}Cd spectral lamp radiations

Vacuum wavelengths, λ , for ^{86}Kr , ^{198}Hg and ^{114}Cd transitions

| Atom | Transition | λ / pm |
|-------------------|-------------------|-----------------------|
| ^{86}Kr | $2p_9 - 5d'_4$ | 645 807.20 |
| ^{86}Kr | $2p_8 - 5d_4$ | 642 280.06 |
| ^{86}Kr | $1s_3 - 3p_{10}$ | 565 112.86 |
| ^{86}Kr | $1s_4 - 3p_8$ | 450 361.62 |
| ^{198}Hg | $6^1P_1 - 6^1D_2$ | 579 226.83 |
| ^{198}Hg | $6^1P_1 - 6^3D_2$ | 577 119.83 |
| ^{198}Hg | $6^3P_2 - 7^3S_1$ | 546 227.05 |
| ^{198}Hg | $6^3P_1 - 7^3S_1$ | 435 956.24 |
| ^{114}Cd | $5^1P_1 - 5^1D_2$ | 644 024.80 |
| ^{114}Cd | $5^3P_2 - 6^3S_1$ | 508 723.79 |
| ^{114}Cd | $5^3P_1 - 6^3S_1$ | 480 125.21 |
| ^{114}Cd | $5^3P_0 - 6^3S_1$ | 467 945.81 |

For ^{86}Kr , the above values with a relative expanded uncertainty $U = 2 \times 10^{-8}$, where $U = ku_c$ ($k = 3$), apply to radiations emitted by a lamp operated under conditions similar to those specified in Section 2.1.

For ^{198}Hg , the above values with a relative expanded uncertainty $U = 5 \times 10^{-8}$, where $U = ku_c$ ($k = 3$), apply to radiations emitted by a discharge lamp when the following conditions are met:

- the radiations are produced using a discharge lamp without electrodes containing ^{198}Hg , of a purity not less than 98 %, and argon at a pressure from 0.5 mm Hg to 1.0 mm Hg (66 Pa to 133 Pa);

- the internal diameter of the capillary of the lamp is about 5 mm, and the radiation is observed transversely;
- the lamp is excited by a high-frequency field at a moderate power and is maintained at a temperature less than 10 °C;
- it is preferred that the volume of the lamp be greater than 20 cm³.

For ¹¹⁴Cd, the above values with a relative expanded uncertainty $U = 7 \times 10^{-8}$, where $U = ku_c$ ($k = 3$), apply to radiations emitted by a discharge lamp under the following conditions:

- the radiations are generated using a discharge lamp without electrodes, containing ¹¹⁴Cd of a purity not less than 95 %, and argon at a pressure of about 1 mm Hg (133 Pa) at ambient temperature;
- the internal diameter of the capillary of the lamp is about 5 mm, and the radiation is observed transversely;
- the lamp is excited by a high-frequency field at a moderate power and is maintained at a temperature such that the green line is not reversed.

2.3 Absorbing molecule ¹²⁷I₂, a₃ component, P(13) 43-0 transition

The values $f = 582\,490\,603.38$ MHz

$$\lambda = 514\,673\,466.4 \text{ fm}$$

with a relative standard uncertainty of 2.5×10^{-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.

2.4 Absorbing molecule ¹²⁷I₂, a₉ component, R(12) 26-0 transition

The values $f = 551\,579\,482.97$ MHz

$$\lambda = 543\,516\,333.1 \text{ fm}$$

with a relative standard uncertainty of 2.5×10^{-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.

2.5 Absorbing molecule ¹²⁷I₂, a₁ component, P(62) 17-1 transition

The values $f = 520\,206\,808.4$ MHz

$$\lambda = 576\,294\,760.4 \text{ fm}$$

with a 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 $(6 \pm 2)^\circ\text{C}$.

2.6 Absorbing molecule $^{127}\text{I}_2$, a_7 component, R(47) 9-2 transition

The values

$$f = 489\,880\,354.9 \text{ MHz}$$

$$\lambda = 611\,970\,770.0 \text{ fm}$$

with a 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 $(-5 \pm 2)^\circ\text{C}$.

2.7 Absorbing molecule $^{127}\text{I}_2$, a_9 component, P(10) 8-5 transition

The values

$$f = 468\,218\,332.4 \text{ MHz}$$

$$\lambda = 640\,283\,468.7 \text{ fm}$$

with a relative standard uncertainty of 4.5×10^{-10} apply to the radiation of a He-Ne laser stabilized with an internal iodine cell having a cold-finger temperature of $(16 \pm 1)^\circ\text{C}$ and a frequency modulation width, peak-to-peak, of $(6 \pm 1) \text{ MHz}$.

APPENDIX L 1.**Working documents submitted to the CCL at its 10th meeting**

Working documents of the CCL can be obtained from the BIPM in their original version. The complete list of documents is given on page 59.

APPENDIX L 2.

Source data for the list of recommended radiations, 2001

This appendix has been derived from data presented at the 10th meeting of the CCL 2001, those of 1982 published in Appendix M 4 of the report of the 7th meeting of the CCDM 1982, of 1992 published in Appendix M 2 of the report of the 8th meeting of the CCDM 1992, and of 1997 published in Appendix M 2 of the report of the 9th meeting of the CCDM 1997 [1]. The source data having numbers in square brackets refer to the reference list at the end of this document. The source data having other types of indication refer to subsequent sections in this document. There have been a number of additional high-accuracy frequency comb measurements since the CCL 2001. Where appropriate, a comment in footnote is added within the body of the same data.

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.

The frequency values and uncertainties adopted by the 10th meeting of the CCL have been rounded in accordance with good metrological practice, bearing in mind the limited number of absolute measurements of a particular radiation in many cases, and broadly in agreement with consistency guidelines drawn up in [2].

It should be noted that the 2001 revision of the recommended frequency and uncertainty of the 633 nm radiation resulted in a correction of many of the other recommended iodine-stabilized laser source radiations. The component of the recommended radiation of 633 nm and near-lying components are denoted by letters, while all other hyperfine components are denoted by letters having a subscript specified by a number, according to [3]. The combined standard and relative uncertainties are denoted by u_c and u_c/y , respectively, according to [4].

1 Recommended radiations of stabilized lasers

1.1 Absorbing ion $^{115}\text{In}^+$, $5s^2\ ^1S_0 - 5s5p\ ^3P_0$ transition, $\lambda \approx 236\text{ nm}$

Adopted value $f = 1\,267\,402\,452\,899.92\ (46)\text{ kHz}$ $u_c/y = 3.6 \times 10^{-13}$

for which $\lambda = 236\,540\,853.549\,75\ (9)\text{ fm}$ $u_c/y = 3.6 \times 10^{-13}$

calculated from:

| f/kHz | u_c/y | Source data |
|----------------------|-----------------------|-------------|
| 1 267 402 452 899.92 | 1.8×10^{-13} | [5] |

With this value, based on one single determination, the CCL considered it prudent to double the relative standard uncertainty giving 3.6×10^{-13} .

1.2 Absorbing atom ^1H , $1S-2S$ two-photon transition, $\lambda \approx 243\text{ nm}$

Adopted value $f = 1\,233\,030\,706\,593.55\ (25)\text{ kHz}$ $u_c/y = 2.0 \times 10^{-13}$

for which $\lambda = 243\,134\,624.626\,04\ (5)\text{ fm}$ $u_c/y = 2.0 \times 10^{-13}$

calculated from:

| $(f_{(1S-2S)}/2)/\text{kHz}$ | u_c/y | Source data |
|---|-----------------------|-------------|
| 1 233 030 706 593.67 | 3.4×10^{-13} | 1.2-1 |
| 1 233 030 706 593.55 | 1.9×10^{-14} | 1.2-2 |
| Weighted mean $f = 1\,233\,030\,706\,593.55\text{ kHz}$ | | |

The CCL considered it prudent to attribute a standard uncertainty of 2.0×10^{-13} .

Source data

1.2-1 Udem *et al.* [6, 7] give the value of the frequency of the two-photon transition as

$$f_{(1S-2S)} = 2\,466\,061\,413\,187.34\text{ kHz} \quad u_c/y = 3.4 \times 10^{-13}.$$

For a single-photon, one calculates:

$$f_{(1S-2S)}/2 = 1\,233\,030\,706\,593.67\text{ kHz} \quad u_c/y = 3.4 \times 10^{-13}.$$

1.2-2 Niering *et al.* [8] give the value of the frequency of the two-photon transition as

$$f_{(1S-2S)} = 2\,466\,061\,413\,187.103 \text{ kHz} \quad u_c/y = 1.9 \times 10^{-14}.$$

For a single-photon, one calculates:

$$f_{(1S-2S)}/2 = 1\,233\,030\,706\,593.551 \text{ kHz} \quad u_c/y = 1.9 \times 10^{-14}.$$

1.3 Absorbing ion $^{199}\text{Hg}^+$, $5d^{10}6s^2S_{1/2}$ ($F=0$) – $5d^96s^2D_{5/2}$ ($F=2$) $\Delta m_F = 0$ transition, $\lambda \approx 282 \text{ nm}$

$$\text{Adopted value } f = 1\,064\,721\,609\,899\,143 \text{ (20) Hz} \quad u_c/y = 1.9 \times 10^{-14}$$

$$\text{for which } \lambda = 281\,568\,867.591\,969 \text{ (5) fm} \quad u_c/y = 1.9 \times 10^{-14}$$

calculated from:

| f/Hz | u_c/y | Source data |
|---|-----------------------|-------------|
| 1 064 721 609 899 143 | 9.4×10^{-15} | [9] |
| 1 064 721 609 899 120 | 2.3×10^{-13} | [10] |
| Weighted mean $f = 1\,064\,721\,609\,899\,143 \text{ Hz}$ | | |

With this value, based on only two separate determinations, the CCL considered it prudent to adopt a standard uncertainty in frequency of 20 Hz, corresponding to a relative standard uncertainty of 1.9×10^{-14} .

1.4 Absorbing ion $^{171}\text{Yb}^+$, $6s^2S_{1/2}$ ($F=0$, $m_F=0$) – $5d^2D_{3/2}$ ($F=2$, $m_F=0$) transition, $\lambda \approx 436 \text{ nm}$

$$\text{Adopted value } f = 688\,358\,979\,309\,312 \text{ (20) Hz} \quad u_c/y = 2.9 \times 10^{-14}$$

$$\text{for which } \lambda = 435\,517\,610.739\,69 \text{ (1) fm} \quad u_c/y = 2.9 \times 10^{-14}$$

calculated from:

| f/Hz | u_c/y | Source data |
|---------------------|-----------------------|-------------|
| 688 358 979 309 312 | 8.7×10^{-15} | [11] |

With this value, based on only one determination, the CCL considered it prudent to adopt a relative standard uncertainty equal three times the reported uncertainty of 6 Hz giving 20 Hz, corresponding to a relative standard uncertainty of 2.9×10^{-14} .

1.5 Absorbing ion $^{171}\text{Yb}^+$, $^2\text{S}_{1/2}$ ($F = 0$, $m_F = 0$) – $^2\text{F}_{7/2}$ ($F = 3$, $m_F = 0$) transition, $\lambda \approx 467$ nm

Adopted value $f = 642\,121\,496\,772.6$ (2.6) kHz $u_c/y = 4.0 \times 10^{-12}$

for which $\lambda = 466\,878\,090.061$ (2) fm $u_c/y = 4.0 \times 10^{-12}$

calculated from:

| f/kHz | u_c/y | Source data |
|-------------------|-----------------------|-------------|
| 642 121 496 772.6 | 2.0×10^{-12} | [12] |

With this value, based on only one determination, the CCL considered it prudent to double the reported uncertainty, giving a relative uncertainty of 4.0×10^{-12} .*

1.6 Absorbing molecule $^{127}\text{I}_2$, a_{10} component, R(56) 32-0 transition, $\lambda \approx 532$ nm

Adopted value $f = 563\,260\,223\,513$ (5) kHz $u_c/y = 8.9 \times 10^{-12}$

for which $\lambda = 532\,245\,036.104$ (5) fm $u_c/y = 8.9 \times 10^{-12}$

calculated from:

| f/kHz | u_c/y | Source data |
|--|-----------------------|-------------|
| 563 260 223 515.0 | 9.2×10^{-12} | 1.6-1 |
| 563 260 223 514.5 | 8.9×10^{-12} | [14, 15] |
| 563 260 223 510.1 | 5×10^{-13} | [16] |
| Unweighted mean $f = 563\,260\,223\,513.2$ kHz | | |

The standard uncertainty calculated from the dispersion of the four values is 2.4 kHz. Taking into account the frequency dependence on the cell quality and other effects, the CCL preferred to adopt a standard uncertainty of 5 kHz, corresponding to a relative standard uncertainty of 8.9×10^{-12} .

Other $^{127}\text{I}_2$ absorbing transitions close to this transition may also be used by making reference to the following frequency differences, using the a_{10} component of the R(56) 32-0 transition as a reference, see also Section 1.6-2.

* A more precise measurement made after the CCL 2001 has confirmed the adopted uncertainty [13].

| Line No. | Transition | | Comp. $f_{xy} = [f(y, x) - f(a_{10}, R(56) 32-0)]/\text{kHz}$ | |
|----------|-------------|----------|---|------------------|
| | x | y | f_{xy} | u_c/kHz |
| 1111 | P(53) 32-0 | a_1 | 2 599 708.0 | 5.0 |
| 1110 | R(56) 32-0 | a_{10} | 0.0 | — |
| 1109 | P(83) 33-0 | a_{21} | −15 682 075.2 | 5.0 |
| | R(134) 36-0 | a_1 | −17 173 681.7 | 5.0 |
| 1108 | R(106) 34-0 | a_1 | −30 434 763.4 | 5.0 |
| 1107 | R(86) 33-0 | a_1 | −32 190 406.0 | 5.0 |
| 1106 | P(119) 35-0 | a_1 | −36 840 163.0 | 5.0 |
| 1105 | P(54) 32-0 | a_1 | −47 588 897.1 | 5.0 |
| 1104 | R(57) 32-0 | a_1 | −50 946 884.7 | 5.0 |
| 1103 | P(132) 36-0 | a_1 | −73 517 088.1 | 5.0 |
| 1101 | R(145) 37-0 | a_1 | −84 992 177.6 | 5.0 |
| | R(122) 35-0 | a_1 | −90 981 724.1 | 5.0 |
| 1100 | P(84) 33-0 | a_1 | −95 929 863.0 | 5.0 |
| 1099 | P(104) 34-0 | a_1 | −98 069 775.0 | 5.0 |
| | P(55) 32-0 | a_1 | −98 766 591.0 | 5.0 |
| 1098 | R(58) 32-0 | a_1 | −102 159 978.2 | 5.0 |
| 1097 | R(87) 33-0 | a_1 | −111 935 173.1 | 5.0 |

where $f(y, x)$ represents the frequency of the transition denoted y, x and $f(a_{10}, R(56) 32-0)$ the frequency of the reference transition. The CCL preferred to assign an uncertainty of 5 kHz to all listed frequency differences, regarding the possible influence of the quality of the iodine cell, background slopes and the small number of data for each frequency difference available.

