Bureau International des Poids et Mesures

Consultative Committee for the Definition of the Metre (CCDM)

9th Meeting (September 1997)

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

MEMBER STATES OF THE METRE CONVENTION

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

THE BIPM AND THE METRE CONVENTION

The Bureau International des Poids et Mesures (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 m^2) of the Pavillon de Breteuil (Parc de Saint-Cloud) placed at its disposal by the French Government; its upkeep is financed jointly by the Member States of the 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 Comité International des Poids et Mesures (CIPM) which itself comes under the authority of the Conférence Générale des Poids et Mesures (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) and to time scales (1988). 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 and in 1984 for the laser work. In 1988 a new building for a library and offices 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, published in the *Procès-Verbaux des Séances du Comité International des Poids et Mesures*, 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 chairman 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 nine 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 (CCQM), set up in 1993.

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

- Comptes Rendus des Séances de la Conférence Générale des Poids et Mesures;
- Procès-Verbaux des Séances du Comité International des Poids et Mesures;
- Reports of Meetings of Consultative Committees.

The BIPM also publishes monographs on special metrological subjects and, under the title *Le Système International d'Unités (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 *Procès-Verbaux* of the CIPM.

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 THE DEFINITION OF THE METRE

as of 16 September 1997

President

M. Chung Myung Sai, member of the Comité International des Poids et Mesures, Korea Research Institute of Standards and Science, Taejon.

Executive secretary

Mr J.-M. Chartier, Bureau International des Poids et Mesures [BIPM], Sèvres.

Members

Bureau National de Métrologie: Institut National de Métrologie [BNM-INM], Paris.
CSIRO, Division of Applied Physics [CSIRO], Lindfield.
D.I. Mendeleyev Institute for Metrology [VNIIM], St Petersburg.
Istituto di Metrologia G. Colonnetti [IMGC], Turin.
Korea Research Institute of Standards and Science [KRISS], Taejon.
National Institute of Metrology [NIM], Beijing.
National Institute of Standards and Technology [NIST], Gaithersburg/Joint Institute for Laboratory Astrophysics [JILA], Boulder.
National Physical Laboratory [NPL], Teddington.
National Research Council of Canada [NRC], Ottawa.
National Research Laboratory of Metrology [NRLM], Tsukuba.
Office Fédéral de Métrologie [OFMET], Wabern.
Physikalisch-Technische Bundesanstalt [PTB], Braunschweig.
The Director of the Bureau International des Poids et Mesures [BIPM], Sèvres.

Consultative Committee
for the Definition of the Metre

Report of the 9th meeting

(16-18 September 1997)

to the Comité International des Poids et Mesures

Agenda

1 Opening of the meeting; designation of a rapporteur.

2 Equivalence of national measurement standards.

3 Examination of replies to the BIPM questionnaire.

4 Presentation of new results relating to items in the questionnaire.

5 Modifications to the 1992 *mise en pratique*, including proposals for new recommended radiations:

- 5.2 Working party proposals;
- 5.2 Discussion of proposals;
- 5.3 Working party for final recommendation to the CIPM.

6 Report of the working group on dimensional metrology.

7 Identification of key comparisons in length metrology:

- 7.1 Proposed comparisons;
- 7.2 Participation in key comparisons;
- 7.3 Role of the regional key comparison;
- 7.4 Results of the CCDM gauge block comparison;
- 7.5 Key comparison for stabilized lasers; provisional equivalence issue.

8 Work at the BIPM:

- 8.1 International comparisons of stabilized lasers;
- 8.2 Research work;
- 8.3 Nanometrology.

9 CCDM working groups:

- 9.1 Working group on the *mise en pratique*;
- 9.2 An equation for determining refractive index;
- 9.3 Working party on future work.

10 Recommendations to the CIPM:

- 10.1 Background to recommendations;
- 10.2 Future work at the BIPM;
- 10.3 Change of name of the CCDM.

11 Date of next meeting.

1 OPENING OF THE MEETING; DESIGNATION OF A RAPPORTEUR

The Consultative Committee for the Definition of the Metre (CCDM) held its 9th meeting at the Bureau International des Poids et Mesures (BIPM), Sèvres, on Tuesday 16, Wednesday 17 and Thursday 18 September 1997. Five sessions were held.

The following were present: L.Y. Abramova (VNIIM), F. Bertinetto (IMGC), N. Brown (CSIRO-NML), M.S. Chung (President of the CCDM), C.I. Eom (KRISS), P. Gill (NPL), J.L. Hall (JILA), J. Helmcke (PTB), P. Juncar (BNM-INM), H. Kunzmann (PTB), A. Madej (NRC), H. Matsumoto (NRLM), J. Pekelsky (NRC), M. Priel (BNM-INM), T.J. Quinn (Director of the BIPM), F. Riehle (PTB), W.R.C. Rowley (NPL), A. Sacconi (IMGC), S. Shen (NIM), J.A. Stone (NIST), R. Thalmann (OFMET), Y.G. Zakharenko (VNIIM).

Invited: J. Blabla (CMI), O. Krüger (CSIR), R. Muijlwijk (NMi-VSL), V. Navratil (SMU), M. Okaji (NRLM), M. Viliesid (CENAM).

Also present: P. Giacomo (Director emeritus of the BIPM); J.-M. Chartier, R. Felder, S. Picard, L. Robertsson, L.F. Vitushkin and A. Zarka (BIPM).

Dr Quinn opened the meeting on behalf of the BIPM and introduced the new President of the CCDM. He pointed out that there are important decisions to be made which include modifications to the practical realization of the definition of the metre and selection of key comparisons, as well as the activities of working groups to be considered.

The President thanked the Director of the BIPM and welcomed members, particularly those attending a CCDM meeting for the first time.

Dr Brown was appointed rapporteur.

The agenda was approved with no additional business proposed.

2 EQUIVALENCE OF NATIONAL MEASUREMENT STANDARDS

Dr Quinn spoke about the new demands being made of Consultative Committees to establish key comparisons which will help to lay the basis for future equivalence agreements between national laboratories. The CCDM is the last to consider this matter and should decide on key comparisons which test a laboratory's ability in length measurements. This will result in a great deal of extra work, so it is important to choose carefully, avoiding undue rigour, and to see the comparisons as a way of testing the capabilities of the laboratory. This should not just be a test of the primary standard, but should also test the work in general so that calibration certificates are mutually recognised. There are many decisions to be made before all the guidelines are established and agreed on, but these will soon be considered by the CIPM and should be in place next year. It is important to start planning the comparison programme at this meeting and appoint pilot laboratories to run key comparisons for the Consultative Committee members. Regional comparisons will need to be organized to allow every national laboratory to take part, and these need to be linked together with a reasonable redundancy. The Consultative Committee must approve the results of the comparison before publication.

3 EXAMINATION OF REPLIES TO THE BIPM QUESTIONNAIRE

Mr Chartier presented the results of the BIPM questionnaire in summary form (CCDM/97-19). Six laboratories have made new frequency measurements and have proposals to include them in a revised *mise en pratique* (the practical realization of the definition of the metre). There is a majority in support of new working groups. All the members have taken part in international comparisons of stabilized lasers and dimensional metrology since the last CCDM. Mr Chartier concluded that there is a need to revise the 1992 *mise en pratique* in order to include corrections, update a laser frequency and add several new interesting laser radiations.

4 PRESENTATION OF NEW RESULTS RELATING TO ITEMS IN THE QUESTIONNAIRE

The NIST/JILA reported on the determination of the frequency of a frequency-doubled Nd:YAG laser stabilized on an absorption line at 532 nm in molecular iodine. Its most recent determination made use of the measurement of the frequency of a two-photon transition in rubidium at the BNM-LPTF.

The NPL discussed recent results using cold single strontium ions in a measurement which parallels the work at the NRC. Line widths below 1 kHz have been achieved and frequency measurements made by the two laboratories show good agreement. The frequency accuracy is already close to that achieved for the 633 nm iodine-stabilized laser and will be further improved. Frequency measurements of an iodine-stabilized frequency-doubled Nd:YAG laser have just been completed to complement the value reported by the NIST/JILA. The wide tuning range of this laser, which spans 8 to 9 absorption lines, means that people can work on different lines. A number of line separations have been measured to solve this problem.

The PTB reported a new frequency measurement for a calcium-stabilized laser which uses cold, trapped calcium atoms. It proposed that the result of this measurement be included in a revised *mise en pratique,* together with a new frequency measurement of the 1S-2S two-photon transition of atomic hydrogen, made at the MPQ. A frequency measurement of a transition in molecular iodine at 815 nm has been performed by measuring the frequency difference between the Ca-stabilized laser and a CH_4-stabilized He-Ne laser.

The NRC reported progress on work with single barium and strontium ions. The frequency of the barium system has been measured using the CO_2 frequency chain; the frequency of the strontium ion system has been measured relative to the iodine-stabilized He-Ne laser at 633 nm. A preliminary comparison with the caesium time standard has been made and this will enable the NRC to make the strontium system its primary realization of length, allowing absolute measurement of 633 nm lasers.

The IMGC described a measurement at the LENS of the frequency of a He transition at 389 nm with respect to a previously calibrated Rb two-photon transition at $2\lambda_0 \approx 778$ nm. In cooperation with the CSELT, it measured the wavelengths of several transitions of C_2H_2 and HI near 1.5 μm, an important spectral region for telecommunications. Work is soon to be published on measurements made with a transportable CO_2/OsO_4 laser.

The BNM-LPTF intimated that the 778 nm laser based on the two-photon transition in rubidium is a very useful standard both because it is simple and readily made portable. Present frequency measurements are limited by the CO_2 laser frequency at 29 THz, but there are plans to solve this.

There was a discussion on the future need for reliable optical-microwave frequency chains that must be capable of operating for long periods if optical standards are ever going to replace the present caesium time standard.

5 MODIFICATIONS TO THE 1992 *MISE EN PRATIQUE*, INCLUDING PROPOSALS FOR NEW RECOMMENDED RADIATIONS

5.1 Working party proposals

The Chairman of the working group on the *mise en pratique* of the definition of the metre introduced the document "Proposal to the 1997 CCDM" (CCDM/97-25). Dr Quinn explained that this is the work of a small informal group which met two weeks previously to consider new frequencies for the *mise en pratique* (the practical realization).

Dr Gill, who chaired the group, proposed three changes to the *mise en pratique*: 1) to include the definition of the metre and the three methods for realizing the metre in the introduction; 2) to revise the existing calcium frequency; and 3) to include five new radiations in the list of recommended radiations.

Other proposals are the eventual removal of two rarely used radiations (576 nm and 640 nm), the publication of recommended values for spectral lamps, the desirability of new reference frequencies in the telecommunication bands, the creation of a data base of lines, and the formation of a formal working group to continue this work for future CCDM meetings.

5.2 Discussion of proposals

The meeting supported these proposals. Drs Hall, Gill and Madej commented that a new measurement for the 532 nm radiation will soon reduce its uncertainty to 5 kHz and that the high signal-to-noise of this laser's control signal has made it popular with many laboratories involved in developing systems. The two-photon transition in rubidium (778 nm) is an attractive laser system because it is based on laser diodes and can be made portable. The 1S-2S two-photon transition in hydrogen provides the most accurate reference for short wavelengths (243 nm). The CO_2 laser system based on osmium tetroxide (10 μm) plays a pivotal role in frequency chains as it links the infrared and visible. An earlier suggestion to include unstabilized He-Ne lasers as a source was dropped following several comments that the emission lines at 633 nm and 640 nm can be, and have been, confused. Dr Hall commented on the possibility of measuring a grid of acetylene lines from 778 nm to 800 nm and the need for a simple system which would allow access to the large number of measured frequencies that will become available. A possible Web site and the consequences of this were discussed.

Dr Rowley raised an objection to the proposed dominant position in the *mise en pratique* of a paragraph on general relativity. Dr Hall supported this and suggested that it be included as an appendix. A vote was taken to determine support for moving the section on general relativity to an appendix. It was carried thirteen for, one against, with one abstention.

5.3 Working party for final recommendation to the CIPM

The President formed a working party to draft the revised list of recommended radiations. Dr Gill was asked to chair the party with Dr Bertinetto, Mr Chartier, Dr Hall, Prof. Juncar, Dr Madej and Dr Riehle forming the party members. They were to draft the frequencies and uncertainties of radiations to be included in the revised *mise en pratique*.

Dr Gill presented the first draft by the working party. Dr Riehle pointed out that for the 633 nm radiation the CIPM had adopted a standard uncertainty of 12 kHz, or a relative standard uncertainty of 2.5×10^{-11}. Accordingly, it should be specified that it is the technique of detecting the third harmonic which is used to stabilize the frequency of this radiation. Dr Helmcke asked for the inclusion of a statement that the wavelength is a vacuum wavelength. There was concern about the correct notation for the radiation transitions. The working party agreed to address these issues before the last session.

Dr Gill presented a second draft to the meeting. The list of radiations is divided into two parts. It was agreed that they all have equal status for the realization of the metre. Dr Rowley stated that the reason for the division is to separate older standards from new ones. The older standards are clearly declining in use, so it is inadvisable to build new equipment based on these standards. A vote taken to accept the list of "radiations of stabilized lasers" which will form part of Recommendation M 1 (1997) was passed unanimously.

The President asked the committee to consider the introductory section to Recommendation M 1. The recommendations made at the last CCDM (1992) concentrated on future research into new radiations. Dr Pekelsky spoke in favour of statements which support the funding of basic research into frequency standards. Dr Helmcke asked that statements be added to meet the growing demands in the field of dimensional metrology. A working party was formed to draw up a recommendation. The meeting passed the working party's draft unanimously (Recommendation M 2).

6 REPORT OF THE WORKING GROUP ON DIMENSIONAL METROLOGY

Dr Pekelsky tabled two reports from the Chairman of the working group on dimensional metrology, "Chairman's report on 1st meeting of CCDM/WGDM" (CCDM/97-20) and "Chairman's report: activities to July 1997" (CCDM/97-21). He presented a slide "Current key topics in dimensional metrology", which listed seven key topics: 1) gauge blocks; 2) length bars; 3) angle standards; 4) diameter standards; 5) coordinate measuring machine (CMM) artefacts; 6) nano-metrology; and 7) thermal expansivity. He explained that this is a minimal list and that it may be necessary to add other topics later, such as line scales. The purpose of identifying key topics was to form small discussion groups to help decide on key comparisons. The main concern is whether the latter provide enough information about a laboratory's abilities to make a statement about equivalence. Dr Quinn commented that the alternative to a limited number of comparisons is an impractical amount of work and that the key comparisons only need to give a broad confidence in the laboratory's ability. Dr Kunzmann pointed out that they should form the backbone and that other comparisons can take place if needed.

Dr Pekelsky displayed the "Guide criteria for identifying CCDM dimensional metrology key comparisons" which breaks the criteria into three parts:

1) a key comparison should challenge a key technique in that area, be important to the community of national metrology institutes, provide an optimal link to regional comparisons, satisfy accreditation needs, and be repeated at selected intervals;

2) artefacts used in a key comparison should exhibit availability (and replaceability if damaged), good performance in previous comparisons, industrial relevance, demonstrated stability, and be a challenge to measure;

3) participating laboratories should provide this measurement (now or in the future) as a calibration service, have measurement uncertainties below a certain level, not get their traceability elsewhere for components of the measurement which make a major contribution to the uncertainty of the measurement, and be willing to participate in the regional comparison.

Application of these criteria has identified six key comparisons, which are planned to start over the next three years. Dr Pekelsky summarized these with a third slide. This showed the key comparisons, proposed pilot laboratory and possible start date:

1) gauge blocks: OFMET, March 1998;

2) length bars: NPL, October 1999;

3) optical polygons: CSIR, July 1998;

4) cylindrical diameter standards: NIST, September 1998;

5) CMM step gauge/ball bar: PTB/NIST, March 1998;

6) CMM 2D ball plate: CENAM, January 2000.

Dr Quinn congratulated the working group on a very satisfactory outcome.

7 IDENTIFICATION OF KEY COMPARISONS IN LENGTH METROLOGY

7.1 Proposed comparisons

For gauge blocks Dr Thalmann proposed circulating 15-20 gauge blocks made from different materials with longer gauges than were used in the last CCDM gauge block comparison. The measurements should be restricted to central length.

In discussions of the length bar comparison Prof. Shen asked why gauge blocks and length bars are in different categories. Dr Helmcke replied that they have always been considered as separate in EUROMET as they can have various shapes and different techniques or instruments are normally used to measure them. Temperature is a critical factor with length bars. It was agreed that key comparisons should test capabilities and not artefacts, so the distinction is appropriate.

For the case of optical polygons Dr Krüger proposed a CCDM key comparison using a 7-sided polygon and a 12- or 24-sided polygon. The 7-sided polygon could be the one currently being used in a EUROMET comparison which would have the advantage of linking the two comparisons.

It was agreed that suitable artefacts for a key comparison in diameter standards would be a cylinder and a plug, and that diameter and form should be measured.

Dr Kunzmann proposed that initially two linear artefacts be circulated for a CMM key comparison. The PTB will pilot a step-gauge key comparison while the NIST will pilot a ball bar key comparison. Laboratories can participate in either or both. The aim will be to measure the artefact and this need not be done on a CMM artefact. This should be followed by a two-dimensional artefact such as a ball plate which should be measured on a CMM system and the CENAM will pilot this.

The meeting agreed to this programme and to the pilot laboratories nominated.

7.2 Participation in key comparisons

When Dr Quinn called for a show of hands to indicate likely participation in the key comparisons, a very high participation rate was indicated. Both the gauge block and polygon comparisons attracted interest from all committee members. The CMI and CSIR are the only members unable to take part in the length bar comparison. The CMI, KRISS and SMU do not wish to participate in the diameter comparison. The NMi and SMU do not wish to be included in either CMM comparison. The CSIR will not take part in the step gauge/ball bar comparison and the VNIIM will not participate in the ball plate comparison.

Dr Thalmann pointed out that these large numbers of participants could not be managed with a single comparison. Dr Quinn commented that this problem is unique to dimensional metrology, nor were there any examples which one could follow from other Consultative Committees. Whatever criteria are adopted in selecting participants for a key comparison, it would not be appropriate to exclude CCDM members except on technical grounds. Where numbers of participants must be limited in order to carry out the comparison in a reasonable time, it will be necessary to organize two parallel key comparisons.

7.3 Role of the regional key comparison

Dr Brown made the point that the number of members taking part in the CCDM key comparison may fall once the regional key comparisons are organized. These have equal status and if organized to run at the same time should be a useful alternative to the CCDM key comparison. Laboratories in the CCDM key comparison may also have to take part in their regional key comparison to provide the redundant linkage now required. As this represents twice the effort, laboratories may prefer simply to participate in the regional comparison. Dr Kunzmann mentioned that there could be strong economic pressures to take part in a CCDM key comparison unless it is explicitly stated in guidelines for making equivalence statements that the CCDM and regional key comparisons are of equal status.

Dr Quinn stressed the intention to make the CCDM and regional key comparisons equal in status. This can be achieved by establishing the guidelines and protocols. Pilot laboratories should consult with other laboratories to draw up these protocols. A vital element will be a list of the major components in the uncertainty and all participants must provide this information. They can add other factors, but the principal ones should be easily compared between participants.

7.4 Results of the CCDM gauge block comparison

Dr Thalmann presented the results of the last CCDM gauge block comparison in order to obtain the approval of the Committee to publish the results, in compliance with the spirit of future key comparisons. Two laboratories remeasured the gauges and both results were shown. Dr Quinn observed that the revised results from the two laboratories show no significant differences with those of other laboratories, the sole criticism being that only one laboratory linked each region. Dr Thalmann agreed and said that this would be changed in the next key comparison. The results were passed for publication.

7.5 Key comparison for stabilized lasers; provisional equivalence issue

The President raised the issue of a key comparison for lasers. Dr Hall pointed out that there could be differences between quantum standards and the standard used for dimensional metrology if a comparison programme is not carried out. It is still necessary for the laboratory to "follow the best good practice concerning methods of stabilization" as specified in the *mise en pratique.* Dr Rowley commented that the 633 nm laser still satisfies the requirements of dimensional metrology. Dr Kunzmann raised the possible need to have a key comparison of secondary laser systems which stabilize the laser to the He-Ne gain curve. This was discussed but it was felt that it could be covered by supplementary comparisons rather than a key comparison. Dr Helmcke remarked that the situation might change when laser diodes become more common as interferometer sources and the calibration procedure may not be as simple. It was agreed that the iodine-stabilized He-Ne laser at 633 nm remain the standard for key comparisons for stabilized lasers.

Dr Quinn stressed that the economic pressures to move quickly on the equivalence issue are very strong and asked the working group on dimensional metrology to draw up a list of past comparisons which could be used to make a provisional list of equivalence statements.

8 WORK AT THE BIPM

8.1 International comparisons of stabilized lasers

Mr Chartier presented slides showing the comparisons that have taken place since the last CCDM meeting. Most activity has occurred with the iodine-stabilized He-Ne lasers at 633 nm for which five bilateral and eight grouped comparisons have been carried out with the BIPM's participation. In total thirty-four laboratories (including all member laboratories of the CCDM) have participated. Practically all the results are within the uncertainty given in the *mise en pratique*. Those that fall outside this limit are generally shown to have a faulty iodine cell or faulty electronics. Limited comparisons have also been carried out with the iodine-stabilized He-Ne at 543 nm, with an iodine-stabilized frequency-doubled Nd:YAG laser at 532 nm and an iodine-stabilized laser diode at 633 nm.

Dr Helmcke asked how many of the participating laser systems have been purchased rather than built by the laboratory. Mr Chartier estimated this at about 50 %.