1.6-2 The following values have been obtained for the frequency differences between several $^{127}\text{I}_2$ absorbing transitions and the R(56) 32-0 transition, at an iodine cold-finger temperature of $-15\text{ }^\circ\text{C}$ (iodine pressure = 0.83 Pa):

| Line No. | Transition | Comp. | [$f(y, x) - f(a_{10}, R(56) 32-0)$]/kHz | | | | | | | |
|----------|-------------|----------|---|---------------|----------------|----------------|---------------|------|----------------|----------|
| | | | x | y | [20] | [21] | [17] | [18] | Unw. mean | u /kHz |
| 1111 | P(53) 32-0 | a_1 | | 2 599 708.0 | 2 599 708.0 | | | | 2 599 708.0 | 0.0 |
| 1110 | R(56) 32-0 | a_{10} | | 0.0 | 0.0 | 0.0 | | | 0.0 | 0.0 |
| 1109 | P(83) 33-0 | a_{21} | | -15 682 074.1 | -15 682 076.2 | | | | -15 682 075.2 | 1.5 |
| | R(134) 36-0 | a_1 | | -17 173 680.4 | -17 173 682.9 | | | | -17 173 681.7 | 1.8 |
| 1108 | R(106) 34-0 | a_1 | | -30 434 761.5 | -30 434 765.2 | | | | -30 434 763.4 | 2.6 |
| 1107 | R(86) 33-0 | a_1 | | -32 190 404.0 | -32 190 408.0 | | | | -32 190 406.0 | 2.8 |
| 1106 | P(119) 35-0 | a_1 | | -36 840 161.5 | -36 840 164.4 | | | | -36 840 163.0 | 2.1 |
| 1105 | P(54) 32-0 | a_1 | | -47 588 892.5 | -47 588 898.2 | -47 588 899.8 | -47 588 898.0 | | -47 588 897.1 | 3.2 |
| 1104 | R(57) 32-0 | a_1 | | -50 946 880.4 | -50 946 886.4 | -50 946 887.2 | | | -50 946 884.7 | 3.7 |
| 1103 | P(132) 36-0 | a_1 | | | -73 517 088.1 | | | | | |
| 1101 | R(145) 37-0 | a_1 | | | -84 992 177.6 | | | | | |
| | R(122) 35-0 | a_1 | | | -90 981 724.1 | | | | | |
| 1100 | P(84) 33-0 | a_1 | | | -95 929 863.0 | | | | | |
| 1099 | P(104) 34-0 | a_1 | | | -98 069 775.0 | | | | | |
| | P(55) 32-0 | a_1 | | | -98 766 590.0 | -98 766 591.9 | | | -98 766 591.0 | 1.4 |
| 1098 | R(58) 32-0 | a_1 | | | -102 159 977.4 | -102 159 979.0 | | | -102 159 978.2 | 1.2 |
| 1097 | R(87) 33-0 | a_1 | | | -111 935 173.1 | | | | | |

where $f(y, x)$ represents the frequency of the transition denoted y, x and $f(a_{10}, \text{R}(56) 32-0)$ the frequency of the reference transition.

Source data

1.6-1 Holzwarth *et al.* [17] give

$$f_{a10} = 563\,260\,223\,508.7 \text{ kHz} \quad u_c = 5.2 \text{ kHz}$$

at a cold-finger temperature of -5°C (iodine pressure = 2.46 Pa)*.

Nevsky *et al.* [18] give

$$f_{a10} = 563\,260\,223\,507.8 \text{ kHz} \quad u_c/y = 2.0 \times 10^{-12}$$

at a cold-finger temperature of -5°C (iodine pressure = 2.46 Pa).

These two measurements have been carried out with the same iodine cell. Therefore, the CCL decided to consider the arithmetic mean of these two data, i.e.

$$f_{a10} = (563\,260\,223\,508.7 + 563\,260\,223\,507.8)/2 = 563\,260\,223\,508.25 \text{ kHz}.$$

For a reference temperature of -15°C (iodine pressure = 0.83 Pa), using a pressure dependence of -4.2 kHz/Pa [18], a correction of $+6.8 \text{ kHz}$ has to be applied, giving

$$f_{a10} = 563\,260\,223\,515.0 \text{ kHz} \quad u_c/y = 9.2 \times 10^{-12}.$$

1.6-2 The following values have been obtained for the frequency differences between several $^{127}\text{I}_2$ absorbing transitions and the R(56) 32-0 transition, at an iodine cold-finger temperature of -15°C (iodine pressure = 0.83 Pa): see table on page 132 (on the left).

1.7 Absorbing molecule $^{127}\text{I}_2$, a_{16} , or f, component, R(127) 11-5 transition, $\lambda \approx 633 \text{ nm}$

$$\text{Adopted value } f = 473\,612\,353\,604 (10) \text{ kHz} \quad u_c/y = 2.1 \times 10^{-11}$$

$$\text{for which } \lambda = 632\,991\,212.579 (13) \text{ fm} \quad u_c/y = 2.1 \times 10^{-11}$$

* For the iodine cold-finger temperature to iodine pressure conversion the formula derived by Gillespie and Fraser [19] has been used from now and here on.

calculated from:

| $(f_{\text{BIPM4}} - f_{\text{CIPM97}})/\text{kHz}$ | u_c/y | Source data |
|--|-----------------------|-------------|
| 8.2 | 4.0×10^{-12} | [22, 23] |
| 7.4 | 3.0×10^{-12} | [22, 24] |
| 4.2 | 1.4×10^{-11} | 1.7-1 |
| 8.2 | 5.3×10^{-12} | [12] |
| Unweighted mean $(f_{\text{BIPM4}} - f_{\text{CIPM97}}) = 7.0 \text{ kHz}$ | | |

The source data are all given in respect to the BIPM4 laser standard frequency. The relative standard uncertainty includes the uncertainty in the absolute frequency measurement and the uncertainty obtained by comparing the different frequency standards with the BIPM4 standard. The CCL proposed that the recommended radiation for the R(127) 11-5 transition, using 633 nm He-Ne lasers, no longer correspond to the a_{13} , or i, component, but is replaced by the a_{16} , or f, component, which was decided by the CIPM in 2002.

The CCL adopted a correction of the previous recommended frequency by +7 kHz, giving the frequency of the f component to be 473 612 353 604 kHz. The CCL also revised the coefficient of the tolerated one-way intracavity beam power influencing the average uncertainty of beat-frequency measurements between two stabilized lasers. This results in a combined uncertainty of $u_c = 10 \text{ kHz}$, corresponding to a relative uncertainty of $u_c/y = 2.1 \times 10^{-11}$, see Section 1.7-2. The grouped laser comparisons from national laboratories undertaken by the BIPM (1993-2000) confirm that the choice of a relative standard uncertainty of 2.1×10^{-11} is valid [25-33]. This series of comparison is a key comparison BIPM.L-K10 and is reported on the BIPM website (<http://www.bipm.org/kcdb>).

For applications where relaxed tolerances, and the resultant wider uncertainty range are acceptable, a laser operated under the conditions recommended in 1983 [34, 35] would lead to a standard uncertainty of about 50 kHz (or a relative standard uncertainty of 1×10^{-10}).

Source data

1.7-1 Sugiyama *et al.* [16] give

$$f_f = 473\,612\,353\,604.3 \text{ kHz} \quad u_c = 1.7 \text{ kHz}$$

as the frequency of the NRLM-P1 laser standard.

This value indicates that

$$f_f = f_{\text{CIPM97}} + f_{\text{corr}} \quad \text{where } f_{\text{corr}} = 7.3 \text{ kHz.}$$

In a comparison with the BIPM4 laser standard [33], they obtained

$$f_f - f_{\text{BIPM4}} = 3.1 \text{ kHz} \quad u_c = 6.4 \text{ kHz.}$$

Assuming that this frequency has been maintained since, one obtains

$$(f_{\text{BIPM4}} - f_{\text{CIPM97}}) = 4.2 \text{ kHz} \quad u_c = 6.6 \text{ kHz.}$$

1.7-2 The uncertainties resulting from variations in operational parameters are listed below.

| Parameter | Recommended Tolerance value | | Coefficient | u/kHz |
|--|-----------------------------|---------|--------------|----------------|
| Iodine cell | | | | |
| • cell-wall temperature | 25 °C | 5 °C | 0.5 kHz/°C | 2.5 |
| • cold-finger temperature | 15 °C | 0.2 °C | −15 kHz/°C | 3.0 |
| • iodine purity | | | | 5.0 |
| Frequency modulation width | | | | |
| peak-to-peak | 6 MHz | 0.3 MHz | −10 kHz/MHz | 3.0 |
| One-way intracavity | | | | |
| beam power | 10 mW | 5 mW | ≤ 1.0 kHz/mW | 5.0 |
| Beat-frequency measurements between two lasers | | | | 5.0 |
| Combined standard uncertainty $u_c = 10.0 \text{ kHz}$ | | | | |

1.8 Absorbing atom ^{40}Ca , $^1\text{S}_0 - ^3\text{P}_1$; $\Delta m_J = 0$ transition, $\lambda \approx 657 \text{ nm}$

Adopted value $f = 455\,986\,240\,494\,150\,(50) \text{ Hz}$ $u_c/y = 1.1 \times 10^{-13}$

for which $\lambda = 657\,459\,439.291\,67\,(7) \text{ fm}$ $u_c/y = 1.1 \times 10^{-13}$

calculated from:

| f/kHz | u_c/y | Source data |
|--|-----------------------|-------------|
| 455 986 240 494.158 | 5.7×10^{-14} | [9, 36] |
| 455 986 240 494.149 | 3.5×10^{-14} | [37, 38] |
| 455 986 240 494.13 | 2.5×10^{-13} | [39] |
| Weighted mean $f = 455\,986\,240\,494\,151 \text{ Hz}$ | | |

The CCL considered it prudent to assume an estimated standard uncertainty of 50 Hz, corresponding to a relative standard uncertainty of 1.1×10^{-13} .

1.9 Absorbing ion $^{88}\text{Sr}^+$, $5\ ^2\text{S}_{1/2} - 4\ ^2\text{D}_{5/2}$ transition, $\lambda \approx 674\text{ nm}$

Adopted value $f = 444\,779\,044\,095.5\ (4)\text{ kHz}$ $u_c/y = 7.9 \times 10^{-13}$

for which $\lambda = 674\,025\,590.8631\ (5)\text{ fm}$ $u_c/y = 7.9 \times 10^{-13}$

calculated from:

| f/kHz | u_c/y | Source data |
|---|-----------------------|-------------|
| 444 779 044 095.4 | 4.5×10^{-13} | [40] |
| 444 779 044 095.6 | 6.7×10^{-13} | [12] |
| Unweighted mean $f = 444\,779\,044\,095.5\text{ kHz}$ | | |

Regarding the improvement of the standard uncertainty of the measurements since the last CCL in 1997, other available values having relative standard uncertainties higher than 2×10^{-11} have not been used. The CCL considered it prudent to adopt an uncertainty of 0.35 kHz, corresponding to a relative standard uncertainty of 7.9×10^{-13} .*

1.10 Absorbing atom ^{85}Rb , $5\text{S}_{1/2}\ (F_g = 3) - 5\text{D}_{5/2}\ (F_e = 5)$ two-photon transition, $\lambda \approx 778\text{ nm}$

Adopted value $f = 385\,285\,142\,375\ (5)\text{ kHz}$ $u_c/y = 1.3 \times 10^{-11}$

for which $\lambda = 778\,105\,421.23\ (1)\text{ fm}$ $u_c/y = 1.3 \times 10^{-11}$

calculated from:

| $f_{5\text{S}_{1/2}\ (F=3) - 5\text{D}_{5/2}\ (F=5)}/2/\text{kHz}$ | u_c/y | Source data |
|--|-----------------------|-------------|
| 385 285 142 378.3 | 5.2×10^{-12} | [42] |
| 385 285 142 373.8 | 3.4×10^{-12} | [43] |
| 385 285 142 372.3 | 1.4×10^{-11} | 1.10-1 |
| Weighted mean $f = 385\,285\,142\,375.0\text{ kHz}$ | | |

* A more precise measurement made after the CCL 2001 has confirmed the adopted uncertainty [41].

applies to the single-photon laser frequency of the two-photon transition. The CCL decided to attribute a standard uncertainty of 5 kHz, corresponding to a relative standard uncertainty of 1.3×10^{-11} .*

1.10-1 Bernard *et al.* [45] give

$$f\{^{87}\text{Rb}, 5S_{1/2}(F_g=2) - 5D_{5/2}(F_e=4)\}/2 = 385\,284\,566\,370.4 \text{ kHz}$$

$$u_c/y = 5.2 \times 10^{-12}.$$

From [130] cited in Table 30

$$f\{^{87}\text{Rb}, 5S_{1/2}(F_g=2) - 5D_{5/2}(F_e=4)\}/2$$

$$- f\{^{85}\text{Rb}, 5S_{1/2}(F_g=3) - 5D_{5/2}(F_e=5)\}/2 = -576\,002 \text{ kHz}$$

$$u_c/y = 1.3 \times 10^{-11},$$

one obtains

$$f\{^{85}\text{Rb}, 5S_{1/2}(F_g=3) - 5D_{5/2}(F_e=5)\}/2 = 385\,285\,142\,371.40 \quad u_c/y = 1.4 \times 10^{-11}.$$

1.11 Absorbing molecule $^{13}\text{C}_2\text{H}_2$, P(16) ($\nu_1+\nu_3$) transition, $\lambda \approx 1.54 \mu\text{m}$

Adopted value $f = 194\,369\,569.4 \text{ (1) MHz}$ $u_c/y = 5.2 \times 10^{-10}$

for which $\lambda = 1\,542\,383\,712 \text{ (1) fm}$ $u_c/y = 5.2 \times 10^{-10}$

calculated from:

| f/MHz | u_c/y | Source data |
|--|-----------------------|-------------|
| 194 369 569.385 | 6.2×10^{-11} | [16] |
| 194 369 569.38 | 6.2×10^{-10} | [46] |
| Unweighted mean $f = 194\,369\,569.38 \text{ MHz}$ | | |

with a provisional standard uncertainty of 0.1 MHz, corresponding to a relative standard uncertainty of 5.2×10^{-10} .

1.12 Absorbing molecule CH_4 , $F_2^{(2)}$ component, P(7) ν_3 transition,
 $\lambda \approx 3.39 \mu\text{m}$

1.12.1 Resolved hyperfine structure

Adopted value $f = 88\,376\,181\,600.18 \text{ (27) kHz}$ $u_c/y = 3 \times 10^{-12}$

for which $\lambda = 3\,392\,231\,397.327 \text{ (10) fm}$ $u_c/y = 3 \times 10^{-12}$

* A recent measurement made after the CCL 2001 has confirmed one of the data [44].

calculated from:

| x/kHz | Laser | Frequency chain | Year | Source data |
|---|-------|-----------------|-----------|-------------|
| 600.29 | LPI | PTB | 1991 | [47] |
| 599.9 | LPI | VNIIFTRI | 1985-1986 | [48] |
| 600.11 | LPI | VNIIFTRI | 1989-1992 | [48] |
| 600.18 | PTB | VNIIFTRI | 1989 | [48] |
| 600.16 | PTB | PTB | 1992 | [49] |
| 600.44 | ILP | ILP | 1988-1991 | [50] |
| Unweighted mean $f = 88\,376\,181\,600.18\text{ kHz}$ | | | | |

where $f = (88\,376\,181\,000 + x)\text{ kHz}$.