8.2 Research work

Dr Robertsson presented a summary of several research efforts. These included beam geometry effects, where detection of part of the laser beam can result in laser frequency offsets, FM line detection, as opposed to third harmonic detection, and frequency-doubled Nd:YAG laser work. This latter work, which was carried out at the JILA as a cooperative effort, achieved frequency stabilities better than 10^{-14} for an averaging time of 60 s. Mr Felder spoke about recent work on a methane-stabilized laser and a laser diode system stabilized on a two-photon transition in rubidium. Dr Picard described new computer software for determining hyperfine components.

Mr Zarka described a laser diode system at 633 nm which uses the P(33)6-3 transition in iodine and achieves a best stability of 3×10^{-12}. An automatic locking system is being developed. The laser has a tuning range of 4 nm and the stability is limited by the electronics. Dr Helmcke asked if there was any evidence of sidebands, commenting on the difficulty of observing these in some cases. None were observed.

8.3 Nanometrology

Dr Vitushkin described his work in nanometrology, in which an interferometer is used for measuring the spacing of gratings.

There was considerable discussion on the scope and definition of nanometrology, and of its importance in manufacturing sectors such as semiconductors. Dr Quinn asked the working group on dimensional metrology to provide a clearer definition of nanometrology to the CCDM.

9 CCDM WORKING GROUPS

9.1 Working group on the *mise en pratique*

The Chairman proposed the formation of a new working group based on the majority support received from the BIPM questionnaire. This working group would be asked to consider the contents of the *mise en pratique* and propose future changes, make proposals for key comparisons, and look into the preparation of a stabilized-laser frequency data base. Ten laboratories volunteered to form the working group: BIPM, BNM-INM, BNM-LPTF, CSIRO-NML, KRISS, NIST, NPL, NRC, NRLM and PTB.

Dr Gill was chosen to chair the working group on the *mise en pratique*.

9.2 An equation for determining refractive index

Dr Sacconi raised the need for a more uniform approach towards the calculation of refractive index. Recent comparisons have shown that laboratories are using different equations. In a discussion on recent work Dr Rowley pointed out that a refractometer would provide the most accurate value. There is support for an equation that is validated at the recommended radiations. Dr Matsumoto mentioned that an international working group already exists. Dr Quinn suggested that the CCDM could adopt an equation to calculate refractive index. The meeting voted to appoint Dr Sacconi to contact known researchers in this field with a view to obtaining expert advice on a suitable equation or to form a discussion group with the purpose of achieving this.

9.3 Working party on future work

Dr Quinn arranged a small working party early in the meeting to draft a new recommendation to the CIPM on future work, Recommendation M 2 (1997). Draft A was considered by the meeting and modified so that a draft B was then considered. This was passed unanimously.

10 RECOMMENDATIONS TO THE CIPM

10.1 Background to recommendations

The President asked Dr Quinn to explain the background to this agenda item. Dr Quinn referred to the past work of the BIPM and to a report by the CIPM entitled *National and international needs relating to metrology, appropriate international collaborations, and the role of BIPM*. It provides insight into the future roles of the BIPM. One role is to work towards worldwide uniformity of measurement. There are also basic tasks to keep units up-to-date, for example, to conserve and disseminate mass. The CCDM needs to inform the CIPM of future needs in the field of length metrology and give practical guidance on suitable work for the BIPM for the next decade.

10.2 Future work at the BIPM

Dr Quinn raised the issue of a replacement for the iodine-stabilized He-Ne laser at 633 nm. A general discussion concluded that the 633 nm laser will remain useful while commercial laser interferometers and low-cost secondary standards are based on this wavelength. Rival laser systems are the frequency-doubled Nd:YAG at 532 nm and the diode laser stabilized on the two-photon transition in rubidium, at 778 nm. But low-cost secondary standards are not yet available. Another possible area of work is in frequency synthesis and while this requires much effort, it may be possible for the BIPM to collaborate with the other laboratories in Paris that can do this work.

Dr Quinn asked for directives in dimensional metrology. The meeting agreed that this field is too large for the BIPM to become involved. There is support for work in nanometrology and Dr Quinn pointed out that this overlaps with their work on new mass standards where surface finish is so important that the BIPM is using a diamond lathe to fabricate accurate cylinders. The BIPM is also producing very accurate apertures for photometry which need to be measured. Mr Priel commented that a large investment is required for high-accuracy measurements of roundness and form and that the BIPM should find a partner for this work. Dr Pekelsky commented that most areas of dimensional metrology are moving into measurement accuracies that are in the nanometre range. It would be desirable for the BIPM to be involved in this area. This was supported by Mr Eom. Dr Sacconi suggested that the BIPM should continue to concentrate on transportable standards for disseminating the metre, as this has been most successful, but a presence in nanometrology would be appropriate.

10.3 Change of name of the CCDM

Dr Quinn raised the subject of a change of name of the CCDM, as proposed by Dr Blevin. While this is a matter for the CIPM to decide, the feelings of the committee are of interest. Dr Helmcke supported the acronym “CCL” (Consultative Committee for Length) as this includes both aspects of the work of the committee, the *mise en pratique* and dimensional metrology. This was generally supported by members, given that “CCM” (Consultative Committee for the Metre) is already allocated to the Consultative Committee for Mass.

11 DATE OF NEXT MEETING

The President thanked delegates for attending the meeting, the working groups for their contributions and Dr Brown for acting as rapporteur. It was agreed that the next meeting would take place in three years’ time, in the year 2000.

N. Brown, Rapporteur
September 1997
revised December 1998

Recommendations
of the Consultative Committee for the Definition of the Metre

submitted to the
Comité International des Poids et Mesures

1 RECOMMENDATION M 1 (1997)*: Revision of the practical realization (*mise en pratique*) of the definition of the metre

The Consultative Committee for the Definition of the Metre,

recalling that

- in 1983 the 17th Conférence Générale des Poids et Mesures (CGPM) adopted a new definition of the metre;
- in the same year the CGPM invited the Comité International des Poids et Mesures (CIPM)
  - to draw up instructions for the practical realization of the metre,
  - to choose radiations which can be recommended as standards of wavelength for the interferometric measurement of length and draw up instructions for their use,
  - to pursue studies undertaken to improve these standards and in due course to extend or revise these instructions;
- in response to this invitation the CIPM made a number of recommendations in 1983 concerning the practical realization of the metre (the *mise en pratique*);

recalling that in 1992 the CIPM revised the *mise en pratique* of the definition of the metre;

considering that

- science and technology continue to demand improved accuracy in the realization of the metre;
- since 1992 work in national laboratories, the BIPM and elsewhere has identified new radiations and their methods whose realization leads to low uncertainties;
- such work has also substantially reduced the uncertainty in the determined value of the frequency and wavelength in vacuum of one of the already recommended radiations;

---

* This Recommendation was approved by the CIPM at its 86th meeting as Recommendation 1 (CI-1997), see on page 92.

- a revision of the list of recommended radiations is desirable for many applications, which include not only the direct realization of the metre by means of optical interferometry for practical length measurement, but also spectroscopy, atomic and molecular physics and the determination of fundamental physical constants;

recommends that the list of recommended radiations given by the CIPM in 1992 (Recommendation 3 (CI-1992)) be revised.

2 RECOMMENDATION M 2 (1997): Future work

The Consultative Committee for the Definition of the Metre,

considering that

- science and technology are continuously demanding more accurate realizations of the metre;
- requirements for advanced dimensional metrology continue to increase;
- there are strong requirements for demonstration of the degree of equivalence between national metrology institutes in the field of length measurements;
- international uniformity and long-term stability of length measurements depend upon realizations of the SI unit of length;
- tolerances in high-technology manufacturing continue to fall and that in some areas they are already at the limit of what is possible today;
- the range over which such requirements exist extends from atomic dimensions to the domain of geophysics;
- many different areas of metrology call upon realizations of SI derived units that themselves include the metre;
- the most demanding requirements often call for the direct realization of the metre by means of optical wavelengths and frequency standards, realization that should be the simplest and the most direct possible;
- to provide for the future and to ensure that the world's metrological system is capable of meeting future demands, continued basic research is essential;

recommends that national laboratories

- maintain a wide research base in length metrology and in particular continue to maintain and develop techniques to meet the growing demands in the field of dimensional metrology and
- maintain their efforts to develop and evaluate new standards for length, wavelength and frequency, and new techniques for the comparison of different standards over a wide range of wavelength and frequency.

Recommendation
of the Consultative Committee for the Definition of the Metre

adopted by the
Comité International des Poids et Mesures

RECOMMENDATION 1 (CI-1997): Revision of the practical realization of the definition of the metre

The Comité International des Poids et Mesures,

recalling

- that in 1983 the 17th Conférence Générale des Poids et Mesures (CGPM) adopted a new definition of the metre;
- that in the same year the CGPM invited the Comité International des Poids et Mesures (CIPM)
  - to draw up instructions for the practical realization of the metre,
  - to choose radiations which can be recommended as standards of wavelength for the interferometric measurement of length and draw up instructions for their use,
  - to pursue studies undertaken to improve these standards and in due course to extend or revise these instructions;
- that in response to this invitation 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 the CIPM had already recommended a list of radiations for this purpose;

recalling also that in 1992 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 1992 work in national laboratories, in the BIPM and elsewhere has identified new radiations and methods for their realization which lead to lower uncertainties;
- that such work has also substantially reduced the uncertainty in the determined value of the frequency and wavelength in vacuum of one of the previously recommended radiations;
- that a revision of the list of recommended radiations is desirable for many applications, which include not only the direct realization of the metre by means of optical interferometry for practical length measurement, but also spectroscopy, atomic and molecular physics and the determination of fundamental physical constants;

recommends

- that the list of recommended radiations given by the CIPM in 1992 (Recommendation 3 (CI-1992)) be replaced by the list of radiations given below;
- that to the rules for the realization of the metre the following note be added concerning general relativity:

  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. 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 CCDS working group on the application of general relativity to metrology (Application of general relativity to metrology, *Metrologia*, 1997, **34**, 261-290).

Note. Current practice is to use c_0 to denote the speed of light in vacuum (ISO 31). In the original Recommendation of 1983, the symbol c was used for this purpose.

CIPM list of approved radiations for the practical realization of the metre, 1997: 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 and *Metrologia*, 1984, **19**, 165-166, 1993/94, **30,** 523-541.

In this list, the values of the frequency f and of the vacuum wavelength λ should be related exactly by the relation $\lambda f = c_0$, 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: Source data for the list of recommended radiations, 1997 and its Annotated bibliography.

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. It should be also noted that to achieve the uncertainties given here it is not sufficient just to meet the specifications for the listed parameters. In addition, it is necessary to follow the best good practice concerning methods of stabilization as described in numerous scientific and technical publications. References to appropriate articles, illustrating accepted good practice for a particular radiation, may be obtained by application to a member laboratory of the CCDM[(1)] or to the BIPM.