Other available values having uncertainties larger than 200 Hz have not been used. The relative standard uncertainty of one measurement was estimated to be 2.9×10^{-12} using the maximum deviation from the mean and rounded to 3×10^{-12} .

1.12.2 Unresolved hyperfine structure

Adopted value $f = 88\,376\,181\,600.5\text{ (2.0) kHz}$ $u_c/y = 2.3 \times 10^{-11}$

for which $\lambda = 3\,392\,231\,397.31\text{ (8) fm}$ $u_c/y = 2.3 \times 10^{-11}$

calculated from:

| x/kHz | Frequency source | Frequency chain | Year | Source data |
|---|----------------------|-----------------|-----------|-------------|
| 600.9 | Stationary device | ILP | 1983 | [50-53] |
| 601.48 | Portable laser 2 | NRC | 1985 | [54, 55] |
| 599.33 | Portable laser 3 | NRC | 1986-1991 | [54, 55] |
| 596.82 | Portable laser 1 | AIST | 1988-1990 | [55] |
| 601.52 | CH ₄ beam | PTB | 1987-1989 | [55-57] |
| 601.77 | Portable laser M101 | VNIIFTRI | 1985-1992 | [48, 55] |
| 600.12 | Portable laser P1 | VNIIFTRI | 1985-1988 | [48, 55] |
| 598.5 | Portable laser PL | VNIIFTRI | 1986 | [48] |
| 600.96 | Portable laser B.3 | BIPM | 1985-1992 | [55] |
| 601.33 | Portable laser VB | BIPM | 1988-1991 | [55] |
| 600.3 | Portable laser VNIBI | BIPM | 1991 | [55, 58] |
| Unweighted mean $f = 88\,376\,181\,600.46\text{ kHz}$ | | | | |

where $f_{\text{CH}_4} = (88\,376\,181\,000 + x)$ kHz.

The standard deviation of one determination is 1.7 kHz. This is equivalent to a relative uncertainty of 1.9×10^{-11} , increased by the CCL to 2.3×10^{-11} to give an uncertainty of 2 kHz.

1.13 Absorbing molecule OsO_4 , transition in coincidence with the $^{12}\text{C}^{16}\text{O}_2$, R(10) (00⁰1)-(10⁰0) laser line, $\lambda \approx 10\ \mu\text{m}$

Adopted value $f = 29\,054\,057\,446\,579$ (20) Hz $u_c/y = 6.9 \times 10^{-13}$

for which $\lambda = 10\,318\,436\,884.460$ (7) fm $u_c/y = 6.9 \times 10^{-13}$

calculated from:

| f/Hz | u_c/y | Source data |
|--------------------|-----------------------|-------------|
| 29 054 057 446 579 | 1.4×10^{-13} | [59] |

With this value, based on measurements made over more than one year, but determined by one single laboratory, the CCL considered it prudent to adopt a standard uncertainty given for standard conditions [60] of 20 Hz, i.e. five times the reported measured uncertainty of 4 Hz, giving a relative standard uncertainty of 6.9×10^{-13} .

This value is linked to the earlier recommended transition, R(12) (00⁰1)-(10⁰0) laser line in $^{12}\text{C}^{16}\text{O}_2$, resonant with OsO_4 [61-64].

2 Recommended values for radiations of spectral lamps and other sources

2.1 ^{86}Kr spectral lamp radiation, $^5\text{d}_5 - ^2\text{p}_{10}$ transition, $\lambda \approx 605\ \text{nm}$

Adopted value $f = 494\,886\,516.4$ (6) MHz $u_c/y = 1.3 \times 10^{-9}$

for which $\lambda = 605\,780\,210.3$ (1) fm $u_c/y = 1.3 \times 10^{-9}$

calculated from:

| f/kHz | u_c/y | Source data |
|---------------------|----------------------|-------------|
| 494 886 516 422 kHz | 1.3×10^{-9} | 2.1-1 |

Source data

2.1-1 The CCDM 1982 [35, 65] gives

$$f_{\text{Kr}}/f_i = 1.044\,919\,242\,05 \quad u_c/y = 1.3 \times 10^{-9},$$

using the recommended operating conditions [66].

Using the recommended value of f_i (Section 1.7 and Table 20), where

$$f_i = 473\,612\,214\,712 \text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

one obtains

$$f_{\text{Kr}} = 494\,886\,516\,422 \text{ kHz} \quad u_c/y = 1.3 \times 10^{-9}.$$

2.2 ^{86}Kr , ^{198}Hg and ^{114}Cd spectral lamp radiations

The recommended wavelengths are those recommended by the CIPM in 1963 [67, 68].

2.3 Absorbing molecule $^{127}\text{I}_2$, a_3 component, P(13) 43-0 transition, $\lambda \approx 515 \text{ nm}$

$$\text{Adopted value} \quad f = 582\,490\,603.38 (15) \text{ MHz} \quad u_c/y = 2.5 \times 10^{-10}$$

$$\text{for which} \quad \lambda = 514\,673\,466.42 (13) \text{ fm} \quad u_c/y = 2.5 \times 10^{-10}$$

calculated from:

| f/kHz | u_c/y | Source data |
|--|-----------------------|-------------|
| 582 490 603 222 | 2.9×10^{-10} | 2.3-1 |
| 582 490 603 218 | 1.0×10^{-10} | 2.3-2 |
| 582 490 603 433 | 7.3×10^{-11} | [69] |
| 582 490 603 483 | 7.3×10^{-11} | [70] |
| 582 490 603 447 | 8.3×10^{-11} | [71] |
| 582 490 603 490 | 8.3×10^{-11} | [72] |
| Unweighted mean $f = 582\,490\,603\,382 \text{ kHz}$ | | |

The relative standard uncertainty calculated from the dispersion of the six values is 2.2×10^{-10} , which the CCL preferred to round up to 2.5×10^{-10} .

Source data

Using the recommended value of f_i (Section 1.7 and Table 20), where

$$f_i = 473\,612\,214\,712 \text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

the following values for f_{a3} are obtained from measured wavelength ratios:

| f_i/f_{a3} | u_c/y | f_{a3}/kHz | u_c/y | Referenced to |
|------------------|-----------------------|---------------------|-----------------------|---------------|
| 0.813 081 296 23 | 2.9×10^{-10} | 582 490 603 222 | 2.5×10^{-10} | 2.3-1 |
| 0.813 081 296 24 | 1×10^{-10} | 582 490 603 218 | 1.0×10^{-10} | 2.3-2 |
| 0.813 081 295 94 | 7×10^{-11} | 582 490 603 433 | 7.3×10^{-11} | [69] |
| 0.813 081 295 87 | 7×10^{-11} | 582 490 603 483 | 7.3×10^{-11} | [70] |
| 0.813 081 295 92 | 8×10^{-11} | 582 490 603 447 | 8.3×10^{-11} | [71] |
| 0.813 081 295 86 | 8×10^{-11} | 582 490 603 490 | 8.3×10^{-11} | [72] |

Other available values having relative uncertainties higher than 3.0×10^{-10} have not been used.

2.3-1 Reference [73] gives $\lambda_{a3}/\lambda_d = 0.813\,081\,579\,7$ $u_c/y = 2.5 \times 10^{-10}$.

Using the recommended value of f_i (Section 1.7 and Table 20), where

$f_i = 473\,612\,214\,712 \text{ kHz}$, and where

$f_d = 473\,612\,379\,828 \text{ kHz}$,

one calculates $f_i/f_{a3} = 0.813\,081\,296\,23$ $u_c/y = 2.9 \times 10^{-10}$.

2.3-2 Reference [74] gives $f_{a3}/f_i = 1.229\,889\,316\,88$ $u_c/y = 1.0 \times 10^{-10}$.

One calculates $f_i/f_{a3} = 0.813\,081\,296\,22$ $u_c/y = 1.0 \times 10^{-10}$.

2.4 Absorbing molecule $^{127}\text{I}_2$, a_9 component, R(12) 26-0 transition,
 $\lambda \approx 543 \text{ nm}$

Adopted value $f = 551\,579\,482.97 (14) \text{ MHz}$ $u_c/y = 2.5 \times 10^{-10}$

for which $\lambda = 543\,516\,333.1 (1) \text{ fm}$ $u_c/y = 2.5 \times 10^{-10}$

calculated from:

| f/kHz | u_c/y | Source data |
|---|-----------------------|-------------|
| 551 579 483 037 | 8.3×10^{-11} | 2.4-1 |
| 551 579 482 908 | 13×10^{-11} | 2.4-2 |
| Unweighted mean $f = 551\,579\,482\,973\text{ kHz}$ | | |

With this mean based on only two determinations, linked by the same reference frequency, the CCL considered it prudent to assume an estimated relative standard uncertainty of 2.5×10^{-10} closely equivalent to the difference between the two values.

Source data

2.4-1 Bönsch *et al.* [72] give

$$\lambda_{a9}/\lambda_i = 0.858\,647\,265\,30 \quad u_c/y = 8 \times 10^{-11}.$$

Using the recommended value of f_i (Section 1.7 and Table 20), where

$$f_i = 473\,612\,214\,712\text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a9} = 551\,579\,483\,045\text{ kHz} \quad u_c/y = 8.3 \times 10^{-11}$$

at a cold-finger temperature of $-10\text{ }^\circ\text{C}$ (iodine pressure = 1.4 Pa). For a reference temperature of $0\text{ }^\circ\text{C}$ (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 [75], giving

$$f_{a9} = 551\,579\,483\,037\text{ kHz} \quad u_c/y = 8.3 \times 10^{-11}.$$

2.4-2 Reference [76] gives

$$f_{b10}/f_i = 1.164\,624\,021\,92 \quad u_c/y = 12 \times 10^{-11}.$$

Using the recommended value of f_i (Section 1.7 and Table 20), where

$$f_i = 473\,612\,214\,712\text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{b10} = 551\,580\,162\,328\text{ kHz} \quad u_c/y = 12.2 \times 10^{-11}$$

at a cold finger temperature of $0\text{ }^\circ\text{C}$ (iodine pressure = 4.1 Pa).

From the measured value (Table 37)

$$f_{b10} - f_{a9} = 679\,420\text{ kHz} \quad u_c = 15\text{ kHz}$$

one obtains

$$f_{a9} = 551\,579\,482\,908\text{ kHz} \quad u_c/y = 12.5 \times 10^{-11}.$$

2.5 Absorbing molecule $^{127}\text{I}_2$, a_1 component, P(62) 17-1 transition,
 $\lambda \approx 576\text{ nm}$

$$\text{Adopted value} \quad f = 520\,206\,808.4\text{ (2) MHz} \quad u_c/y = 4 \times 10^{-10}$$

$$\text{for which} \quad \lambda = 576\,294\,760.4\text{ (2) fm} \quad u_c/y = 4 \times 10^{-10}$$

calculated from:

| f/kHz | u_c/y | Source data |
|---|-----------------------|-------------|
| 520 206 808 491 | 1.5×10^{-10} | 2.5-1 |
| 520 206 808 280 | 1×10^{-10} | 2.5-2 |
| Unweighted mean $f = 520\,206\,808\,388\text{ kHz}$ | | |

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

Source data

2.5-1 Reference [77] gives

$$f_{a1} = 520\,206\,808\,547\text{ kHz} \quad u_c/y = 1.5 \times 10^{-10},$$

reduced by 12 kHz at the request of the NBS delegate at the CCDM meeting in 1982 [35, 65]. This value has been multiplied by the ratio (88 376 181 600.5/88 376 181 608) to account for the 1992 reference value of the methane frequency (Section 1.12.2) giving:

$$f_{a1} = 520\,206\,808\,491\text{ kHz} \quad u_c/y = 1.5 \times 10^{-10}.$$

2.5-2 Barwood *et al.* [78] give

$$f_{a1}/f_i = 1.098\,381\,317\,29 \quad u_c/y = 1 \times 10^{-10}.$$

Using the recommended value of f_f (Section 1.7 and Table 20), where

$$f_i = 473\,612\,214\,712\text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a1} = 520\,206\,808\,280 \text{ kHz} \quad u_c/y = 1 \times 10^{-10}.$$

2.6 Absorbing molecule $^{127}\text{I}_2$, a_7 component, R(47) 9-2 transition,
 $\lambda \approx 612 \text{ nm}$

Adopted value $f = 489\,880\,354.93 \text{ (15) MHz}$ $u_c/y = 3.0 \times 10^{-10}$

for which $\lambda = 611\,970\,769.97 \text{ (18) fm}$ $u_c/y = 3.0 \times 10^{-10}$

calculated from:

| f/kHz | u_c/y | Source data |
|--|-----------------------|-------------|
| 489 880 354 979 | 1×10^{-10} | 2.6-1 |
| 489 880 354 728 | 2.1×10^{-10} | 2.6-2 |
| 489 880 355 026 | 8.3×10^{-11} | 2.6-3 |
| 489 880 355 062 | 3.0×10^{-10} | 2.6-4 |
| 489 880 358 850 | 8.5×10^{-11} | 2.6-5 |
| Unweighted mean $f = 489\,880\,354\,929 \text{ kHz}$ | | |

Other available values having relative uncertainties higher than 3.0×10^{-10} have not been used. The relative standard uncertainty calculated from the dispersion of the six values is 2.8×10^{-10} , which the CCL preferred to round up to 3.0×10^{-10} .

Source data

2.6-1 Reference [74] gives

$$f_{a7}/f_i = 1.034\,349\,072\,43 \quad u_c/y = 1 \times 10^{-10}.$$

Using the recommended value of f_i (Section 1.7 and Table 20), where

$$f_i = 473\,612\,214\,712 \text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a7} = 489\,880\,354\,979 \text{ kHz} \quad u_c/y = 1 \times 10^{-10}.$$

2.6-2 Reference [73] gives

$$f_{a7}/f_i = 1.034\,349\,071\,90 \quad u_c/y = 2.1 \times 10^{-10}.$$

Using the recommended value of f_i (Section 1.7 and Table 20), where

$$f_i = 473\,612\,214\,712 \text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a7} = 489\,880\,354\,728 \text{ kHz} \quad u_c/y = 2.1 \times 10^{-10}.$$

2.6-3 Bönsch *et al.* [71] give

$$\lambda_{b15}/\lambda_i = 0.966\,791\,921\,43 \quad u_c/y = 8 \times 10^{-11}.$$

Using the recommended value of f_f (Section 1.7 and Table 20), where

$$f_i = 473\,612\,214\,712 \text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{b15} = 489\,880\,194\,708 \text{ kHz} \quad u_c/y = 8.3 \times 10^{-11}.$$

From the measured value (Table 40)

$$f_{b15} - f_{a7} = -160\,318 \text{ kHz} \quad u_c = 3 \text{ kHz}$$

one calculates

$$f_{a7} = 489\,880\,355\,026 \text{ kHz} \quad u_c/y = 8.3 \times 10^{-11}.$$

2.6-4 Vitushkin *et al.* [79] give

$$\lambda_d/\lambda_{a7} = 1.034\,348\,712 \quad u_c/y = 3 \times 10^{-10}.$$

Using the recommended value of f_f (Section 1.7 and Table 20), where

$$f_d = 473\,612\,379\,828 \text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a7} = 489\,880\,355\,062 \text{ kHz} \quad u_c/y = 3.0 \times 10^{-10}.$$

2.6-5 Himbert *et al.* [80] give

$$f_{a13} = 489\,880\,604\,541 \text{ kHz} \quad u_c = 88 \text{ kHz}.$$

This value is a result of the frequency ratio f_{a13}/f_e , to which the recommended value adopted by the CIPM in 1983 [34, 35] was applied, i.e.

$f_i = 473\,612\,214.8 \text{ MHz}$. Knowing the frequency difference (Table 20)

$$f_e - f_i = 152\,255 \text{ kHz} \quad u_c = 5 \text{ kHz},$$

one obtains

$$f_e = 473\,612\,367\,055 \text{ kHz},$$

and hence

$$f_{a13}/f_e = 1.034\,349\,267 \quad u_c/y = 8 \times 10^{-11}.$$

Using the recommended value of f_f (Section 1.7 and Table 20), where

$$f_e = 473\,612\,366\,967 \text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a13} = 489\,880\,604\,450 \quad u_c/y = 8.3 \times 10^{-11}.$$

Knowing the frequency difference (Table 39)

$$f_{a7} - f_{a13} = -249\,600 \text{ kHz} \quad u_c = 10 \text{ kHz},$$

one obtains

$$f_{a7} = 489\,880\,354\,850 \quad u_c/y = 8.5 \times 10^{-11}.$$

2.7 Absorbing molecule $^{127}\text{I}_2$, a_9 component, P(10) 8-5 transition,
 $\lambda \approx 640 \text{ nm}$

$$\text{Adopted value} \quad f = 468\,218\,332.4 \text{ (2) MHz} \quad u_c/y = 4.5 \times 10^{-10}$$

$$\text{for which} \quad \lambda = 640\,283\,468.7 \text{ (3) fm} \quad u_c/y = 4.5 \times 10^{-10}$$

calculated from:

| f/kHz | u_c/y | Source data |
|--|-----------------------|-------------|
| 468 218 332 419 | 1.0×10^{-10} | 2.7-1 |
| 468 218 332 310 | 1.2×10^{-10} | 2.7-2 |
| 468 218 332 069 | 4.6×10^{-10} | 2.7-3 |
| Weighted mean $f = 468\,218\,332\,366 \text{ kHz}$ | | |

Given the small number of determinations, the CCL considered it prudent to assume a relative standard uncertainty of 4.5×10^{-10} .

Source data

2.7-1 Bennet and Mills-Baker [81] give

$$\lambda_{a9} = 640.283\,468\,6 \text{ nm}.$$

From this paper the ratio f_{a9}/f_i is calculated as

$$f_{a9}/f_i = 0.988\,611\,184\,191 \quad u_c/y = 1 \times 10^{-10}.$$

Using the recommended value of f_i (Section 1.7 and Table 20), where

$$f_i = 473\,612\,214\,712 \text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a9} = 468\,218\,332\,434 \text{ kHz} \quad u_c/y = 1.0 \times 10^{-10}$$

at a cold-finger temperature of 14.3°C (iodine pressure = 16 Pa) and a modulation width of 7 MHz. For a reference temperature of 16°C (iodine pressure = 18.9 Pa) and a modulation width of 6 MHz, corrections of

–23 kHz and +8 kHz has to be applied to this value assuming a pressure dependence of –7.8 kHz/Pa and a modulation dependence of –7.6 kHz/MHz, similar to that reported in [82], giving

$$f_{a9} = 468\,218\,332\,419\text{ kHz} \quad u_c/y = 1.0 \times 10^{-10}.$$

2.7-2 Zhao *et al.* [82, 83] give

$$\lambda_{a9} = 640.283\,468\,8\text{ nm} \quad 3 \times (u_c/y) = 1.1 \times 10^{-9}.$$

Bönsch *et al.* [72] give

$$\lambda_i/\lambda_{a9} = 0.988\,611\,183\,86 \quad u_c/y = 12 \times 10^{-11}.$$

Using the recommended value of f_i (Section 1.7 and Table 20), where

$$f_i = 473\,612\,214\,712\text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a9} = 468\,218\,332\,277\text{ kHz} \quad u_c/y = 1.2 \times 10^{-10}$$

at a cold-finger temperature of 18 °C (iodine pressure = 22.6 Pa) and a modulation width of 6.5 MHz. For a reference temperature of 16 °C (iodine pressure = 18.9 Pa) and a modulation width of 6 MHz, corrections of +29 kHz and +4 kHz have to be applied to this value, knowing a pressure dependence of –7.8 kHz/Pa and a modulation dependence of –7.6 kHz/MHz, giving

$$f_{a9} = 468\,218\,332\,310\text{ kHz} \quad u_c/y = 1.2 \times 10^{-10}.$$

2.7-3 [58, 84] give

$$\lambda_{a9}(17\text{ °C})/\lambda_e(20\text{ °C}) = 1.011\,520\,341\,04 \quad u_c/y = 4.6 \times 10^{-10}.$$

Using the recommended value of f_i (Section 1.7 and Table 20), where

$$f_e = 473\,612\,366\,967\text{ kHz} \quad u_c/y = 2.2 \times 10^{-11},$$

one calculates

$$f_{a9} = 468\,218\,332\,055\text{ kHz} \quad u_c/y = 4.6 \times 10^{-10}$$

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, assuming a pressure dependence of –7.8 kHz/Pa similar to that reported in [82], giving

$$f_{a9} = 468\,218\,332\,069\text{ kHz} \quad u_c/y = 4.6 \times 10^{-10}.$$

APPENDIX L 3.**Absolute frequency of the other transitions related to those adopted as recommended and frequency intervals between transitions and hyperfine components**

These tables replace those published in *BIPM Com. Cons. Déf. Mètre*, 1982, 7, M 140-M 150 and *Metrologia*, 1984, 19, 170-178; in *BIPM Com. Cons. Déf. Mètre*, 1992, 8, M 154-M 164 and *Metrologia*, 1993/94, 30, 523-541; and in *BIPM Com. Cons. Déf. Mètre*, 1997, 9, 133-152 and *Metrologia*, 1999, 36, 226-242.

The notation for the transitions and the components is that used in the source references. The values adopted for the frequency intervals are the weighted means of the values given in the references.

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.

In the tables, u_c represents the estimated combined standard uncertainty (1σ).

All transitions in molecular iodine refer to the B-X system.

When a two-photon transition is listed, the listed frequency indicates the one-photon laser frequency.

Table 1
 $\lambda \approx 778 \text{ nm}$ ^1H $2\text{S} - 8\text{S}$ and $2\text{S} - 8\text{D}$ two-photon transitions

| Transition | $[f(2\text{S} - 8\text{S/D})/2]/\text{MHz}$ | u_c/MHz |
|-------------------------------------|---|------------------|
| $2\text{S}_{1/2} - 8\text{D}_{5/2}$ | 385 324 780.793 | 0.005 |
| $2\text{S}_{1/2} - 8\text{D}_{3/2}$ | 385 324 752.227 | 0.007 |
| $2\text{S}_{1/2} - 8\text{S}_{1/2}$ | 385 324 675.008 | 0.008 |
| [85] | | |

Table 2
 $\lambda \approx 778 \text{ nm}$ ^2H $2\text{S} - 8\text{S}$ and $2\text{S} - 8\text{D}$ two-photon transitions

| Transition | $[f(2\text{S} - 8\text{S/D})/2]/\text{MHz}$ | u_c/MHz |
|-------------------------------------|---|------------------|
| $2\text{S}_{1/2} - 8\text{D}_{5/2}$ | 385 429 626.426 | 0.004 |
| $2\text{S}_{1/2} - 8\text{D}_{3/2}$ | 385 429 597.852 | 0.004 |
| $2\text{S}_{1/2} - 8\text{S}_{1/2}$ | 385 429 520.626 | 0.005 |
| [85] | | |

Table 3

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ R(87) 33-0 [No. 1097]}$ | | | | | |
|--|--|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_{12} | 582.6721 | 0.0020 |
| a_2 | 51.5768 | 0.0020 | a_{13} | 622.8375 | 0.0020 |
| a_3 | 101.4407 | 0.0020 | a_{14} | 663.9140 | 0.0020 |
| a_4 | 282.4331 | 0.0020 | a_{15} | 730.3226 | 0.0020 |
| a_5 | 332.2313 | 0.0020 | a_{16} | 752.4797 | 0.0020 |
| a_6 | 342.2223 | 0.0020 | a_{17} | 778.0522 | 0.0020 |
| a_7 | 390.3168 | 0.0020 | a_{18} | 799.4548 | 0.0020 |
| a_8 | 445.6559 | 0.0020 | a_{19} | 893.1211 | 0.0020 |
| a_9 | 462.0620 | 0.0020 | a_{20} | 907.5209 | 0.0020 |
| a_{10} | 497.5450 | 0.0020 | a_{21} | 923.5991 | 0.0020 |
| a_{11} | 511.9546 | 0.0020 | | | |
| Frequency | $a_{10}, \text{R(56) 32-0, } ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ | | | | [1] |
| referenced to | $f(a_1, \text{R(87) 33-0}) - f(a_{10}, \text{R(56) 32-0})$ | | | | |
| | $= -111\,935\,173 \text{ (5) kHz}$ | | | | [1] |

[86]

Table 4

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ R(58) 32-0 [No. 1098]}$ | | | | | |
|--|--|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_{10} | 571.5686 | 0.0020 |
| a_2 | 259.1938 | 0.0020 | a_{11} | 697.9347 | 0.0020 |
| a_5 | 311.8933 | 0.0020 | a_{12} | 702.8370 | 0.0020 |
| a_6 | 401.3702 | 0.0020 | a_{13} | 726.0151 | 0.0020 |
| a_7 | 416.7177 | 0.0020 | a_{14} | 732.3220 | 0.0020 |
| a_8 | 439.9735 | 0.0020 | a_{15} | 857.9730 | 0.0020 |
| a_9 | 455.4891 | 0.0020 | | | |
| Frequency referenced to | $a_{10}, \text{R(56) 32-0, } ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ $f(a_1, \text{R(58) 32-0}) - f(a_{10}, \text{R(56) 32-0})$ $= -102\,159\,978 (5) \text{ kHz}$ | | | | [1] [1] |

[87]

Table 5

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ P(55) 32-0}$ | | | | | |
|---|--|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_{13} | 609.4478 | 0.0020 |
| a_2 | 37.8987 | 0.0020 | a_{14} | 648.9064 | 0.0020 |
| a_3 | 73.8521 | 0.0020 | a_{15} | 714.0690 | 0.0020 |
| a_4 | 272.2124 | 0.0020 | a_{16} | 739.8350 | 0.0020 |
| a_7 | 373.1260 | 0.0020 | a_{17} | 763.0081 | 0.0020 |
| a_8 | 437.4166 | 0.0020 | a_{18} | 788.2234 | 0.0020 |
| a_9 | 455.3851 | 0.0020 | a_{19} | 879.7357 | 0.0020 |
| a_{10} | 477.0210 | 0.0020 | a_{20} | 893.4676 | 0.0020 |
| a_{11} | 490.5588 | 0.0020 | a_{21} | 910.3088 | 0.0020 |
| a_{12} | 573.0377 | 0.0020 | | | |
| Frequency referenced to | $a_{10}, \text{R(56) 32-0}, ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ $f(a_1, \text{P(55) 32-0}) - f(a_{10}, \text{R(56) 32-0})$ $= -98\,766\,591 (5) \text{ kHz}$ | | | | [1] [1] |

[87]

Table 6

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ P}(104) 34\text{-}0 \text{ [No. 1099]}$ | | | | | |
|--|--|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_9 | 466.6137 | 0.0020 |
| a_2 | 238.8227 | 0.0020 | a_{10} | 570.8323 | 0.0020 |
| a_3 | 277.4934 | 0.0020 | a_{11} | 688.5193 | 0.0020 |
| a_4 | 293.3463 | 0.0020 | a_{12} | 699.1488 | 0.0020 |
| a_5 | 331.4333 | 0.0020 | a_{13} | 727.8544 | 0.0020 |
| a_6 | 389.0585 | 0.0020 | a_{14} | 739.2895 | 0.0020 |
| a_7 | 405.6376 | 0.0020 | a_{15} | 856.7001 | 0.0020 |
| a_8 | 450.2193 | 0.0020 | | | 0.0020 |
| Frequency referenced to | $a_{10}, \text{R}(56) 32\text{-}0, ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ $f(a_1, \text{P}(104) 34\text{-}0) - f(a_{10}, \text{R}(56) 32\text{-}0)$ $= -98\,069\,775 (5) \text{ kHz}$ | | | | [1] [1] |
| [87] | | | | | |

Table 7

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ P(84) 33-0 [No. 1100]}$ | | | | | |
|--|--|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_9 | 459.8476 | 0.0020 |
| a_2 | 249.8445 | 0.0020 | a_{10} | 571.2806 | 0.0020 |
| a_3 | 281.2957 | 0.0020 | a_{11} | 694.0020 | 0.0020 |
| a_4 | 290.0304 | 0.0020 | a_{12} | 701.7501 | 0.0020 |
| a_5 | 320.9041 | 0.0020 | a_{13} | 726.3808 | 0.0020 |
| a_6 | 396.5400 | 0.0020 | a_{14} | 735.0562 | 0.0020 |
| a_7 | 411.5392 | 0.0020 | a_{15} | 857.4151 | 0.0020 |
| a_8 | 444.9362 | 0.0020 | | | |
| Frequency referenced to | $a_{10}, \text{R(56) 32-0, } ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ $f(a_1, \text{P(84) 33-0}) - f(a_{10}, \text{R(56) 32-0})$ $= -95\,929\,863\,(5) \text{ kHz}$ | | | | [1] [1] |
| [88] | | | | | |

Table 8

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ R}(122) 35\text{-}0$ | | | | | |
|---|--|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_9 | 475.9553 | 0.0020 |
| a_2 | 224.7302 | 0.0020 | a_{10} | 570.3004 | 0.0020 |
| a_3 | 273.2394 | 0.0020 | a_{11} | 681.2572 | 0.0020 |
| a_4 | 297.0396 | 0.0020 | a_{12} | 695.4307 | 0.0020 |
| a_5 | 344.9343 | 0.0020 | a_{13} | 730.2395 | 0.0020 |
| a_6 | 378.8637 | 0.0020 | a_{14} | 745.1865 | 0.0020 |
| a_7 | 398.2113 | 0.0020 | a_{15} | 855.9386 | 0.0020 |
| a_8 | 456.8479 | 0.0020 | | | |
| Frequency referenced to | $a_{10}, \text{R}(56) 32\text{-}0, ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ $f(a_1, \text{R}(122) 35\text{-}0) - f(a_{10}, \text{R}(56) 32\text{-}0)$ $= -90\,981\,724 (5) \text{ kHz}$ | | | | [1] [1] |
| [88] | | | | | |