1 Recommended radiations of stabilized lasers

1.1 Absorbing atom ^{1}H, 1S-2S, two-photon transition

The values f = 1 233 030 706 593.7 kHz

λ = 243 134 624.6260 fm

with a relative standard uncertainty of 8.5×10^{-13} apply to radiation 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.

Other hydrogen-absorbing transitions may be similarly used, and are given in Appendix M 3 to the CCDM Report (1997).

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

The values f = 582 490 603.37 MHz

λ = 514 673 466.4 fm

with 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)].

1.3 Absorbing molecule $^{127}I_2$, transition 32-0, R(56), component a_{10}

The values f = 563 260 223.48 MHz

λ = 532 245 036.14 fm

with a relative standard uncertainty of 7×10^{-11} 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 between –10 °C and –20 °C.

---

(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).

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

Other $^{127}I_2$ absorbing transitions close to this transition may also be used by making reference to the following frequency differences, for which the standard uncertainty is u_c = 2 kHz.

Wavelengths for $^{127}I_2$ transitions

Transition	Frequency difference
x	$[f(x) - f(32\text{-}0, R(56), a_{10})]$/kHz
32-0, R(57), a_1	−50 946 880.4
32-0, P(54), a_1	−47 588 892.5
35-0, P(119), a_1	−36 840 161.5
33-0, R(86), a_1	−32 190 404.0
34-0, R(106), a_1	−30 434 761.5
36-0, R(134), a_1	−17 173 680.4
33-0, P(83), a_{21}	−15 682 074.1
32-0, R(56), a_{10}	0
32-0, P(53), a_1	+2 599 708.0

Here, f(x) represents the frequency of the transition denoted x and f(32-0, R(56), a_{10}) the frequency of the reference transition.

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

The values f = 551 579 482.96 MHz

λ = 543 516 333.1 fm

with 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.

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

The values f = 489 880 354.9 MHz

λ = 611 970 770.0 fm

with 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 ± 2) °C.

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

The values f = 473 612 214 705 kHz

λ = 632 991 398.22 fm

with a relative standard uncertainty of 2.5×10^{-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 ± 5) °C;
- cold-finger temperature (15 ± 0.2) °C;
- frequency modulation width, peak to peak (6 ± 0.3) MHz;
- one-way intracavity beam power (i.e. the output power divided by the transmittance of the output mirror) (10 ± 5) mW for an absolute value of the power shift coefficient ≤ 1.4 kHz/mW.

These conditions are by themselves insufficient to ensure that the stated standard uncertainty will be achieved. It is also necessary for the optical and electronic control systems to be operating with the appropriate technical performance. The iodine cell may also be operated under relaxed conditions, leading to the larger uncertainty specified in Appendix M 2 of the CCDM Report (1997).

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

The values f = 468 218 332.4 MHz

λ = 640 283 468.7 fm

with 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 ± 1) °C and a frequency modulation width, peak-to-peak, of (6 ± 1) MHz.

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

The values f = 455 986 240 494.15 kHz

λ = 657 459 439.2917 fm

with a relative standard uncertainty of 6×10^{-13} apply to the radiation of a laser stabilized to Ca atoms. The values correspond to the mean frequency of the two recoil-split components for atoms which are effectively stationary, i.e. the values are corrected for second-order Doppler shift.

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

The values $f = 444\ 779\ 044.04$ MHz

$\lambda = 674\ 025\ 590.95$ fm

with a relative standard uncertainty of 1.3×10^{-10} 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, $5S_{1/2}$ (F = 3) – $5D_{5/2}$ (F = 5), two-photon transition

The values $f = 385\ 285\ 142\ 378$ kHz

$\lambda = 778\ 105\ 421.22$ 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 °C, are corrected to zero laser power, and for second-order Doppler shift.

Other rubidium-absorbing transitions may also be used, and are given in Appendix M 3 to the CCDM Report (1997).

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

1.11.1 The values $f = 88\ 376\ 181\ 600.18$ kHz

$\lambda = 3\ 392\ 231\ 397.327$ 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.

1.11.2 The values $f = 88\ 376\ 181\ 600.5$ kHz

$\lambda = 3\ 392\ 231\ 397.31$ 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 ≤ 3 Pa;
- mean one-way intracavity surface power density (i.e., the output power density divided by the transmittance of the output mirror) ≤ 10^4 Wm^{-2};
- radius of wavefront curvature ≥ 1 m;
- inequality of power between counter-propagating waves ≤ 5 %;
- servo referenced to a detector placed at the output facing the laser tube.

1.12 Absorbing molecule OsO_4, transition in coincidence with the $^{12}C^{16}O_2$, R(12) laser line

The values f = 29 096 274 952.34 kHz

λ = 10 303 465 254.27 fm

with a relative standard uncertainty of 6×10^{-12} apply to the radiation of a CO_2 laser stabilized with an external OsO_4 cell at a pressure below 0.2 Pa.

Other transitions may also be used, and are given in Appendix M 3 of the CCDM Report (1997).

2 Recommended values for radiations of spectral lamps and other sources

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

The value λ = 605 780 210.3 fm

with a relative expanded uncertainty(3), $U = ku_c$ (k = 3), of 4×10^{-9} [equal to three times the relative standard uncertainty of 1.3×10^{-9}] , applies to the radiation emitted by a discharge lamp operated under the conditions recommended by the CIPM in 1960 (*BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1960, **28**, 71-72 and *BIPM Comptes Rendus 11e Conf. Gén. Poids et Mesures*, 1960, 85). These are as follows :

(3) The uncertainty quoted in the 1960 document was 1×10^{-8} and was subsequently improved to 4×10^{-9} (*BIPM Com. Cons. Définition du Mètre*, 1973, **5**, M 12).

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 the following characteristics: inner diameter from 2 mm to 4 mm, wall thickness 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:

1. the capillary is observed end-on from the side closest to the anode;
2. 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;
3. the current density in the capillary is (0.3 ± 0.1) A/cm^2.

2.2 Radiations for atoms of ^{86}Kr, ^{198}Hg and ^{114}Cd

In 1963 the CIPM (*BIPM Com. Cons. Déf. Mètre*, 1962, **3**, 18-19 and *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1963, **52**, 26-27) specified values for the vacuum wavelengths, λ, operating conditions, and the corresponding uncertainties, for certain transitions in ^{86}Kr, ^{198}Hg and ^{114}Cd.

Vacuum wavelengths, λ, for ^{86}Kr transitions

Transition	λ/pm
$2p_9 - 5d'_4$	645 807.20
$2p_8 - 5d_4$	642 280.06
$1s_3 - 3p_{10}$	565 112.86
$1s_4 - 3p_8$	450 361.62

For ^{86}Kr, the above values apply, with a relative uncertainty of 2×10^{-8} to radiations emitted by a lamp operated under conditions similar to those specified in (2.1).

Vacuum wavelengths, λ, for ^{198}Hg transitions

Transition	λ/pm
$6^1P_1 - 6^1D_2$	579 226.83
$6^1P_1 - 6^3D_2$	577 119.83
$6^3P_2 - 7^3S_1$	546 227.05
$6^3P_1 - 7^3S_1$	435 956.24

For ^{198}Hg, the above values apply, with a relative uncertainty of 5×10^{-8}, to radiations emitted by a discharge lamp when the following conditions are met:

a) 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);

b) the internal diameter of the capillary of the lamp is about 5 mm, and the radiation is observed transversely;

c) the lamp is excited by a high-frequency field at a moderate power and is maintained at a temperature less than 10 °C;

d) it is preferred that the volume of the lamp be greater than 20 cm^3.

Vacuum wavelengths, λ, for ^{114}Cd transitions

Transition	λ/pm
$5^1P_1 - 5^1D_2$	644 024.80
$5^3P_2 - 6^3S_1$	508 723.79
$5^3P_1 - 6^3S_1$	480 125.21
$5^3P_0 - 6^3S_1$	467 945.81

For ^{114}Cd, the above values apply, with a relative uncertainty of 7×10^{-8}, to radiations emitted by a discharge lamp under the following conditions:

a) the radiations are generated using a discharge lamp without electrodes, containing ^{114}Cd of a purity not less than 95 %, and argon at a pressure of about 1 mm Hg (133 Pa) at ambient temperature;

b) the internal diameter of the capillary of the lamp is about 5 mm, and the radiation is observed transversely;

c) 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. [*sic*]

Note. The uncertainties quoted throughout Section 2.2 are judged to correspond to relative expanded uncertainties $U = ku_c$ ($k = 3$), equal to three times the relative combined standard uncertainties.

2.3 Absorbing molecule $^{127}I_2$, transition 17-1, P(62) component a_1, as recommended by the CIPM in 1992 (*BIPM Com. Cons. Déf. Mètre*, 1992, **8**, M 18 and M 137, and *Mise en Pratique* of the Definition of the Metre (1992), *Metrologia*, 1993/94, **30**, 523-541).

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

$\lambda = 576\ 294\ 760.4$ 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 ± 2) °C.

APPENDIX M 1.
Working documents submitted to the CCDM at its 9th meeting

(see the list of documents on page 51)

APPENDIX M 2.
Source data for the list of recommended radiations, 1997, and annotated bibliography

This appendix has been derived from data presented at the 9th meeting of the CCDM, 1997, and those of 1982 published in Appendix M 4 of the report of the 7th meeting of the CCDM 1982 and of 1992 published in Appendix M 2 of the report of the 8th meeting of the CCDM, 1992 [1]. The numbers in square brackets refer to the bibliography and notes at the end of this appendix.

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

The frequency values and uncertainties adopted by the 9th meeting of the CCDM 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 [1-1].

1 Recommended radiations of stabilized lasers

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

The following value has been obtained for the frequency $f_{(1S-2S)}/2$ of this transition:

MPQ 1997 [1.1-1]

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

To take into account that this value is issued from a single determination, bearing in mind also the degree of agreement between the MPQ (Germany) and the Kastler Brossel BNM-LPTF (France) laboratories in respect of recent measurements of the Rydberg constant, the CCDM considered it prudent to assume an estimated relative standard uncertainty of 8.5×10^{-13}.

Adopted value:

$f_{(1S-2S)}/2$ = 1 233 030 706 593.7 kHz
standard uncertainty 1.05 kHz
relative standard uncertainty 8.5×10^{-13}.

From which:

$\lambda_{(1S-2S)} \times 2$ = 243 134 624.6260 fm
standard uncertainty 0.0002 fm
relative standard uncertainty 8.5×10^{-13}.

Other absolute frequency values for hydrogen and deuterium of the 2S−8S/D transitions are given in Appendix M 3, Tables 1 and 2.