Table 9

$\lambda \approx 532 \text{ nm}$ $^{127}\text{I}_2$ R(145) 37-0 [No. 1101]

| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
|----------------------------|--|------------------|----------|--------------------------------|------------------|
| a_1 | 0 | — | a_{12} | 608.2166 | 0.0020 |
| a_2 | 111.3681 | 0.0020 | a_{13} | 680.6255 | 0.0020 |
| a_3 | 220.5695 | 0.0020 | a_{14} | 752.7967 | 0.0020 |
| a_4 | 298.7582 | 0.0020 | a_{15} | 769.5347 | 0.0020 |
| a_5 | 376.9445 | 0.0020 | a_{16} | 799.1414 | 0.0020 |
| a_6 | 414.9517 | 0.0020 | a_{17} | 846.4138 | 0.0020 |
| a_7 | 469.8127 | 0.0020 | a_{18} | 874.8758 | 0.0020 |
| a_8 | 491.2288 | 0.0020 | a_{19} | 940.0615 | 0.0020 |
| a_9 | 495.5179 | 0.0020 | a_{20} | 964.5342 | 0.0020 |
| a_{10} | 580.7013 | 0.0020 | a_{21} | 990.2893 | 0.0020 |
| a_{11} | 605.3833 | 0.0020 | | | |
| Frequency referenced to | a_{10} , R(56) 32-0, $^{127}\text{I}_2$: $f = 563\,260\,223\,513 \text{ kHz}$ $f(a_1, \text{R}(145) 37-0) - f(a_{10}, \text{R}(56) 32-0)$ $= -84\,992\,178 (5) \text{ kHz}$ | | | | [1] [1] |

[86]

Table 10

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ P}(132) 36\text{-}0 \text{ [No. 1103]}$ | | | | | |
|--|--|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_9 | 482.3956 | 0.0020 |
| a_2 | 215.0115 | 0.0020 | a_{10} | 569.8339 | 0.0020 |
| a_3 | 270.3841 | 0.0020 | a_{11} | 676.1016 | 0.0020 |
| a_4 | 299.4166 | 0.0020 | a_{12} | 692.6715 | 0.0020 |
| a_5 | 354.1318 | 0.0020 | a_{13} | 731.8283 | 0.0020 |
| a_6 | 371.6729 | 0.0020 | a_{14} | 749.1808 | 0.0020 |
| a_7 | 393.0781 | 0.0020 | a_{15} | 855.2633 | 0.0020 |
| a_8 | 461.2856 | 0.0020 | | | |
| Frequency referenced to | $a_{10}, \text{R}(56) 32\text{-}0, ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ $f(a_1, \text{P}(132) 36\text{-}0) - f(a_{10}, \text{R}(56) 32\text{-}0)$ $= -73\,517\,088 (5) \text{ kHz}$ | | | | [1] [1] |
| [86] | | | | | |

Table 11

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ R(57) 32-0 [No. 1104]}$ | | | | | |
|--|--|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_{13} | 610.925 | 0.001 |
| a_2 | 39.372 | 0.001 | a_{14} | 650.805 | 0.001 |
| a_3 | 76.828 | 0.001 | a_{15} | 715.550 | 0.001 |
| a_4 | 273.042 | 0.001 | a_{16} | 741.175 | 0.001 |
| a_7 | 375.284 | 0.001 | a_{17} | 764.716 | 0.001 |
| a_8 | 438.243 | 0.001 | a_{18} | 789.777 | 0.001 |
| a_9 | 456.183 | 0.001 | a_{19} | 881.116 | 0.001 |
| a_{10} | 479.201 | 0.001 | a_{20} | 895.016 | 0.001 |
| a_{11} | 492.915 | 0.001 | a_{21} | 911.901 | 0.001 |
| a_{12} | 573.917 | 0.001 | | | |
| Frequency referenced to | $a_{10}, \text{R(56) 32-0, } ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ $f(a_1, \text{R(57) 32-0}) - f(a_{10}, \text{R(56) 32-0})$ $= -50\,946\,885\,(5) \text{ kHz}$ | | | | [1] [1] |
| [20, 89] | | | | | |

Table 12

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ P(54) 32-0 [No. 1105]}$ | | | | | |
|--|--|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_9 | 454.563 | 0.001 |
| a_2 | 260.992 | 0.001 | a_{10} | 571.536 | 0.001 |
| a_3 | 285.008 | 0.001 | a_{11} | 698.614 | 0.001 |
| a_4 | 286.726 | 0.001 | a_{12} | 702.935 | 0.001 |
| a_5 | 310.066 | 0.001 | a_{13} | 725.834 | 0.001 |
| a_6 | 402.249 | 0.001 | a_{14} | 731.688 | 0.001 |
| a_8 | 417.668 | 0.001 | a_{15} | 857.961 | 0.001 |
| a_8 | 438.919 | 0.001 | | | |
| Frequency referenced to | $a_{10}, \text{R(56) 32-0, } ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ $f(a_1, \text{P(54) 32-0}) - f(a_{10}, \text{R(56) 32-0})$ $= -47\,588\,897\,(5) \text{ kHz}$ | | | | [1] [1] |
| [20, 89] | | | | | |

Table 13

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ P}(119) 35-0 \text{ [No. 1106]}$ | | | | | |
|---|--|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_{13} | 645.617 | 0.002 |
| a_2 | 75.277 | 0.002 | a_{14} | 697.723 | 0.002 |
| a_3 | 148.701 | 0.002 | a_{15} | 747.389 | 0.003 |
| a_4 | 290.376 | 0.003 | a_{16} | 771.197 | 0.003 |
| a_5 | 349.310 | 0.002 | a_{17} | 804.769 | 0.003 |
| a_6 | 371.567 | 0.002 | a_{18} | 827.641 | 0.003 |
| a_9 | 474.953 | 0.004 | a_{19} | 912.125 | 0.002 |
| a_{10} | 530.727 | 0.002 | a_{20} | 930.053 | 0.002 |
| a_{11} | 548.787 | 0.002 | a_{21} | 949.288 | 0.003 |
| Frequency referenced to | $a_{10}, \text{R}(56) 32-0, ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ | | | | [1] |
| | $f(a_1, \text{P}(119) 35-0) - f(a_{10}, \text{R}(56) 32-0)$ $= -36\,840\,163 \text{ (5) kHz}$ | | | | [1] |

[90, 91]

Table 14

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ R(86) 33-0 [No. 1107]}$ | | | | | |
|--|--|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_9 | 460.973 | 0.002 |
| a_2 | 248.206 | 0.002 | a_{10} | 571.262 | 0.002 |
| a_3 | 280.802 | 0.002 | a_{11} | 693.205 | 0.002 |
| a_4 | 290.502 | 0.002 | a_{12} | 701.377 | 0.002 |
| a_5 | 322.524 | 0.002 | a_{13} | 726.710 | 0.002 |
| a_6 | 395.386 | 0.002 | a_{14} | 735.795 | 0.002 |
| a_7 | 410.696 | 0.002 | a_{15} | 857.383 | 0.002 |
| a_8 | 445.759 | 0.002 | | | |
| Frequency referenced to | $a_{10}, \text{R(56) 32-0, } ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ $f(a_1, \text{R(86) 33-0}) - f(a_{10}, \text{R(56) 32-0})$ $= -32\,190\,406\,(5) \text{ kHz}$ | | | | [1] [1] |
| [91, 92] | | | | | |

Table 15

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ R(106) 34-0 [No. 1108]}$ | | | | | |
|---|---|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_9 | 467.984 | 0.002 |
| a_2 | 236.870 | 0.002 | a_{10} | 570.799 | 0.002 |
| a_3 | 276.941 | 0.002 | a_{11} | 687.539 | 0.002 |
| a_4 | 293.861 | 0.002 | a_{12} | 698.663 | 0.002 |
| a_5 | 333.350 | 0.002 | a_{13} | 728.261 | 0.002 |
| a_6 | 387.636 | 0.002 | a_{14} | 740.185 | 0.002 |
| a_7 | 404.635 | 0.002 | a_{15} | 856.675 | 0.002 |
| a_8 | 451.175 | 0.002 | | | |
| Frequency referenced to | $a_{10}, \text{R(56) 32-0}, ^{127}\text{I}_2 : f = 563\,260\,223\,513 \text{ kHz}$ $f(a_1, \text{R(106) 34-0}) - f(a_{10}, \text{R(56) 32-0})$ $= -30\,434\,763\,(5) \text{ kHz}$ | | | | [1] [1] |
| [91-93] | | | | | |

Table 16

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ R}(134) 36-0$ | | | | | |
|--|---|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_8 | 462.603 | 0.009 |
| a_2 | 212.287 | 0.007 | a_9 | 484.342 | 0.007 |
| a_3 | 269.634 | 0.022 | a_{11} | 674.703 | 0.009 |
| a_4 | 300.097 | 0.011 | a_{12} | 691.951 | 0.008 |
| a_5 | 356.801 | 0.008 | a_{13} | 732.405 | 0.008 |
| a_6 | 369.644 | 0.008 | a_{14} | 750.434 | 0.009 |
| a_7 | 391.684 | 0.009 | | | |
| Frequency | $a_{10}, \text{R}(56) 32-0, ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ | | | | [1] |
| referenced to | $f(a_1, \text{R}(134) 36-0) - f(a_{10}, \text{R}(56) 32-0)$ | | | | |
| | $= -17\,173\,682\,(5) \text{ kHz}$ | | | | [1] |
| [91, 92] | | | | | |

Table 17
 $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ P}(83) 33-0 \text{ [No. 1109]}$

| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
|----------------------------|---|------------------|----------|--------------------------------|------------------|
| a_1 | 0 | — | a_{11} | 507.533 | 0.004 |
| a_2 | 48.789 | 0.004 | a_{13} | 620.065 | 0.004 |
| a_3 | 95.839 | 0.008 | a_{14} | 659.930 | 0.004 |
| a_4 | 281.343 | 0.010 | a_{15} | 728.070 | 0.004 |
| a_5 | 330.230 | 0.004 | a_{16} | 750.131 | 0.004 |
| a_6 | 338.673 | 0.004 | a_{17} | 774.805 | 0.004 |
| a_7 | 385.830 | 0.004 | a_{18} | 796.125 | 0.004 |
| a_8 | 444.365 | 0.006 | a_{19} | 890.709 | 0.005 |
| a_9 | 460.503 | 0.004 | a_{20} | 904.712 | 0.005 |
| a_{10} | 493.533 | 0.006 | a_{21} | 920.475 | 0.004 |
| Frequency referenced to | $a_{10}, \text{R}(56) 32\text{-}0, {}^{127}\text{I}_2\text{:}f = 563\,260\,223\,513\text{ kHz}$ $f(a_{21}, \text{P}(83) 33\text{-}0) - f(a_{10}, \text{R}(56) 32\text{-}0)$ $= -15\,682\,075\,(5)\text{ kHz}$ | | | | [1] [1] |
| [91, 92] | | | | | |

Table 18

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ R(56) 32-0 [No. 1110]}$ | | | | | |
|--|--|------------------|----------|---------------------------------|------------------|
| a_n | $[f(a_n)-f(a_{10})]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n)-f(a_{10})]/\text{MHz}$ | u_c/MHz |
| a_1 | -571.542 | 0.0015 | a_{10} | 0 | — |
| a_2 | -311.844 | 0.0015 | a_{11} | 126.513 | 0.0015 |
| a_5 | -260.176 | 0.0015 | a_{12} | 131.212 | 0.0015 |
| a_6 | -170.064 | 0.0015 | a_{13} | 154.488 | 0.0015 |
| a_7 | -154.548 | 0.0015 | a_{14} | 160.665 | 0.0015 |
| a_8 | -131.916 | 0.0015 | a_{15} | 286.412 | 0.0015 |
| a_9 | -116.199 | 0.0015 | | | |
| Frequency referenced to | $a_{10}, \text{R(56) 32-0, } ^{127}\text{I}_2:$ $f= 563\,260\,223\,513 \text{ kHz}$ | | | | [1] |
| [91, 92, 94-99] | | | | | |

Table 19

| $\lambda \approx 532 \text{ nm } ^{127}\text{I}_2 \text{ P}(53) 32\text{-}0 \text{ [No. 1111]}$ | | | | | |
|---|---|------------------|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| a_1 | 0 | — | a_{17} | 762.623 | 0.006 |
| a_2 | 37.530 | 0.006 | a_{18} | 788.431 | 0.008 |
| a_3 | 73.060 | 0.007 | a_{19} | 879.110 | 0.006 |
| a_4 | 271.326 | 0.016 | a_{20} | 892.953 | 0.009 |
| a_{15} | 712.935 | 0.012 | a_{21} | 910.093 | 0.006 |
| a_{16} | 739.274 | 0.008 | | | |
| Frequency referenced to | $a_{10}, \text{R}(56) 32\text{-}0, ^{127}\text{I}_2: f = 563\,260\,223\,513 \text{ kHz}$ $f(a_1, \text{P}(53) 32\text{-}0) - f(a_{10}, \text{R}(56) 32\text{-}0)$ $= 2\,599\,708 (5) \text{ kHz}$ | | | | [1] [1] |
| [91, 92] | | | | | |

Table 20

| $\lambda \approx 633 \text{ nm } ^{127}\text{I}_2 \text{ R}(127) \text{ 11-5}$ | | | | | | | |
|---|-----|---------------------------------|------------------|----------|-----|---------------------------------|------------------|
| a_n | x | $[f(a_n)-f(a_{16})]/\text{MHz}$ | u_c/MHz | a_n | x | $[f(a_n)-f(a_{16})]/\text{MHz}$ | u_c/MHz |
| a_2 | t | -721.8 | 0.5 | a_{12} | j | -160.457 | 0.005 |
| a_3 | s | -697.8 | 0.5 | a_{13} | i | -138.892 | 0.005 |
| a_4 | r | -459.62 | 0.01 | a_{14} | h | -116.953 | 0.005 |
| a_5 | q | -431.58 | 0.05 | a_{15} | g | -13.198 | 0.005 |
| a_6 | p | -429.18 | 0.05 | a_{16} | f | 0 | — |
| a_7 | o | -402.09 | 0.01 | a_{17} | e | 13.363 | 0.005 |
| a_8 | n | -301.706 | 0.005 | a_{18} | d | 26.224 | 0.005 |
| a_9 | m | -292.693 | 0.005 | a_{19} | c | 144.114 | 0.005 |
| a_{10} | l | -276.886 | 0.005 | a_{20} | b | 152.208 | 0.005 |
| a_{11} | k | -268.842 | 0.005 | a_{21} | a | 161.039 | 0.005 |
| Frequency referenced to a_{16} (f), R(127) 11-5, $^{127}\text{I}_2$: $f = 473\,612\,353\,604 \text{ kHz}$ [1] | | | | | | | |
| [100-111] | | | | | | | |

Table 21

| $\lambda \approx 633 \text{ nm } ^{127}\text{I}_2 \text{ P(33) 6-3}$ | | | | | | | |
|--|---|---------------------------------|------------------|----------|-----|---------------------------------|------------------|
| b_n | x | $[f(b_n)-f(b_{21})]/\text{MHz}$ | u_c/MHz | b_n | x | $[f(b_n)-f(b_{21})]/\text{MHz}$ | u_c/MHz |
| b_1 | u | -922.571 | 0.008 | b_{12} | j | -347.354 | 0.007 |
| b_2 | t | -895.064 | 0.008 | b_{13} | i | -310.30 | 0.01 |
| b_3 | s | -869.67 | 0.01 | b_{14} | h | -263.588 | 0.009 |
| b_4 | r | -660.50 | 0.02 | b_{15} | g | -214.53 | 0.02 |
| b_5 | q | -610.697 | 0.008 | b_{16} | f | -179.312 | 0.005 |
| b_6 | p | -593.996 | 0.008 | b_{17} | e | -153.942 | 0.005 |
| b_7 | o | -547.40 | 0.02 | b_{18} | d | -118.228 | 0.007 |
| b_8 | n | -487.074 | 0.009 | b_{19} | c | -36.73 | 0.01 |
| b_9 | m | -461.30 | 0.03 | b_{20} | b | -21.980 | 0.007 |
| b_{10} | l | -453.21 | 0.03 | b_{21} | a | 0 | — |
| b_{11} | k | -439.01 | 0.01 | | | | |
| Frequency | $a_{16} (f), \text{R}(127) \text{ 11-5}, ^{127}\text{I}_2: f= 473\,612\,353\,604 \text{ kHz}$ | | | | | | [1] |
| referenced to | $f(b_{21}, \text{P(33) 6-3}) - f(a_{16}, \text{R}(127) \text{ 11-5})$ | | | | | | [112] |
| | $= -532.42 \text{ (2) MHz}$ | | | | | | |
| [107, 112-116] | | | | | | | |

[107, 112-116]

Table 22 $\lambda \approx 633 \text{ nm}$ $^{129}\text{I}_2$ P(54) 8-4

| a_n | x | $[f(a_n) - f(a_{28})]/\text{MHz}$ | u_c/MHz | a_n | x | $[f(a_n) - f(a_{28})]/\text{MHz}$ | u_c/MHz |
|----------------------------|------|--|------------------|----------|-------|--------------------------------------|----------------------|
| a_2 | z' | -449 | 2 | a_{16} | i' | -197.73 | 0.08 |
| a_3 | y' | -443 | 2 | a_{17} | h' | -193.23 | 0.08 |
| a_4 | x' | -434 | 2 | a_{18} | g' | -182.74 | 0.03 |
| a_5 | w' | -429 | 2 | a_{19} | f' | -162.61 | 0.05 |
| a_6 | v' | -360.9 | 1 | a_{20} | e' | -155.72 | 0.05 |
| a_7 | u' | -345.1 | 1 | a_{21} | d' | -138.66 | 0.05 |
| a_8 | t' | -340.8 | 1 | a_{22} | c' | -130.46 | 0.05 |
| a_9 | s' | -325.4 | 1 | a_{23} | a' | -98.22 | 0.03 |
| a_{10} | r' | -307.0 | 1 | a_{24} | n_2 | -55.6 see m ₈ Table 26 | 0.5 |
| a_{11} | q' | -298.2 | 1 | a_{25} | n_1 | -55.6 see m ₈ Table 26 | 0.5 |
| a_{12} | p' | -293.1 | 1 | a_{26} | m_2 | -43.08 | 0.03 |
| a_{13} | o' | -289.7 | 1 | a_{27} | m_1 | -41.24 | 0.05 |
| a_{14} | n' | -282.7 | 1 | a_{28} | k | 0 | — |
| a_{15} | j' | -206.1 | 0.2 | | | | |
| Frequency referenced to | | $a_{16} (f), \text{R}(127) 11-5, ^{127}\text{I}_2: f = 473\,612\,353\,604 \text{ kHz}$ $f(a_{28}, \text{P}(54) 8-4) - f(a_{16}, \text{R}(127) 11-5 \{^{127}\text{I}_2\})$ $= -42.99 (4) \text{ MHz}$ | | | | | [1] [117, 118] |

[117-125]

Table 23

| $\lambda \approx 633 \text{ nm } ^{129}\text{I}_2 \text{ P(69) 12-6}$ | | | | | | | |
|---|---------|---|------------------|----------|------|---------------------------------|------------------|
| b_n | x | $[f(b_n)-f(a_{28})]/\text{MHz}$ | u_c/MHz | b_n | x | $[f(b_n)-f(a_{28})]/\text{MHz}$ | u_c/MHz |
| b_1 | b''' | 99.12 | 0.05 | b_{21} | q' | 507.66 | 0.10 |
| b_2 | a''' | 116.08 | 0.05 | b_{22} | o' | 532.65 | 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 see m_{28} Table 26 | 0.05 | b_{25} | l' | 560.94 | 0.05 |
| b_6 | q'' | 264.84 see m_{29} Table 26 | 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_1 | i_2'' | 358.8 | 0.5 | b_{30} | g' | 632.42 | 0.03 |
| b_1 | f'' | 373.80 | 0.05 | b_{31} | f' | 644.09 | 0.03 |
| b_1 | d'' | 387.24 | 0.05 | b_{32} | e' | 655.47 | 0.03 |
| b_1 | c'' | 395.3 | 0.2 | b_{33} | d' | 666.81 | 0.10 |
| b_1 | b'' | 402.45 | 0.05 | b_{34} | c' | 692.45 | 0.10 |
| b_1 | a'' | 407 | 4 | b_{35} | b' | 697.96 | 0.10 |
| b_1 | z' | 412.37 | 0.05 | b_{36} | a' | 705.43 | 0.10 |
| b_1 | y' | 417 | 4 | | | | |
| Frequency | | $a_{16} (f), R(127) 11-5, ^{127}\text{I}_2: f=473\,612\,353\,604 \text{ kHz}$ | | | | | [1] |
| referenced to | | $f(a_{28}, P(54) 8-4) - f(a_{16}, R(127) 11-5 \{^{127}\text{I}_2\})$ | | | | | [117, |
| | | $= -42.99 (4) \text{ MHz}$ | | | | | 118] |

[120, 123, 125]

Table 24

| $\lambda \approx 633 \text{ nm } ^{129}\text{I}_2 \text{ R}(60) \text{ 8-4}$ | | | | | | | |
|--|-----|---|------------------|----------|-----|---------------------------------|------------------|
| d_n | x | $[f(d_n)-f(a_{28})]/\text{MHz}$ | u_c/MHz | d_n | x | $[f(d_n)-f(a_{28})]/\text{MHz}$ | u_c/MHz |
| d_2 | A' | -555 | 5 | d_{26} | M | -499 | 2 |
| d_2 | N | -511 | 2 | d_{27} | M | -499 | 2 |
| d_2 | N | -511 | 2 | d_{28} | K | -456 | 2 |
| Frequency | | $a_{16} (f), \text{R}(127) \text{ 11-5}, ^{127}\text{I}_2: f = 473\,612\,353\,604 \text{ kHz}$ | | | | | [1] |
| referenced to | | $f(a_{28}, \text{P}(54) \text{ 8-4}) - f(a_{16}, \text{R}(127) \text{ 11-5 } \{^{127}\text{I}_2\})$ | | | | | [117, |
| | | $= -42.99 (4) \text{ MHz}$ | | | | | 118] |

[120]

Table 25

| $\lambda \approx 633 \text{ nm } ^{129}\text{I}_2 \text{ P}(33) \text{ 6-3}$ | | | | | | | |
|--|-----|--|------------------|----------|-----|------------------------------|------------------|
| e_n | x | $[f(e_n)-f(e_2)]/\text{MHz}$ | u_c/MHz | e_n | x | $[f(e_n)-f(e_2)]/\text{MHz}$ | u_c/MHz |
| e_1 | A | -19.82 | 0.05 | e_{10} | J | 249 | 2 |
| e_2 | B | 0 | — | e_{11} | K | 260 | 2 |
| e_3 | C | 17.83 | 0.03 | e_{12} | L | 269 | 3 |
| e_4 | D | 102.58 | 0.05 | e_{13} | M | 273 | 4 |
| e_5 | E | 141 | 2 | e_{14} | N | 287 | 4 |
| e_6 | F | 157 | 2 | e_{15} | O | 293 | 5 |
| e_7 | G | 191 | 2 | e_{16} | P | 295 | 5 |
| e_8 | H | 208 | 2 | e_{17} | Q | 306 | 6 |
| e_9 | I | 239 | 2 | | | | |
| Frequency | | $a_{16} (f), \text{R}(127) \text{ 11-5}, ^{127}\text{I}_2: f = 473\,612\,353\,604 \text{ kHz}$ | | | | | [1] |
| referenced to | | $f(e_2, \text{P}(33) \text{ 6-3}) - f(a_{16}, \text{R}(127) \text{ 11-5 } \{^{127}\text{I}_2\})$ | | | | | [126, |
| | | $= 849.4 (2) \text{ MHz}$ | | | | | 127] |

[120, 125, 126, 128]

Table 26

| $\lambda \approx 633 \text{ nm}$ $^{127}\text{I}^{129}\text{I}$ P(33) 6-3 | | | | | | |
|---|---------|---|------------------|----------|-----------------------------------|------------------|
| m_n | | $[f(m_n) - f(a_{28})]/\text{MHz}$ | u_c/MHz | m_n | $[f(m_n) - f(a_{28})]/\text{MHz}$ | u_c/MHz |
| m_1 | m' | -254 | 3 | m_{26} | u'' | 212.80 |
| m_2 | l' | -233.71 | 0.10 | m_{27} | t'' | 219.43 |
| m_3 | k' | -226.14 | 0.10 | m_{28} | r'' | 256.90 |
| | | | | | see b_5 Table 23 | |
| m_4 | j' | -207 | 2 | m_{29} | q'' | 264.84 |
| | | | | | see b_6 Table 23 | |
| m_5 | b' | -117.79 | 0.10 | m_{30} | o'' | 299.22 |
| m_6 | p | -87.83 | 0.15 | m_{31} | n'' | 312.43 |
| m_7 | o | -78.2 | 0.5 | m_{32} | m'' | 324.52 |
| m_8 | n | -56 | 1 | m_{33} | l'' | 333.14 |
| | | see a_{24} and a_{25} Table 22 | | | | |
| m_9 | l | -17.55 | 0.05 | m_{34} | k_2'' | 337.7 |
| m_{10} | j | 12.04 | 0.03 | m_{35} | k_1'' | 337.7 |
| m_{11} | i | 15.60 | 0.03 | m_{36} | j'' | 345.05 |
| m_{12} | h | 33.16 | 0.03 | m_{37} | h'' | 362.18 |
| m_{13} | g_2 | 39.9 | 0.2 | m_{38} | g'' | 369.78 |
| m_{14} | g_1 | 41.3 | 0.2 | m_{39} | e'' | 380.37 |
| m_{15} | f | 50.72 | 0.03 | m_{40} | d'' | 385 |
| m_{16} | e | 54.06 | 0.10 | m_{41} | x' | 431 |
| m_{17} | d | 69.33 | 0.03 | m_{42} | w' | 445 |
| m_{18} | c | 75.06 | 0.03 | m_{43} | v' | 456.7 |
| m_{19} | b | 80.00 | 0.03 | m_{44} | u' | 477.17 |
| m_{20} | a | 95.00 | 0.03 | m_{45} | t' | 486.43 |
| m_{21} | y'' | 160.74 | 0.03 | m_{46} | s' | 495.16 |
| m_{22} | x'' | 199.52 | 0.03 | m_{47} | r' | 503.55 |
| m_{23} | w'' | 205.06 | 0.05 | m_{48} | p' | 515.11 |
| m_{24} | v_2'' | 207.9 | 0.5 | | | |
| m_{25} | v_1'' | 207.9 | 0.5 | | | |
| Frequency | | a_{16} , R(127) 11-5, $^{127}\text{I}_2$: $f = 473\,616\,353\,604 \text{ kHz}$ | | | | [1] |
| referenced to | | $f(a_{28}, \text{P}(54) \text{ 8-4}) - f(a_{16}, \text{R}(127) \text{ 11-5 } \{^{127}\text{I}_2\})$ | | | | [117, |
| | | $= -42.99 (4) \text{ MHz}$ | | | | 118] |

[73, 120, 123-125]

Table 27
 $\lambda \approx 778 \text{ nm}$ ^{85}Rb $5S_{1/2} - 5D_{3/2}$ two-photon transition

| $F_g - F_e$ | $[f(5S_{1/2}(F_g) - 5D_{3/2}(F_e))/2 - f_{\text{ref}}]/\text{kHz}$ | u_c/kHz |
|---------------|--|------------------|
| 3-1 | -44 462 655 | 7 |
| 3-2 | -44 459 151 | 7 |
| 3-3 | -44 453 175 | 7 |
| 3-4 | -44 443 871 | 7 |
| 2-1 | -42 944 789 | 7 |
| 2-2 | -42 941 283 | 7 |
| 2-3 | -42 935 308 | 7 |
| 2-4 | -42 926 004 | 7 |
| Frequency | $f_{\text{ref}} = f(5S_{1/2}(F_g=3) - 5D_{5/2}(F_e=5))/2 \{^{85}\text{Rb}\}$ | |
| Referenced to | $f_{\text{ref}} = 385\,285\,142\,375 \text{ kHz}$ | [1] |

[129]

Table 28
 $\lambda \approx 778 \text{ nm}$ ^{85}Rb $5S_{1/2} - 5D_{5/2}$ two-photon transition

| $F_g - F_e$ | $[f(5S_{1/2}(F_g) - 5D_{5/2}(F_e))/2 - f_{\text{ref}}]/\text{kHz}$ | u_c/kHz |
|----------------------------|---|------------------|
| 3-5 | 0 | — |
| 3-4 | 4 718 | 9 |
| 3-3 | 9 228 | 9 |
| 3-2 | 13 031 | 9 |
| 3-1 | 15 771 | 14 |
| 2-4 | 1 522 595 | 9 |
| 2-3 | 1 527 094 | 9 |
| 2-2 | 1 530 887 | 9 |
| 2-1 | 1 533 631 | 11 |
| 2-0 | 1 535 084 | 26 |
| Frequency referenced to | $f_{\text{ref}} = f(5S_{1/2}(F_g=3) - 5D_{5/2}(F_e=5))/2 \{^{85}\text{Rb}\}$ $f_{\text{ref}} = 385\,285\,142\,375 \text{ kHz}$ | [1] |

[129, 130*]

* Improved interval measurements are available for certain components and can be used provided appropriate consideration to uncertainties is made.

Table 29 $\lambda \approx 778 \text{ nm}$ ^{87}Rb $5S_{1/2} - 5D_{3/2}$ two-photon transition

| $F_g - F_e$ | $[f(5S_{1/2}(F_g) - 5D_{3/2}(F_e))/2 - f_{\text{ref}}]/\text{kHz}$ | u_c/kHz |
|-------------|--|------------------|
| 2-0 | -45 047 389 | 7 |
| 2-1 | -45 040 639 | 7 |
| 2-2 | -45 026 674 | 7 |
| 2-3 | -45 004 563 | 7 |
| 1-1 | -41 623 297 | 7 |
| 1-2 | -41 609 335 | 7 |
| 1-3 | -41 587 223 | 7 |

Frequency $f_{\text{ref}} = f(5S_{1/2}(F_g=3) - 5D_{5/2}(F_e=5))/2 \{^{85}\text{Rb}\}$
referenced to $f_{\text{ref}} = 385\,285\,142\,375 \text{ kHz}$ [1]

[129]

Table 30 $\lambda \approx 778 \text{ nm}$ ^{87}Rb $5S_{1/2} - 5D_{5/2}$ two-photon transition

| $F_g - F_e$ | $[f(5S_{1/2}(F_g) - 5D_{5/2}(F_e))/2 - f_{\text{ref}}]/\text{kHz}$ | u_c/kHz |
|-------------|--|------------------|
| 2-4 | -576 001 | 9 |
| 2-3 | -561 589 | 9 |
| 2-2 | -550 112 | 9 |
| 2-1 | -542 142 | 9 |
| 1-3 | 2 855 755 | 9 |
| 1-2 | 2 867 233 | 9 |
| 1-1 | 2 875 200 | 9 |

Frequency $f_{\text{ref}} = f(5S_{1/2}(F_g=3) - 5D_{5/2}(F_e=5))/2 \{^{85}\text{Rb}\}$
referenced to $f_{\text{ref}} = 385\,285\,142\,375 \text{ kHz}$ [1]

[129, 130*]

* Improved interval measurements are available for certain components and can be used provided appropriate consideration to uncertainties is made.