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

The following values have been obtained for the ratio of the frequency f_{a_3} of this transition to the frequency f_i (Section 1.6):

NPL 1982 [1.2-1]
f_{a_3}/f_i = 1.229 889 316 88 $(1 \pm 1 \times 10^{-10})$
BIPM 1982 [1.2-1]
f_{a_3}/f_i = 1.229 889 316 88 $(1 \pm 2.5 \times 10^{-10})$
PTB 1989 [1.2-2]
f_{a_3}/f_i = 1.229 889 317 33 $(1 \pm 7 \times 10^{-11})$
PTB 1985 [1.2-3]
f_{a_3}/f_i = 1.229 889 317 44 $(1 \pm 7 \times 10^{-11})$
PTB 1986 [1.2-4]
f_{a_3}/f_i = 1.229 889 317 36 $(1 \pm 8 \times 10^{-11})$
PTB 1991 [1.2-5]
f_{a_3}/f_i = 1.229 889 317 45 $(1 \pm 8 \times 10^{-11})$
Unweighted mean f_{a_3}/f_i = 1.229 889 317 22.

Other available values having relative uncertainties higher than 2.5×10^{-10} have not been used.

Taking the recommended value f_i = 473 612 214 705 kHz (Section 1.6), the following value for f_{a_3} is obtained:

f_{a_3} = 582 490 603 371 kHz.

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

Adopted value:

f_{a_3} = 582 490 603.37 MHz
standard uncertainty 0.15 MHz
relative standard uncertainty 2.5×10^{-10}.

From which:

λ_{a_3} = 514 673 466.4 fm
standard uncertainty 0.13 fm
relative standard uncertainty 2.5×10^{-10}.

In 1983, the value adopted by the CIPM was f_{a_3} = 582 490 603.6 MHz with an estimated overall relative uncertainty of 1.3×10^{-9} (equivalent to three times the relative standard uncertainty).

1.3 Absorbing molecule $^{127}I_2$, transition 32-0, R(56), component a_{10} ($\lambda \approx 532$ nm)

The following value has been obtained for the frequency $f_{a_{10}}$ of this transition:
JILA/NIST 1995 [1.3-1]

$f_{a_{10}}$ = 563 260 223 471 $(1 \pm 7.1 \times 10^{-11})$ kHz.

Taking into account absolute interferometric measurements made at the NPL [1.3-2] of transitions other than the 32-0, R(56), and frequency differences between iodine transitions determined at JILA/NIST [1.3-3], the CCDM decided the following:

Adopted value:

$f_{a_{10}}$ = 563 260 223.48 MHz
standard uncertainty 0.04 MHz
relative standard uncertainty 7×10^{-11}.

From which:

$\lambda_{a_{10}}$ = 532 245 036.14 fm
standard uncertainty 0.04 fm
relative standard uncertainty 7×10^{-11}.

The following values have been obtained for the frequency differences between several $^{127}I_2$ absorbing transitions and the 32-0, R(56) or 1110 transition:

JILA/NIST 1997 [1.3-3]

Transition	Frequency difference
x	$[f(x) - f(32\text{-}0, R(56), a_{10})]$/kHz
32-0, R(57) or 1104, a_1	−50 946 880.400
32-0, P(54) or 1105, a_1	−47 588 892.482
35-0, P(119) or 1106, a_1	−36 840 161.450
33-0, R(86) or 1107, a_1	−32 190 404.022
34-0, R(106) or 1108, a_1	−30 434 761.496
36-0, R(134), a_1	−17 173 680.381
33-0, P(83) or 1109, a_{21}	−15 682 074.068
32-0, R(56) or 1110, a_{10}	0
32-0, P(53) or 1111, a_1	+2 599 707.967

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

To take into account that these values are issued from only one laboratory, the CCDM considered it prudent to assume a standard uncertainty of 2 kHz.

Adopted value:

Transition	Frequency difference
x	$[f(x) - f(32\text{-}0, R(56), a_{10})]$/kHz
32-0, R(57) or 1104, a_1	−50 946 880.4
32-0, P(54) or 1105, a_1	−47 588 892.5
35-0, P(119) or 1106, a_1	−36 840 161.5
33-0, R(86) or 1107, a_1	−32 190 404.0
34-0, R(106) or 1108, a_1	−30 434 761.5
36-0, R(134), a_1	−17 173 680.4
33-0, P(83) or 1109, a_{21}	−15 682 074.1
32-0, R(56) or 1110, a_{10}	0
32-0, P(53) or 1111, a_1	+2 599 708.0

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

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

PTB 1991 [1.4-1]

$f_{a_9} = 551\,579\,483\,029\,(1 \pm 8.4 \times 10^{-11})$ kHz

NPL 1992 [1.4-2]

$f_{a_9} = 551\,579\,482\,900\,(1 \pm 13 \times 10^{-11})$ kHz

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

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

Adopted value:

$f_{a_9} = 551\,579\,482.96$ MHz
standard uncertainty 0.14 MHz
relative standard uncertainty 2.5×10^{-10}.

From which:

$\lambda_{a_9} = 543\,516\,333.1$ fm
standard uncertainty 0.14 fm
relative standard uncertainty 2.5×10^{-10}.

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

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

NPL 1982 [1.5-1]

$f_{a_7} = 489\,880\,354\,972\,(1 \pm 1 \times 10^{-10})$ kHz

BIPM 1982 [1.5-1]

$f_{a_7} = 489\,880\,354\,721\,(1 \pm 2.1 \times 10^{-10})$ kHz

PTB/BIPM 1986 [1.5-2]

$f_{a_7} = 489\,880\,355\,019\,(1 \pm 8.4 \times 10^{-11})$ kHz

VNIIM 1989 [1.5-3]

$f_{a_7} = 489\,880\,355\,055\,(1 \pm 3.0 \times 10^{-10})$ kHz

BNM-INM 1991 [1.5-4]

$f_{a_7} = 489\,880\,354\,841\,(1 \pm 8.4 \times 10^{-11})$ kHz

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

Other available values having relative standard uncertainties higher than 3×10^{-10} have not been used. The relative standard deviation calculated from the dispersion of these five values is 2.8×10^{-10}. This value is rounded to 3×10^{-10} as the relative standard uncertainty.

Adopted value:

f_{a_7} = 489 880 354.9 MHz
standard uncertainty 0.15 MHz
relative standard uncertainty 3×10^{-10}.

From which:

λ_{a_7} = 611 970 770.0 fm
standard uncertainty 0.18 fm
relative standard uncertainty 3×10^{-10}.

In 1983, the value adopted by the CIPM was f_{a_7} = 489 880 335.1 MHz with an estimated overall relative uncertainty of 1.1×10^{-9} (equivalent to three times the relative standard uncertainty).

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

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

BNM-LPTF/ETCA/INM 1992 [1.6-1]

f_i = 473 612 214 705.4 ($1 \pm 2.5 \times 10^{-11}$) kHz.

Adopted value:

f_i = 473 612 214 705 kHz
standard uncertainty 12 kHz
relative standard uncertainty 2.5×10^{-11}.

From which:

λ_i = 632 991 398.22 fm
standard uncertainty 0.02 fm
relative standard uncertainty 2.5×10^{-11}.

At the request of the CCDM, a series of grouped laser comparisons from national laboratories undertaken by the BIPM (1993-1997) confirmed that the choice of a relative standard uncertainty of 2.5×10^{-11} in 1992 by the CIPM was valid [1.6-2].

For applications where relaxed tolerances, and the resultant wider uncertainty range are acceptable, the coefficients detailed in the annotated bibliography [1.6-1] would lead to a standard uncertainty of about 50 kHz (or a relative standard uncertainty of 1×10^{-10}) for a laser operated under the conditions recommended in 1983 [1.1.2-7].

In 1983, the value adopted by the CIPM was f_i = 473 612 214.8 MHz with an estimated overall relative uncertainty of 1×10^{-9} (equivalent to three times the relative standard uncertainty).

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

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

NPL 1984 [1.7-1]

f_{a_9} = 468 218 332 412 ($1 \pm 1.0 \times 10^{-10}$) kHz

NIM/CSMU/PTB 1985 [1.7-2]

f_{a_9} = 468 218 332 303 ($1 \pm 1.2 \times 10^{-10}$) kHz

IMGC/BIPM 1985 [1.7-3]

f_{a_9} = 468 218 332 062 ($1 \pm 4.6 \times 10^{-10}$) kHz

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

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

Adopted value:

f_{a_9} = 468 218 332.4 MHz
standard uncertainty 0.2 MHz
relative standard uncertainty 4.5×10^{-10}.

From which:

λ_{a_9} = 640 283 468.7 fm
standard uncertainty 0.3 fm
relative standard uncertainty 4.5×10^{-10}.

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

The following value has been obtained by stabilizing a laser to an ensemble of ballistic Ca atoms which were laser cooled and trapped in a magneto-optical trap prior to each probing of the reference transition [1.8-1]:

PTB [1.8-2]
f_{Ca} = 455 986 240 494.15 (1 ± 2.5 × 10^{-13}) kHz.

This value has been obtained by a phase-coherent frequency measurement [1.8-3] starting from the primary standard of time and frequency, the Cs atomic clock. The frequency value f_{Ca} applies to the mean frequency of the recoil doublet.

With this value based on only one determination, the CCDM considered it prudent to assume an estimated relative standard uncertainty of 6 × 10^{-13}.

Adopted value:
f_{Ca} = 455 986 240 494.15 kHz
standard uncertainty 0.27 kHz
relative standard uncertainty 6 × 10^{-13}.

From which:
λ_{Ca} = 657 459 439.2917 fm
standard uncertainty 0.0004 fm
relative standard uncertainty 6 × 10^{-13}.

In 1992, the value adopted by the CIPM was f_{Ca} = 455 986 240.5 MHz with a relative standard uncertainty of 4.5 × 10^{-10}.

1.9 Absorbing ion $^{88}Sr^{+}$, transition $5^2S_{1/2} - 4^2D_{5/2}$ ($\lambda \approx$ 674 nm)

The following values have been obtained for the frequency of the transition's Zeeman multiplet line centre:

NPL 1997 [1.9-1]
f_{Sr+} = 444 779 043.98 (1 ± 1.3 × 10^{-10}) MHz
NRC 1997 [1.9-2]
f_{Sr+} = 444 779 044.04 (1 ± 9.0 × 10^{-11}) MHz
NRC 1997 [1.9-3]
f_{Sr+} = 444 779 044.09 (1 ± 4.5 × 10^{-11}) MHz
unweighted mean f_{Sr+} = 444 779 044.04 MHz.

Other available values having relative standard uncertainties higher than 2 × 10^{-10} have not been used. Given the preliminary nature of the phase-coherent frequency chain measurement of [1.9-3], the CCDM considered it prudent to determine the mean as an unweighted average. The value based on reference [1.9-2] is a correction to an earlier heterodyne frequency measurement [1.9-4] where the absolute frequency of one of the lasers involved in the determination was remeasured under improved conditions.

The relative standard deviation for the final mean value was calculated as the sample deviation of the individual contributing measurements giving 1.24×10^{-10}, which the CCDM rounded up to 1.3×10^{-10}.

Adopted value:

$f_{Sr+} = 444\ 779\ 044.04$ MHz
standard uncertainty 0.06 MHz
relative standard uncertainty 1.3×10^{-10}.

From which:

$\lambda_{Sr+} = 674\ 025\ 590.95$ fm
standard uncertainty 0.09 fm
relative standard uncertainty 1.3×10^{-10}.