Table 31

| $\lambda \approx 1.54 \text{ }\mu\text{m } ^{13}\text{C}_2\text{H}_2 \text{ }\nu_1 + \nu_3 \text{ band}$ | | | | | |
|--|-----------------------------|---|----|-----------------------------|------------------|
| J | $f(\text{P(J)})/\text{MHz}$ | u_c/MHz | J | $f(\text{R(J)})/\text{MHz}$ | u_c/MHz |
| 30 | −1 149 564.7 | 0.2 | 0 | 1 219 093.1 | 0.2 |
| 29 | −1 063 105.1 | 0.2 | 1 | 1 284 955.8 | 0.2 |
| 28 | −977 244.4 | 0.2 | 2 | 1 350 174.0 | 0.2 |
| 27 | −892 105.5 | 0.2 | 3 | 1 414 736.5 | 0.2 |
| 26 | −807 638.2 | 0.2 | 4 | 1 478 632.0 | 0.2 |
| 25 | −723 847.1 | 0.2 | 5 | 1 541 851.4 | 0.2 |
| 24 | −640 722.1 | 0.2 | 6 | 1 604 387.0 | 0.2 |
| 23 | −558 275.9 | 0.2 | 7 | 1 666 233.6 | 0.2 |
| 22 | −476 502.7 | 0.2 | 8 | 1 727 380.4 | 0.2 |
| 21 | −395 403.0 | 0.2 | 9 | 1 787 844.3 | 0.2 |
| 20 | −314 976.3 | 0.2 | 10 | 1 847 604.8 | 0.2 |
| 19 | −235 222.8 | 0.2 | 11 | 1 906 665.9 | 0.2 |
| 18 | −156 142.2 | 0.2 | 12 | 1 965 025.9 | 0.2 |
| 17 | −77 734.4 | 0.2 | 13 | 2 022 683.7 | 0.2 |
| 16 | 0.0 | — | 14 | 2 079 635.6 | 0.2 |
| 15 | 77 062.9 | 0.2 | 15 | 2 135 883.2 | 0.2 |
| 14 | 153 451.2 | 0.2 | 16 | 2 191 422.0 | 0.2 |
| 13 | 229 165.9 | 0.2 | 17 | 2 246 250.5 | 0.2 |
| 12 | 304 206.5 | 0.2 | 18 | 2 300 366.6 | 0.2 |
| 11 | 378 572.2 | 0.2 | 19 | 2 353 768.0 | 0.2 |
| 10 | 452 257.0 | 0.2 | 20 | 2 406 452.4 | 0.2 |
| 9 | 525 279.1 | 0.2 | 21 | 2 458 417.6 | 0.2 |
| 8 | 597 619.6 | 0.2 | 22 | 2 509 661.5 | 0.2 |
| 7 | 669 287.3 | 0.2 | 23 | 2 560 176.5 | 0.2 |
| 6 | 740 285.1 | 0.2 | | | |
| 5 | 810 618.3 | 0.2 | | | |
| 4 | 880 294.4 | 0.2 | | | |
| 3 | 949 322.3 | 0.2 | | | |
| 2 | 1 017 710.7 | 0.2 | | | |
| 1 | 1 085 467.1 | 0.2 | | | |
| Frequency referenced to | | P(16) $\nu_1 + \nu_3$, $^{13}\text{C}_2\text{H}_2$; $f = 194\,369\,569.4 \text{ MHz}$ [1] | | | |
| [46] | | | | | |

Table 32

| $\lambda \approx 10.3 \mu\text{m}$ OsO ₄ | | | | | | | |
|---|------------|-----------------------|-----------|--|------------------|---|------------------|
| ¹² C ¹⁶ O ₂ | | OsO ₄ | | | | | |
| <i>n</i> | Laser line | Line | [Isotope] | $[f_n - f\{\text{R}(10)\}]/\text{kHz}$ | u_c/kHz | $[f(\text{OsO}_4) - f(\text{CO}_2)]/\text{kHz}$ | u_c/kHz |
| 1 | P(22) | P(74)A1(5) | [192] | -802 127 930.98 | 0.09 | -12 149.5 | 0.2 |
| 2 | P(20) | <i>not identified</i> | | -747 823 325.30 | 0.09 | 9 229.6 | 0.2 |
| 3 | P(18) | <i>n. i.</i> | | -694 298 622.36 | 0.08 | -14 992 | 5 |
| 4 | P(18) | <i>n. i.</i> | | -694 287 490.14 | 0.08 | -3 855.2 | 0.1 |
| 5 | P(18) | P(64)A1(2)- | [188] | -694 228 479.74 | 0.08 | 55 150 | 5 |
| 6 | P(18) | P(64)A1(2)+ | [188] | -694 222 035.30 | 0.08 | 61 594 | 5 |
| 7 | P(16) | <i>n. i.</i> | | -641 510 912.32 | 0.08 | -43 197 | 5 |
| 8 | P(16) | <i>n. i.</i> | | -641 434 335.52 | 0.08 | 33 384.6 | 0.1 |
| 9 | P(14) | <i>n. i.</i> | | -589 380 507.62 | 0.08 | 3 219.6 | 0.2 |
| 10 | P(12) | P(39)A1(3) | [192] | -538 005 458.32 | 0.08 | 25 330.6 | 0.1 |
| 11 | P(12) | P(39)A1(2) | [192] | -538 005 001.14 | 0.08 | 25 782 | 5 |
| 12 | P(10) | <i>n. i.</i> | | -487 427 074.66 | 0.08 | -18 821.1 | 0.1 |
| 13 | P(8) | P(30)A1(1) | [188] | -437 503 817.04 | 0.08 | 11 864.7 | 0.1 |
| 14 | P(6) | <i>n. i.</i> | | -388 374 844.21 | 0.08 | -22 003 | 5 |
| 15 | P(4) | <i>n. i.</i> | | -339 945 022.42 | 0.08 | -25 299 | 5 |
| 16 | P(4) | <i>n. i.</i> | | -339 937 689.31 | 0.08 | -17 966 | 5 |
| 17 | P(4) | <i>n. i.</i> | | -339 929 467.51 | 0.08 | 9 744 | 5 |
| 18 | R(0) | Q(15)A2(2) | [188] | -222 040 746.1 | 2.0 | -9 519.0 | 2 |
| 19 | R(2) | <i>n. i.</i> | | -176 145 049.74 | 0.08 | 9 955 | 5 |
| 20 | R(4) | <i>n. i.</i> | | -131 026 773.25 | 0.08 | -15 760 | 5 |
| 21 | R(6) | <i>n. i.</i> | | -86 634 255.43 | 0.08 | -33 873.0 | 0.1 |
| 22 | R(8) | <i>n. i.</i> | | -42 940 582.49 | 0.08 | -16 145 | 5 |
| 23 | R(8) | <i>n. i.</i> | | -42 920 080 | 1 | 4 368 | 1 |
| 24 | R(8) | <i>n. i.</i> | | -42 898 034.29 | 0.08 | 26 402 | 5 |
| 25 | R(8) | <i>n. i.</i> | | -42 894 454.94 | 0.08 | 29 982 | 5 |
| 26 | R(8) | R(26)A1(0) | [189] | -42 876 821.68 | 0.08 | 47 615 | 5 |
| 27 | R(8) | <i>n. i.</i> | | -42 876 683.60 | 0.08 | 47 753 | 5 |
| 28 | R(8) | <i>n. i.</i> | | -42 875 301.45 | 0.08 | 49 135 | 5 |
| 29 | R(8) | <i>n. i.</i> | | -42 875 199.99 | 0.08 | 49 237 | 5 |
| 30 | R(10) | <i>n. i.</i> | | 0 | — | -15 252.7 | 0.6 |
| 31 | R(12) | <i>n. i.</i> | | 42 217 505.67 | 0.08 | 558.1 | 0.1 |
| 32 | R(14) | <i>n. i.</i> | | 83 689 586.75 | 0.08 | 10 919.1 | 0.1 |
| 33 | R(16) | R(49)A1(2) | [187] | 124 411 469.06 | 0.08 | 13 237.9 | 0.1 |
| 34 | R(18) | <i>n. i.</i> | | 164 349 843.53 | 0.08 | -23 400 | 5 |
| 35 | R(18) | <i>n. i.</i> | | 164 392 583.43 | 0.08 | 19 342.6 | 0.1 |
| 36 | R(18) | <i>n. i.</i> | | 164 394 642.25 | 0.08 | 21 398 | 5 |
| 37 | R(20) | R(67) | [192] | 203 576 376.40 | 0.08 | -24 706.6 | 0.2 |
| 38 | R(22) | R(73)A1(0) | [192] | 242 072 138.79 | 0.08 | -6 788 | 5 |
| 39 | R(22) | <i>n. i.</i> | | 242 088 910.50 | 0.08 | 9 986.0 | 0.2 |
| 40 | R(24) | <i>n. i.</i> | | 279 818 815.98 | 0.09 | 15 102.1 | 0.1 |
| 41 | R(26) | <i>n. i.</i> | | 316 756 631.74 | 0.09 | -15 542.5 | 0.1 |

Frequencies referenced to R(10) / CO₂, OsO₄; $f = 29\,054\,057\,446\,579\text{ Hz}$
[1]

[64, 131-140]

Table 33

| $\lambda \approx 515 \text{ nm } ^{127}\text{I}_2 \text{ P}(13) 43-0$ | | | | | |
|---|--------------------------------|---|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_3)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_3)]/\text{MHz}$ | u_c/MHz |
| a_1 | -131.770 | 0.001 | a_{12} | 435.599 | 0.003 |
| a_2 | -59.905 | 0.001 | a_{13} | 499.712 | 0.005 |
| a_3 | 0 | — | a_{14} | 518 | 1 |
| a_4 | 76.049 | 0.002 | a_{15} | 587.396 | 0.002 |
| a_5 | 203.229 | 0.005 | a_{16} | 616.756 | 0.005 |
| a_6 | 240.774 | 0.005 | a_{17} | 660.932 | 0.005 |
| a_7 | 255.005 | 0.001 | a_{18} | 740 | 1 |
| a_8 | 338.699 | 0.005 | a_{19} | 742 | 1 |
| a_9 | 349.717 | 0.005 | a_{20} | 757.631 | 0.010 |
| a_{10} | 369 | 1 | a_{21} | 817.337 | 0.005 |
| a_{11} | 393.962 | 0.002 | | | |
| Frequency referenced to | | $a_3, \text{P}(13) 43-0, ^{127}\text{I}_2$: $f= 582\,490\,603.38 \text{ MHz}$ | | | [1] |
| [141-144] | | | | | |

Table 34

| $\lambda \approx 515 \text{ nm } ^{127}\text{I}_2 \text{ R(15) 43-0}$ | | | | | |
|---|---|------------------|----------|--------------------------------|--------------------------|
| b_n | $[f(b_n) - f(b_1)]/\text{MHz}$ | u_c/MHz | b_n | $[f(b_n) - f(b_1)]/\text{MHz}$ | u_c/MHz |
| b_1 | 0 | — | b_{12} | 566.287 | 0.005 |
| b_2 | 69.739 | 0.005 | b_{13} | 630.782 | 0.005 |
| b_3 | 129.155 | 0.005 | b_{14} | 658.178 | 0.005 |
| b_4 | 217 | 1 | b_{15} | 725.166 | 0.005 |
| b_5 | 335.828 | 0.005 | b_{16} | 739.394 | 0.005 |
| b_6 | 368 | 1 | b_{17} | 791.673 | 0.005 |
| b_7 | 396.442 | 0.005 | b_{18} | 865.523 | 0.005 |
| b_8 | 471 | 1 | b_{19} | 874.840 | 0.005 |
| b_9 | 472 | 1 | b_{20} | 892.895 | 0.010 |
| b_{10} | 500.627 | 0.005 | b_{21} | 947.278 | 0.010 |
| b_{11} | 525.207 | 0.005 | | | |
| Frequency referenced to | $a_3, \text{P(13) 43-0, } ^{127}\text{I}_2:$ $f = 582\,490\,603.38 \text{ MHz}$ $f(a_1, \text{P(13) 43-0}) - f(a_3, \text{P(13) 43-0})$ $= -131.770 (1) \text{ MHz}$ $f(b_1, \text{R(15) 43-0}) - f(a_1, \text{P(13) 43-0})$ $= 283.835 (5) \text{ MHz}$ | | | | [1] [142] |
| [142, 143] | | | | | |

Table 35

| $\lambda \approx 515 \text{ nm } ^{127}\text{I}_2 \text{ R(98) 58-1}$ | | | | | |
|---|---|------------------|----------|------------------------------|------------------|
| d_n | $[f(d_n)-f(d_6)]/\text{MHz}$ | u_c/MHz | d_n | $[f(d_n)-f(d_6)]/\text{MHz}$ | u_c/MHz |
| d_1 | -413.488 | 0.005 | d_9 | 225.980 | 0.005 |
| d_2 | -359.553 | 0.005 | d_{10} | 253 | 1 |
| d_3 | -194.521 | 0.005 | d_{11} | 254 | 1 |
| d_4 | -159.158 | 0.005 | d_{12} | 314.131 | 0.005 |
| d_5 | -105.769 | 0.005 | d_{13} | 426.691 | 0.005 |
| d_6 | 0 | — | d_{14} | 481.574 | 0.005 |
| d_7 | 172.200 | 0.005 | d_{15} | 510.246 | 0.005 |
| d_8 | 200.478 | 0.005 | | | |
| Frequency referenced to | $a_3, \text{P(13) 43-0, } ^{127}\text{I}_2:$ $f= 582\,490\,603.38 \text{ MHz}$ $f(d_6, \text{R(98) 58-1})-f(a_3, \text{P(13) 43-0})$ $= -2100 \text{ (1) MHz}$ | | | | [1] [145] |
| [143, 145] | | | | | |