1.10 Absorbing atom ^{85}Rb, $5S_{1/2}$ ($F = 3$) $-5D_{5/2}$ ($F = 5$), two-photon transition ($\lambda \approx 778$ nm)

The following value has been obtained for the frequency $f_{(5S_{1/2} - 5D_{5/2})}$ of this transition:

BNM-LPTF 1997 [1.10-1]

$f_{(5S_{1/2} - 5D_{5/2})} = 385\ 285\ 142\ 378.28\ (1 \pm 5.2 \times 10^{-12})$ kHz.

With this value based on only one determination the CCDM considered it prudent to assume an estimated relative standard uncertainty of 1.3×10^{-11}.

Adopted value:

$f_{(5S_{1/2} - 5D_{5/2})} = 385\ 285\ 142\ 378$ kHz
standard uncertainty 5 kHz
relative standard uncertainty 1.3×10^{-11}.

From which:

$\lambda_{(5S_{1/2} - 5D_{5/2})} = 778\ 105\ 421.22$ fm
standard uncertainty 0.01 fm
relative standard uncertainty 1.3×10^{-11}.

1.11 Absorbing molecule CH_4, transition ν_3, P(7), component $F_2^{(2)}$ ($\lambda \approx 3.39$ µm)

1.11.1 Hyperfine structure resolved

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

Year	Laser	Frequency chain	CCDM document/	x/kHz
1991	Lebedev Phys. Inst.	PTB	92-8*a*	600.29
1985-1986	Lebedev Phys. Inst.	VNIIFTRI	92-9*a*	599.9
1989-1992	Lebedev Phys. Inst.	VNIIFTRI	92-9*a*	600.11
1989	PTB	VNIIFTRI	92-9*a*	600.18
1992	PTB	PTB	92-14*a*	600.16
1988-1991	Inst. Laser Phys. (IPL), Novosibirsk	IPL	92-23*a*	600.44

Unweighted mean f_{CH_4} = 88 376 181 600.180 kHz.

Measurements whose uncertainties were larger than 200 Hz have not been taken into account in the calculation of this mean. The relative standard uncertainty of one realization of 2.9×10^{-12} was estimated using the maximum deviation from the mean and rounded to 3×10^{-12}.

Adopted value*:

f_{CH_4} = 88 376 181 600.18 kHz
standard uncertainty 0.27 kHz
relative standard uncertainty 3×10^{-12}.

From which:

λ_{CH_4} = 3 392 231 397.327 fm
standard uncertainty 0.010 fm
relative standard uncertainty 3×10^{-12}.

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

1.11.2 Hyperfine structure unresolved

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

Year	Institute	Device	References	x/kHz
1983	Inst. Laser Phys.* (Novosibirsk)	Stationary device	CCDM/92-23*a* also 1.11.2-1,2,3	602.9
1985	NRC (Ottawa)	Portable laser 2	CCDM/92-4*a* also 1.11.2-4	601.48
Mean value 1986/89/90/91	NRC (Ottawa)	Portable laser 3	CCDM/92-4*a* also 1.11.2-4	599.33
Mean value 1988/1990	NRLM (Tsukuba)	Portable laser 1	1.11.2-4	596.82
Mean value 1987/1989	PTB (Braunschweig)	CH_4 beam	1.11.2-5,6 also 1.11.2-4	601.52
Mean value over 7 years	VNIIFTRI (Moscow)	Portable laser M101	CCDM/92-9*a* also 1.11.2-4	601.77
Mean value 1985/86/88	VNIIFTRI (Moscow)	Portable laser P1	CCDM/92-9*a* also 1.11.2-4	600.12
1986	VNIIFTRI (Moscow)	Portable laser PL	CCDM/92-9*a*	598.5
Mean value over 7 years	BIPM (Sèvres)	Portable laser B.3	1.11.2-4	600.96
Mean value 1988/89/91	BIPM (Sèvres)	Portable laser VB	1.11.2-4	601.33
1991	BIPM (Sèvres)	Portable laser VNIBI	CCDM/92-20*a* also 1.11.2-4	600.3

Unweighted mean f_{CH_4} = 88 376 181 600.46 kHz.

* Two other values from this laboratory, obtained in 1991, were communicated to the BIPM as personal communications. If these two additional values are taken into account the unweighted mean changes by only +0.14 kHz.

The standard deviation of one determination is 1.7 kHz. This is equivalent to a relative uncertainty of 1.92×10^{-11}, increased by the CCDM to 2.3×10^{-11} to give an uncertainty of 2 kHz.

Adopted value:

f_{CH_4} = 88 376 181 600.5 kHz
standard uncertainty 2 kHz
relative standard uncertainty 2.3×10^{-11}.

From which:

λ_{CH_4} = 3 392 231 397.31 fm
standard uncertainty 0.08 fm
relative standard uncertainty 2.3×10^{-11}.

In 1983 [1.11.2-7], the value adopted by the CIPM was

f_{CH_4} = 88 376 181 608 kHz

with an estimated overall relative uncertainty of 1.3×10^{-10} (equivalent to three times the relative standard uncertainty).

1.12 Absorbing molecule OsO_4, transition in coincidence with the $^{12}C^{16}O_2$, R(12) laser line ($\lambda \approx 10.3$ µm)

The following value has been obtained for the frequency f_{OsO_4} of this transition:

BNM-LPTF 1985 [1.12.1]
BNM-LPTF 1988 [1.12.2]
BNM-LPTF 1997 [1.12.3]

f_{OsO_4} = 29 096 274 952.340 ($1 \pm 2.4 \times 10^{-12}$) kHz.

With this value based on only one determination, the CCDM considered it prudent to assume an estimated relative standard uncertainty of 6×10^{-12}.

This value has been recently confirmed after the CCDM meeting:

BNM/LPL 1997 [1.12.4]

Adopted value:

f_{OsO_4} = 29 096 274 952.34 kHz
standard uncertainty 0.18 kHz
relative standard uncertainty 6×10^{-12}.

From which:

λ_{OsO_4} = 10 303 465 254.27 fm
standard uncertainty 0.06 fm

relative standard uncertainty 6×10^{-12}.

2 Recommended values for radiations of spectral lamps and other sources

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

The following value was obtained from $(\lambda_i)_{Kr} \times (1/\lambda_{Kr})$:
[2.1-1]

$f_{Kr}/f_i = 1.044\ 919\ 242\ 05$.

Taking the recommended value of f_i = 473 612 214 705 kHz (Section 1.6) and using the relative standard uncertainty as given in [2.1-1] of 1.3×10^{-9}, the following value for f_{Kr} is obtained:

f_{Kr} = 494 886 516 415 kHz

Adopted value:

f_{Kr} = 494 886 516.4 MHz
standard uncertainty 0.6 MHz
relative standard uncertainty 1.3×10^{-9}.

From which:

λ_{Kr} = 605 780 210.3 fm
standard uncertainty 0.8 fm
relative standard uncertainty 1.3×10^{-9}.

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

2.2 Radiations of atoms ^{86}Kr, ^{198}Hg and ^{114}Cd

The values given in the list of the recommended wavelengths are those recommended by the CIPM in 1963 [2.2-1] and [2.2-2].

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

This transition was recommended by the CIPM in 1992 (*BIPM Com. Cons. Déf. Mètre*, 1992, **8**, M 18 and M 137, and *Mise en Pratique of the Definition of the Metre* (1992), *Metrologia*, 1993-1994, **30**, 523-541).

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

NBS 1982 [2.3-1]

f_{a_1} = 520 206 808 491 (1 ± 1.5 × 10^{-10}) kHz

NPL 1984 [2.3-2]

f_{a_1} = 520 206 808 272 (1 ± 1 × 10^{-10}) kHz

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

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

Adopted value:

f_{a_1} = 520 206 808.4 MHz

standard uncertainty 0.2 MHz

relative standard uncertainty 4 × 10^{-10}.

From which:

λ_{a_1} = 576 294 760.4 fm

standard uncertainty 0.2 fm

relative standard uncertainty 4 × 10^{-10}.

In 1983, the value adopted by the CIPM was f_{a_1} = 520 206 808.51 MHz with an estimated overall relative uncertainty of 6 × 10^{-10} (equivalent to three times the relative standard uncertainty).

Annotated bibliography

1 *BIPM Com. Cons. Déf. Mètre*, 1982, **7**, M 53-M 64 and 1992, **8**, M 36-M 50.

1-1 Rowley W.R.C., Proposed Guidelines for CCL (former CCDM) Frequency and Wavelength Value Rounding and Uncertainties [Document CCDM/97-9*c*].

1.1-1 Udem Th., Huber A., Gross B., Reichert J., Prevedelli M., Weitz M., Hänsch T.W., Phase-Coherent Measurement of the Hydrogen 1S-2S Transition Frequency with an Optical Frequency Interval Divider Chain, submitted for publication. See also Udem Th.,

Huber A., Weitz M., Leibfried D., König W., Prevedelli M., Dimitriev A., Geiger H., Hänsch T.W., *IEEE Trans. Instrum. Meas.*, 1997, **46**, 166 and Document CCDM/97-11.

These papers give the value of the frequency of the two-photon transition:

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

For a single-photon transition, one calculates:

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

1.2-1 *BIPM Com. Cons. Déf. Mètre*, 1982, **7**, M 57 and Documents Concerning the New Definition of the Metre, *Metrologia*, 1984, **19**, 168.

These papers give:

NPL 1982 [12]

$f_{a_3}/f_i = 1.229\,889\,316\,88\,(1 \pm 1 \times 10^{-10})$

BIPM 1982 [27]

$f_{a_3}/f_i = 1.229\,889\,316\,88\,(1 \pm 2.5 \times 10^{-10})$.

Measurements whose relative uncertainties were larger than 2.5×10^{-10} have not been taken into account.

1.2-2 Bönsch G., Nicolaus A., Brand U., Wellenlängenbestimmung der Ca-Interkombinationslinie mit dem Michelson-Interferometer der PTB, *PTB Mitteilungen*, 1989, **99**, 329-334 [Document CCDM/92-14*i*].

This paper gives:

$f_i/f_{a_3} = 0.813\,081\,295\,94\,(1 \pm 7 \times 10^{-11})$.

One calculates:

$f_{a_3}/f_i = 1.229\,889\,317\,33\,(1 \pm 7 \times 10^{-11})$.

1.2-3 Bönsch G., Simultaneous Wavelength Comparison of Iodine-Stabilized Lasers at 515 nm, 633 nm, and 640 nm, *IEEE Trans. Instrum. Meas.*, 1985, **IM-34**, 248-251.

This paper gives:

$f_i/f_{a_3} = 0.813\,081\,295\,87\,(1 \pm 7 \times 10^{-11})$.

One calculates:

$f_{a_3}/f_i = 1.229\ 889\ 317\ 44\ (1 \pm 7 \times 10^{-11})$.

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

This paper gives:

$f_i/f_{a_3} = 0.813\ 081\ 295\ 92\ (1 \pm 8 \times 10^{-11})$.

One calculates:

$f_{a_3}/f_i = 1.229\ 889\ 317\ 36\ (1 \pm 8 \times 10^{-11})$.

1.2-5 Bönsch G., Nicolaus A., Brand U., Wellenlängenbestimmung für den I_2-stabilisierten He-Ne Laser bei 544 nm, *PTB Jahresbericht*, 1991, 173-174 [Document CCDM/92-14*l*].

This paper gives:

$f_i/f_{a_3} = 0.813\ 081\ 295\ 86\ (1 \pm 8 \times 10^{-11})$.

One calculates:

$f_{a_3}/f_i = 1.229\ 889\ 317\ 45\ (1 \pm 8 \times 10^{-11})$.

1.3-1 Junger P.A., Eickhoff M., Swartz S.D., Ye Jun, Hall J.L., Waltman S., Stability and Absolute Frequency of Molecular Iodine Transitions Near 532 nm, *Proc. SPIE* 2378, 1995, 22-34 and Document CCDM/97-3.

These papers give:

$f_{a_{10}} = (563\ 260\ 223\ 471 \pm 40)$ kHz.

1.3-2 Macfarlane G.M., Barwood G.P.B., Rowley W.R.C., Gill P., Interferometric Frequency Measurements of an Iodine-stabilized Nd:YAG Laser [Document CCDM/97-9*b*] and separate paper of same title, submitted to *IEEE Trans. Instrum. Meas.*

Document CCDM/97-9*b* gives for f_{a_1} of the 32-0, R(57) (or 1104) iodine transition

$f_{a_1} = (563\ 209\ 276\ 588 \pm 60)$ kHz (one standard deviation) and gives for f_{a1} of the 32-0, P(54) (or 1105) iodine transition

$$f_{a_1} = (563\ 212\ 634\ 612 \pm 68)\ \text{kHz (one standard deviation)}$$

The *IEEE Trans. Instrum. Meas.* submission confirms the value of f_{a_1} of the 32-0, R(57) (or 1104) transition, but corrects a misquoted value for f_{a_1} of the 32-0, P(54) (or 1105), giving a corrected value for this transition:

$$f_{a_1} = (563\ 212\ 634\ 587 \pm 68)\ \text{kHz (one standard deviation).}$$

The agreement between these interferometrically determined values and those derived from the NIST a_{10} 32-0, R(56) reference and the appropriate frequency differences between the iodine transitions [1.3-3] is 3 kHz and 8 kHz respectively, well within the combined uncertainties.

1.3-3 Document CCDM/97-3*b*.

1.4-1 Documents CCDM/92-14*a*, Bönsch G., Nicolaus A., Brand U., Wellenlängenbestimmung für den I_2-stabilisierten He-Ne laser bei 544 nm, *Jahresbericht*, 1991, 173-174 [CCDM/92-14*l*] and Brand U., Ein iodstabilisiertes He-Ne Laser-Wellenlängennormal grüner Strahlung, *PTB Bericht*, 1991, **Opt. 34**, 1-109 [Document CCDM/ 92-14*j*].

These papers give:

$$\lambda_{a_9}/\lambda_i = 0.858\ 647\ 265\ 30\ (1 \pm 8 \times 10^{-11})\ \text{(1 standard deviation).}$$

With the recommended value (Section 1.6) of

$$f_i = 473\ 612\ 214\ 705\ (1 \pm 2.5 \times 10^{-11})\ \text{kHz,}$$

one calculates:

$$f_{a_9} = 551\ 579\ 483\ 037\ (1 \pm 8.4 \times 10^{-11})\ \text{kHz,}$$

at a cold-finger temperature of −10 °C (iodine pressure = 1.4 Pa). For a reference temperature of 0 °C (iodine pressure = 4.1 Pa), a correction of –8 kHz has to be applied to this value with the pressure dependence of −3.0 kHz/Pa (Document CCDM/92-14*j*, p. 44), giving:

$$f_{a_9} = 551\ 579\ 483\ 029\ (1 \pm 8.4 \times 10^{-11})\ \text{kHz.}$$

1.4-2 Document CCDM/92-12*a*.

This paper gives:

$f_{b_{10}}(0\ °C)/f_i = 1.164\ 624\ 021\ 92\ (1 \pm 12 \times 10^{-11})$.

With the recommended value (Section 1.6) of

$f_i = 473\ 612\ 214\ 705\ (1 \pm 2.5 \times 10^{-11})$ kHz,

one calculates:

$f_{b_{10}} = 551\ 580\ 162\ 320\ (1 \pm 12.3 \times 10^{-11})$ kHz

at a cold finger temperature of 0 °C (iodine pressure = 4.1 Pa).

From the measured value [Appendix M 3, Table 16] of

$f_{b_{10}} - f_{ba_9} = (679\ 420 \pm 15)$ kHz (standard uncertainty),

one calculates:

$f_{a_9} = 551\ 579\ 482\ 900\ (1 \pm 13 \times 10^{-11})$ kHz.

1.5-1 *BIPM Com. Cons. Déf. Mètre*, 1982, **7**, M 57 and Documents Concerning the New Definition of the Metre, *Metrologia*, 1984, **19**, 167.

These papers give:

NPL 1982 [12]

$f_o/f_i = 1.034\ 349\ 072\ 43\ (1 \pm 1 \times 10^{-10})$

BIPM 1982 [24]

$f_o/f_i = 1.034\ 349\ 071\ 90\ (1 \pm 2.1 \times 10^{-10})$.

Measurements whose relative uncertainties were larger than 3×10^{-10} have not been taken into account.

From the values of these ratios and with the recommended value (Section 1.6) of

$f_i = 473\ 612\ 214\ 705\ (1 \pm 2.5 \times 10^{-11})$ kHz,

one calculates:

NPL 1982

f_o or $f_{a_7} = 489\ 880\ 354\ 972\ (1 \pm 1 \times 10^{-10})$ kHz,

BIPM 1982

f_o or $f_{a_7} = 489\ 880\ 354\ 721\ (1 \pm 2.1 \times 10^{-10})$ kHz.

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

These papers give:

$\lambda_{b_{15}}/\lambda_i = 0.966\ 791\ 921\ 43\ (1 \pm 8 \times 10^{-11})$.

With the recommended value (Section 1.6) of

$f_i = 473\ 612\ 214\ 705\ (1 \pm 2.5 \times 10^{-11})$ kHz,

one calculates:

$f_{b_{15}} = 489\ 880\ 194\ 701\ (1 \pm 8.4 \times 10^{-11})$ kHz.

Using the frequency difference [Appendix M 3, Table 18]

$f_{b_{15}} - f_{a_7} = (-160\ 318 \pm 3)$ kHz,

one calculates:

$f_{a_7} = 489\ 880\ 355\ 019\ (1 \pm 8.4 \times 10^{-11})$ kHz.

1.5-3 Vitushkin L.F., Zakharenko Yu.G., Yvanov I.V., Leibengardt G.I., Shur V.L., Measurements of Wavelength of High-Stabilized He-Ne/I_2 Laser at 612 nm, *Opt. Spektr.*, 1990, **68**, 705-707.

This paper gives:

$\lambda_d/\lambda_o = 1.034\ 348\ 712\ (1 \pm 3 \times 10^{-10})$.

With the recommended value (Section 1.6) of

$f_i = 473\ 612\ 214\ 705\ (1 \pm 2.5 \times 10^{-11})$ kHz,

and using the frequency difference between the components d and i [Appendix M 3, Table 22] of

$f_d - f_i = (165\ 116 \pm 5)$ kHz,

one calculates:

$f_d = 473\ 612\ 379\ 821\ (1 \pm 2.7 \times 10^{-11})$ kHz and

f_o or $f_{a_7} = 489\ 880\ 355\ 055\ (1 \pm 3.0 \times 10^{-10})$ kHz.

1.5-4 Himbert M., Bouchareine P., Hachour A., Juncar P., Millerioux Y., Razet A., Measurements of Optical Wavelength Ratios Using a Compensated Field Sigmameter, *IEEE Trans. Instrum. Meas.*, 1991, **40**, 200-203 [Document CCDM/92-19*g*] and Document CCDM/92-19*a*.

These papers give:

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

With the values adopted by the CIPM in 1983 [1] of

f_i = 473 612 214.8 MHz

and the frequency difference [Appendix M 3, Table 22] of

$f_e - f_i$ = (152 255 ± 5) kHz,

one obtains:

f_e = 473 612 367 055 kHz and

$f_{a_{13}}/f_e$ = 1.034 349 267.

With the recommended value (Section 1.6) of

f_i = 473 612 214 705 (1 ± 2.5 × 10^{-11}) kHz

and the frequency difference f_e - f_i ,

one calculates:

f_e = 473 612 366 960 kHz and

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

Using the uncertainty on the ratio $f_{a_{13}}/f_e$ given in Document CCDM/92-19*g* of ± 8 × 10^{-11},

one obtains:

$f_{a_{13}}$ = 489 880 604 443 (1 ± 8.4 × 10^{-11}) kHz.

Using the frequency difference between the components a_7 and a_{13} [Appendix M 3, Table 17] of

$f_{a_7} - f_{a_{13}}$ = (-249 602 ± 10) kHz,

one calculates:

f_{a_7} = 489 880 354 841 (1 ± 8.4 × 10^{-11}) kHz.

1.6-1 Acef O., Zondy J.-J., Abed M., Rovera D.G., Gérard A.H., Clairon A., Laurent Ph., Millerioux Y., Juncar P., A CO_2 to Visible Optical Frequency Synthesis Chain: Accurate Measurement of the 473 THz He-Ne/I_2 Laser, *Opt. Commun.*, 1993, **97**, 29-34 and Document CCDM/92-19*a*.

These papers give:

f_f(INM) = (473 612 353 586 ± 3.4) kHz.

Taking into account the frequency difference

$f_f - f_i$ = (138 892 ± 5) kHz

between the components f and i [Appendix M 3, Table 22], the frequency of component i of the BNM-INM laser is:

f_i (INM) = 473 612 214 694.0 kHz.

Document CCDM/92-20*a*.

This paper gives:

$f_{INM12} - f_{BIPM4}$ = (-11.4 ± 1.5) kHz.

Chartier J.-M., Robertsson L., Fredin-Picard S., Recent Activities at the BIPM in the Field of Stabilized Lasers – Radiations Recommended for the Definition of the Meter, *IEEE Trans. Instrum. Meas.*, 1991, **40**, 181-184 [Document CCDM/92-20*p*].

Chartier J.-M., Robertsson L., Sommer M., Tschirnich J., Navratil V., Gata R., Pucek B., Blabla J., Smydke J., Ziegler M., Veleny V., Petru F., Vesela Z., Tomanyiczka K., Banreti E., Zakharenko Yu.G., Vitushkin L.F., International Comparison of Iodine-Stabilized Helium-Neon Lasers at $\lambda \approx 633$ nm Involving Seven Laboratories, *Metrologia,* 1991, **28**, 19-25 [Document CCDM/92-20*q*].