Table 36

| $\lambda \approx 543 \text{ nm } ^{127}\text{I}_2 \text{ R}(12) 26-0$ | | | | | |
|---|--------------------------------|--|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_9)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_9)]/\text{MHz}$ | u_c/MHz |
| a_1 | -482.82 | 0.02 | a_9 | 0 | — |
| a_2 | -230.45 | 0.02 | a_{10} | 83.286 | 0.005 |
| a_3 | -220.69 | 0.03 | a_{11} | 193.81 | 0.01 |
| a_4 | -173.916 | 0.005 | a_{12} | 203.07 | 0.01 |
| a_5 | -168.711 | 0.005 | a_{13} | 256.19 | 0.01 |
| a_6 | -116.50 | 0.01 | a_{14} | 269.41 | 0.01 |
| a_7 | -72.962 | 0.005 | a_{15} | 373.510 | 0.005 |
| a_8 | -53.714 | 0.005 | | | |
| Frequency referenced to | | $a_9, \text{R}(12) 26-0, ^{127}\text{I}_2$: $f = 551\,579\,482.97 \text{ MHz}$ | | | [1] |
| [146-152] | | | | | |

| $\lambda \approx 543 \text{ nm } ^{127}\text{I}_2 \text{ R}(106) 28\text{-}0$ | | | | | |
|---|--|------------------|----------|--------------------------------|------------------|
| b_n | $[f(b_n) - f(a_9)]/\text{MHz}$ | u_c/MHz | b_n | $[f(b_n) - f(a_9)]/\text{MHz}$ | u_c/MHz |
| b_1 | 105.655 | 0.005 | b_9 | 564.845 | 0.005 |
| b_2 | 358.958 | 0.005 | b_{10} | 679.420 | 0.005 |
| b_3 | 387.83 | 0.01 | b_{11} | 804.25 | 0.01 |
| b_4 | 397.277 | 0.005 | b_{12} | 811.73 | 0.01 |
| b_5 | 425.745 | 0.005 | b_{13} | 833.93 | 0.01 |
| b_6 | 506.727 | 0.005 | b_{14} | 842.07 | 0.01 |
| b_7 | 519.992 | 0.005 | b_{15} | 966.66 | 0.01 |
| b_8 | 551.660 | 0.005 | | | |
| Frequency referenced to | $a_9, \text{R}(12) 26\text{-}0, ^{127}\text{I}_2:$ $f = 551\,579\,482.97 \text{ MHz}$ | | | | [1] |

[146-152]

| $\lambda \approx 576 \text{ nm } ^{127}\text{I}_2 \text{ P(62) 17-1}$ | | | | | | | |
|---|-----|--------------------------------|---|----------|-----|--------------------------------|------------------|
| a_n | x | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz | a_n | x | $[f(a_n) - f(a_1)]/\text{MHz}$ | u_c/MHz |
| 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_{15} | A | 869.53 | 0.03 |
| a_6 | j | 416.67 | 0.02 | | | | |
| Frequency referenced to | | | $a_1, \text{P(62) 17-1, } ^{127}\text{I}_2:$ $f = 520\,206\,808.4 \text{ MHz}$ | | | | |
| [78, 153] | | | | | | | |

Table 39

| $\lambda \approx 612 \text{ nm } ^{127}\text{I}_2 \text{ R}(47) \text{ 9-2}$ | | | | | | | |
|--|-----|--------------------------------|--|----------|-----|--------------------------------|------------------|
| a_n | x | $[f(a_n) - f(a_7)]/\text{MHz}$ | u_c/MHz | a_n | x | $[f(a_n) - f(a_7)]/\text{MHz}$ | u_c/MHz |
| a_1 | u | -357.16 | 0.02 | a_{12} | j | 219.602 | 0.006 |
| a_2 | t | -333.97 | 0.01 | a_{13} | i | 249.60 | 0.01 |
| a_3 | s | -312.46 | 0.02 | a_{14} | h | 284.30 | 0.01 |
| a_4 | r | -86.168 | 0.007 | a_{15} | g | 358.37 | 0.03 |
| a_5 | q | -47.274 | 0.004 | a_{16} | f | 384.66 | 0.01 |
| a_6 | p | -36.773 | 0.003 | a_{17} | e | 403.76 | 0.02 |
| a_7 | o | 0 | — | a_{18} | d | 429.99 | 0.02 |
| a_8 | n | 81.452 | 0.003 | a_{19} | c | 527.16 | 0.02 |
| a_9 | m | 99.103 | 0.003 | a_{20} | b | 539.22 | 0.02 |
| a_{10} | l | 107.463 | 0.005 | a_{21} | a | 555.09 | 0.02 |
| a_{11} | k | 119.045 | 0.006 | | | | |
| Frequency referenced to | | | $a_7, \text{R}(47) \text{ 9-2, } ^{127}\text{I}_2:$ $f = 489\,880\,354.9 \text{ MHz}$ | | | | |
| [147, 154-158] | | | | | | | |

Table 40

| $\lambda \approx 612 \text{ nm } ^{127}\text{I}_2 \text{ P(48) 11-3}$ | | | | | |
|--|--------------------------------|------------------|----------|--------------------------------|------------------|
| b_n | $[f(b_n) - f(a_7)]/\text{MHz}$ | u_c/MHz | b_n | $[f(b_n) - f(a_7)]/\text{MHz}$ | u_c/MHz |
| 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 | | | |
| Frequency referenced to $a_7, \text{R(47) 9-2, } ^{127}\text{I}_2: f = 489\,880\,354.9 \text{ MHz} \quad [1]$ | | | | | |
| [147, 154, 156-159] | | | | | |

Table 41

| $\lambda \approx 612 \text{ nm } ^{127}\text{I}_2 \text{ R(48) 15-5}$ | | | | | |
|---|------------------------------|---|-------|------------------------------|------------------|
| c_n | $[f(c_n)-f(a_7)]/\text{MHz}$ | u_c/MHz | c_n | $[f(c_n)-f(a_7)]/\text{MHz}$ | u_c/MHz |
| c_1 | -513.83 | 0.03 | c_5 | -209.96 | 0.03 |
| c_2 | -237.40 | 0.03 | c_6 | -97.74 | 0.03 |
| c_3 | -228.08 | 0.03 | c_8 | -73.92 | 0.03 |
| c_4 | -218.78 | 0.03 | c_9 | -59.30 | 0.03 |
| Frequency referenced to | | $a_7, \text{R(47) 9-2, } ^{127}\text{I}_2:$ $f= 489\,880\,354.9 \text{ MHz}$ | | | |
| [154] | | [1] | | | |

Table 42

[illegible]

Table 43

| $\lambda \approx 612 \text{ nm } ^{129}\text{I}_2 \text{ R}(113) 14-4$ | | | | | | | |
|--|-----|---|---|----------|-----|---|------------------|
| b_n | x | $[f(b_n) - f(a_7 \{^{127}\text{I}_2\})]/\text{MHz}$ | u_c/MHz | b_n | x | $[f(b_n) - f(a_7 \{^{127}\text{I}_2\})]/\text{MHz}$ | u_c/MHz |
| b_1 | r | -410.4 | 0.3 | b_{28} | i | -289.4 | 0.5 |
| b_2 | q | -390.0 | 0.3 | b_{29} | h | -273.1 | 0.3 |
| b_2 | p | -383.9 | 0.5 | b_{30} | g | -255.7 | 0.5 |
| b_2 | o | -362.8 | 0.3 | b_{31} | f | -247 | 5 |
| b_2 | n | -352.9 | 0.3 | b_{32} | e | -237 | 5 |
| b_2 | m | -346.4 | 0.3 | b_{33} | d | -223 | 5 |
| b_2 | l | -330.0 | 0.3 | b_{34} | c | -198.6 | 0.3 |
| b_2 | k | -324.9 | 0.3 | b_{35} | b | -193.1 | 0.3 |
| b_2 | j | -304.7 | 0.3 | b_{36} | a | -187.0 | 0.3 |
| Frequency referenced to | | | $a_7, \text{R}(47) 9-2, ^{127}\text{I}_2:$ $f = 489\,880\,354.9 \text{ MHz}$ | | | | [1] |

[161, 162]

Table 44

| $\lambda \approx 640 \text{ nm } ^{127}\text{I}_2 \text{ P}(10) \text{ 8-5}$ | | | | | |
|--|--------------------------------|---|----------|--------------------------------|------------------|
| a_n | $[f(a_n) - f(a_9)]/\text{MHz}$ | u_c/MHz | a_n | $[f(a_n) - f(a_9)]/\text{MHz}$ | u_c/MHz |
| 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 | 0.4 | 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 | 0.2 |
| a_6 | -130.8 | 0.1 | a_{14} | 272.75 | 0.07 |
| a_7 | -82.45 | 0.03 | a_{15} | 374.0 | 0.2 |
| a_8 | -61.85 | 0.14 | | | |
| Frequency referenced to | | $a_9, \text{P}(10) \text{ 8-5, } ^{127}\text{I}_2$: $f = 468\,218\,332.4 \text{ MHz}$ | | | [1] |
| [147, 157, 163-168] | | | | | |

Table 45

| $\lambda \approx 640 \text{ nm } ^{127}\text{I}_2 \text{ R}(16) \text{ 8-5}$ | | |
|--|--------------------------------|---|
| b_n | $[f(b_n) - f(a_9)]/\text{MHz}$ | u_c/MHz |
| b_1 | 62.834 | 0.01 |
| b_2 | 329.8 | 0.2 |
| b_3 | 335.99 | 0.02 |
| Frequency referenced to | | $a_9, \text{P}(10) \text{ 8-5, } ^{127}\text{I}_2$ $f = 468\,218\,332.4 \text{ MHz}$ |
| [147, 157, 163-168] | | |

APPENDIX L 4.

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LIST OF ACRONYMS USED IN THE PRESENT VOLUME

1 Acronyms for laboratories, committees and conferences

| | |
|----------|---|
| AIST* | National Institute of Advanced Industrial Science and Technology, see NMIJ/AIST |
| ASMW* | Amt für Standardisierung, Messwesen und Warenprüfung, Berlin (Germany), see PTB |
| BIPM | International Bureau of Weights and Measures/Bureau International des Poids et Mesures |
| BNM | Bureau National de Métrologie, Paris (France) |
| BNM-INM | Bureau National de Métrologie, Institut National de Métrologie, Paris (France) |
| BNM-LPTF | Bureau National de Métrologie, Laboratoire Primaire du Temps et des Fréquences, Paris (France) |
| CCDM | Consultative Committee for the Definition of the Metre/Comité Consultatif pour la Définition du Mètre, see CCL |
| CCDS* | Consultative Committee for the Definition of the Second/Comité Consultatif pour la Définition de la Seconde, see CCTF |
| CCL | (formerly the CCDM) Consultative Committee for Length/Comité Consultatif des Longueurs |
| CCTF | (formerly the CCDS) Consultative Committee for Time and Frequency/Comité Consultatif du Temps et des Fréquences |
| CEM | Centro Español de Metrología, Madrid (Spain) |
| CENAM | Centro Nacional de Metrología, Mexico (Mexico) |
| CGPM | General Conference on Weights and Measures/Conférence Générale des Poids et Mesures |
| CIPM | International Committee for Weights and Measures/Comité International des Poids et Mesures |
| CMI | Český Metrologický Institut/Czech Metrological Institute, Prague and Brno (Czech Rep.) |
| COOMET | Cooperation in Metrology among the Central European Countries |
| CPEM | Conference on Precision Electromagnetic Measurements |

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

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| CSIR-NML | Council for Scientific and Industrial Research, National Metrology Laboratory, Pretoria (South Africa) |
| CSIRO | see NML CSIRO |
| DG | Discussion Group |
| EUROMET | European Collaboration in Measurement Standards |
| IEC | International Commission on Illumination |
| IEEE | Institute of Electrical and Electronics Engineers, Piscataway NJ (United States) |
| IFCC | International Federation of Clinical Chemistry and Laboratory Medicine |
| ILP RAS | Institute of Laser Physics, Academy of Sciences of Russia, Novosibirsk (Russian Fed.) |
| ILP SOI | Institute of Laser Physics, S.I. Vavilov State Optical Institute, St Petersburg (Russian Fed.) |
| IMGC | Istituto di Metrologia G. Colonnetti, Turin (Italy) |
| IMGC-CNR | Istituto di Metrologia G. Colonnetti, Consiglio Nazionale delle Ricerche, Turin (Italy) |
| ISO | International Organization for Standardization |
| IUPAC | International Union of Pure and Applied Chemistry |
| IUPAP | International Union of Pure and Applied Physics |
| JCRB | Joint Committee of the Regional Metrology Organizations and the BIPM |
| JILA | Joint Institute for Laboratory Astrophysics, Boulder CO (United States) |
| KRISS | Korea Research Institute of Standards and Science, Daejeon (Rep. of Korea) |
| LPI | P.N. Lebedev Physics Institute, Moscow (Russian Fed.) |
| MePWG | CCL Working Group on the <i>Mise en Pratique</i> |
| METAS | (formerly the OFMET) Swiss Federal Office of Metrology and Accreditation/Office Fédéral de Métrologie et d'Accréditation, Wabern (Switzerland) |
| MIKES | Mittatekniikan Keskus, Helsinki (Finland) |
| MRA | Mutual Recognition Arrangement |
| NBS* | National Bureau of Standards (United States), see NIST |
| NCM | National Centre of Metrology, Sofia (Bulgaria) |
| NIM | National Institute of Metrology, Beijing (China) |
| NIPLPR | National Institute for Physics of Lasers, Plasmas and Radiation, Bucharest (Romania) |

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| NIST | (formerly the NBS) National Institute of Standards and Technology, Gaithersburg MD (United States) |
| NMi VSL | Nederlands Meetinstituut, Van Swinden Laboratorium, Delft (The Netherlands) |
| NMI | National Metrology Institute |
| NMIJ/AIST | (formerly NRLM) National Metrology Institute of Japan, Tsukuba (Japan) |
| NML | see CSIR |
| NML CSIRO | National Measurement Laboratory, CSIRO, Lindfield (Australia) |
| NMS | National Measurement Service/Justervesenet, Oslo (Norway) |
| NORAMET | North American Metrology Cooperation |
| NPL | National Physical Laboratory, Teddington (United Kingdom) |
| NRC | National Research Council of Canada, Ottawa (Canada) |
| NRLM* | National Research Laboratory of Metrology, Tsukuba (Japan), see NMIJ/AIST |
| OFMET* | Office Fédéral de Métrologie/Eidgenössisches Amt für Messwesen, Wabern (Switzerland), see METAS |
| OIML | Organisation Internationale de Métrologie Légale |
| PSB* | Singapore Productivity and Standards Board, Singapore (Singapore), see SPRING |
| PTB | Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin (Germany) |
| RMO | Regional Metrology Organization |
| SMU | Slovenský Metrologický Ústav/Slovak Institute of Metrology, Bratislava (Slovakia) |
| SPIE | International Society for Optical Engineering |
| SPRING | (formerly the PSB) Standards, Productivity and Innovation Board, Singapore (Singapore) |
| TC | Technical Committee |
| UME | Ulusal Metroloji Enstitüsü/National Metrology Institute, Gebze-Kocaeli (Turkey) |
| VNIIFTRI | All-Russian Research Institute for Physical, Technical and Radiophysical Measurements, Gosstandart of Russia, Moscow (Russian Fed.) |
| VNIIM | D.I. Mendeleyev Institute for Metrology, Gosstandart of Russia, St Petersburg (Russian Fed.) |

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| VNIIMS | Russian Research Institute for Metrological Service, Gosstandart of Russia, Moscow (Russian Fed.) |
| WGDM | CCL Working Group on Dimensional Metrology |

2 Acronyms for scientific terms

| | |
|------|------------------------------------|
| CMC | Calibration Measurement Capability |
| CMM | Coordinate Measuring Machine |
| GPS | Global Positioning System |
| KCDB | BIPM Key Comparison Database |
| SI | International System of Units |

STEDI
1, Boulevard Ney, 75018 Paris
Dépôt légal, n° 7927
ISBN 92-822-2197-0
ISSN 1684-8845
Achevé d'imprimer : avril 2003
Imprimé en France