Chartier J.-M., Darnedde H., Frennberg M., Henningsen J., Kärn U., Pendrill L., Jianpei Hu., Petersen J.C., Poulsen O., Ramanujam P.S., Riehle F., Robertsson L., Ståhlberg B., Wahlgren H., Inter-comparison of Northern European $^{127}I_2$ Stabilized He-Ne Lasers at $\lambda \approx 633$ nm, *Metrologia*, 1992, **29**, 331-339 [Document CCDM/ 92-20*y*].

These papers show that the frequency of laser BIPM4 is very close to the mean. It was agreed that the CCDM should adopt an international value close to this average.

By applying the corresponding frequency difference [Document CCDM/92-20*a*], f_i(BIPM) - f_i(INM) = 11.4 kHz, the value is:

f_i = 473 612 214 705.4 kHz.

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

Iodine cell			
cell-wall	temperature (25 ± 5) °C	[coefficient 0.5 kHz/°C]	2.5 kHz
cold-finger	temperature (15 ± 0.2) °C	[coefficient -15 kHz/°C]	3.0 kHz
uncertainty of the iodine purity			5.0 kHz
Frequency modulation width, peak-to-peak, (6 ± 0.3) MHz		[coefficient -10 kHz/MHz]	3.0 kHz
One-way intracavity beam power, (10 ± 5) mW		[absolute value of the coefficient ≤ 1.4 kHz/mW]	7.0 kHz
Uncertainty of the interval $f_f - f_i$			5.0 kHz
Uncertainty of the frequency difference $f_{INM} - f_{BIPM}$			1.5 kHz
Uncertainty of the BNM-LPTF/ETCA/INM frequency measurement			3.4 kHz
Combined standard uncertainty			11.7 kHz
Relative standard uncertainty			2.5×10^{-11}

1.6-2 Quinn T.J., Results of Recent International Comparisons of National Measurement Standards Carried out by the BIPM 1996, *Metrologia*, 1996, **33**, 271-287.

Chartier J.-M., Chartier A., International Comparisons of He-Ne Lasers Stabilized with $^{127}I_2$ at $\lambda \approx 633$ nm (July 1993 - September 1995), Part I: Generality, *Metrologia*, 1997, **34**, 297-300.

Chartier J.-M., Chartier A., Felder R., Goebel R., Labot J., Picard S., Robertsson L., Vitushkin L., Zarka A., BIPM Activities Related to Realization of the Definition of the Metre, *CPEM Digest,* 1998, ISBN 98-CH36254, 293-294.

These papers give the results of a wide programme of laser comparisons begun in 1993 and completed in 1997. These results confirm that the relative standard uncertainty of 2.5×10^{-11} adopted by the CIPM in 1992 is valid when the parameters which affect the laser frequency are set to the recommended values.

1.7-1 Bennett S.J., Mills-Baker P., Iodine Stabilized 640 nm Helium-Neon, *Opt. Commun.,* 1984, **51**, 322-324 [Document CCDM/ 92-12*d*].

From this paper the ratio f_g/f_i has been calculated [Document CCDM/92-12*a*] as:

$$f_g/f_i = 0.988\ 611\ 184\ 191\ (1 \pm 1 \times 10^{-10})\ \text{(1 standard deviation).}$$

With the recommended value (Section 1.6) of

$$f_i = 473\ 612\ 214\ 705\ (1 \pm 2.5 \times 10^{-11})\ \text{kHz,}$$

one calculates:

f_g = 468 218 332 427 (1 ± 1.03 × 10^{-10}) kHz,

at an iodine pressure of 16 Pa (or a cold-finger reference temperature of 14.3 °C) and a modulation width of 7 MHz. For a reference temperature of 16 °C and a modulation width of 6 MHz, peak-to-peak, corrections of –23 kHz and +8 kHz have to be applied to this value assuming a pressure-dependent frequency shift of –7.8 kHz/Pa and modulation-dependent shift of -7.6 kHz/MHz, similar to that reported in [1.7-2], giving:

f_{a_9} = 468 218 332 412 (1 ± 1.0 × 10^{-10}) kHz.

1.7-2 Zhao K.G., Blabla J., Helmcke J., $^{127}I_2$-Stabilized ^{3}He-^{22}Ne Laser at 640 nm Wavelength, *IEEE Trans. Instrum. Meas.*, 1985, **IM-34**, 252-256 [Document CCDM/92-10.2*c*].

This paper gives:

λ_{a_9} = 640.283 468 8 (1 ± 1.1 × 10^{-9}) nm (3 standard deviations).

Bönsch G., Simultaneous Wavelength Comparison of Iodine-Stabilized Lasers at 515 nm, 633 nm and 640 nm, *IEEE Trans. Instrum. Meas.*, 1985, **IM-34**, 248-251 and Document CCDM/92-14*a*.

These papers give:

λ_i/λ_{a_9} = 0.988 611 183 86 (1 ± 12 × 10^{-11}) (1 standard deviation).

With the recommended value (Section 1.6) of

f_i = 473 612 214 705 (1 ± 2.5 × 10^{-11}) kHz,

one calculates:

f_{a_9} = 468 218 332 270 (1 ± 1.23 × 10^{-10}) kHz,

at a cold-finger reference temperature of 18 °C (iodine pressure = 22.6 Pa). For a reference temperature of 16 °C (iodine pressure = 18.9 Pa) a correction of +29 kHz (using -7.8 kHz/Pa) has to be applied to this value. To account for the modulation width of 6.5 MHz, peak-to-peak, and a modulation dependence of -7.6 kHz/MHz, an additional correction of +4 kHz has to be applied, giving:

f_{a_9} = 468 218 332 303 (1 ± 1.2 × 10^{-10}) kHz.

1.7-3 Document CCDM/92-6*a* and Document CCDM/92-20*a*.

These papers give:

$\lambda_{a_9}(17\ °C)/\lambda_{a_{17}}(20\ °C) = 1.011\ 520\ 341\ 04\ (1 \pm 4.6 \times 10^{-10})$.

With the recommended value (Section 1.6) of

$f_i = 473\ 612\ 214\ 705\ (1 \pm 2.5 \times 10^{-11})$ kHz,

one calculates:

$f_{a_9} = 468\ 218\ 332\ 048\ (1 \pm 4.6 \times 10^{-10})$ kHz,

at a cold-finger reference temperature of 17 °C (iodine pressure = 20.7 Pa). For a reference temperature of 16 °C (iodine pressure = 18.9 Pa) a correction of +14 kHz has to be applied to this value, giving:

$f_{a_9} = 468\ 218\ 332\ 062\ (1 \pm 4.6 \times 10^{-10})$ kHz.

1.8-1 Riehle F., Schnatz H., Lipphardt B., Zinner G., Trebst T., Helmcke J., The Optical Calcium Frequency Standard, *IEEE Trans. Instrum. Meas.*, 1999, **48**, 613-617.

1.8-2 Helmcke J., Riehle F., Status of the Ca Optical Frequency Standard of the PTB, Document CCDM/97-11*b*.

This paper gives:

$f_{Ca} = 455\ 986\ 240\ 494.15\ (1 \pm 2.5 \times 10^{-13})$ kHz.

1.8-3 Schnatz H., Lipphardt B., Helmcke J., Riehle F., First Phase-Coherent Frequency Measurement of Visible Radiation, *Phys. Rev. Lett.*, 1996, **76**, 18.

1.9-1 Barwood G.P., Gill P., Klein H.A., Rowley W.R.C., Clearly Resolved Secular Sidebands on the $^2S_{1/2} - {}^2D_{5/2}$ 674 nm Clock Transition in a Single Trapped Sr^+ Ion, *IEEE Trans. Instrum. Meas.*, 1997, **46**, 133-136.

This paper gives:

$f_{Sr+} = 444\ 779\ 043.98\ (1 \pm 1.3 \times 10^{-10})$ MHz.

This value is based on precision interferometric measurements of the 674 nm probe laser radiation.

1.9-2 Siemsen K.J., Madej A.A., Marmet L., Bernard J.E., Updated Precision Measurement of a CO_2 Laser Based Reference Frequency for the Frequency Measurement of the 445 THz $^{88}Sr^+$ Single Ion Transition, *NRC Internal Report* No. NRCC 41372, 1997, National Research Council of Canada, Ottawa, Canada.

The determination of the absolute frequency of the 674 nm, 445 THz radiation was based on the heterodyne mixing of radiation referenced to a 633 nm, 474 THz I_2/He-Ne laser standard and a 29 THz CO_2 laser stabilized on the ν_2 band sQ (4,3) transition of $^{15}NH_3$ having the relation:

$$f_{(445\ \mathrm{THz})} = f_{(474\ \mathrm{THz})} - f_{(29\ \mathrm{THz})} - f_{(\mathrm{beat})}.$$

An improved absolute value for the 29 THz laser source was determined using known reference OsO_4 lines to be:

$$f_{(29\ \mathrm{THz})} = 28\ 832\ 030\ 602\ (1 \pm 1.1 \times 10^{-9})\ \mathrm{kHz}.$$

Using the experimental beat measurements of [1.9-4] and the above determined 29 THz frequency, a corrected value is determined for the strontium ion frequency of:

$$f_{\mathrm{Sr+}} = 444\ 779\ 044.04\ (1 \pm 9.0 \times 10^{-11})\ \mathrm{MHz}.$$

1.9-3 Bernard J.E., Whitford B.G., Madej A.A., Marmet L., Siemsen K.J., Preliminary Phase-Coherent Frequency Chain Measurements of the 445 THz $^{88}Sr^+$ single ion Transition, *NRC Internal Report* No. 41373, 1997, National Research Council of Canada, Ottawa, Canada.

This preliminary frequency determination employed the NRC frequency chain extended to measure the 445 THz transition relative to a Hydrogen Maser referenced to a Cs frequency/time standard. The value is based on 21 measurements of 1 s sampling time of complete phase-locked operation of the chain giving:

$$f_{\mathrm{Sr+}} = 444\ 779\ 044\ 093\ (1 \pm 4.5 \times 10^{-11})\ \mathrm{kHz}.$$

The sample deviation of the readings is 14.5 kHz and the relative uncertainty of 20 kHz based on comparisons with other measurements of the chain in frequency-locked operation.

1.9-4 Marmet L., Madej A.A., Siemsen K.J., Bernard J.E., Whitford B.G., Precision Frequency Measurement of the $^2S_{1/2}–^2D_{5/2}$ Transition of Sr^+ with a 674 nm Diode Laser Locked to an Ultrastable Cavity, *IEEE Trans. Instrum. Meas.*, 1997, **46**, 169-173. The values of this paper were based on a measurement of the 29 THz stabilized CO_2 laser of:

$$f_{(29\ \mathrm{THz})} = 28\ 832\ 030\ 680\ (1 \pm 7.3 \times 10^{-10})\ \mathrm{kHz}$$

which was determined relative to four known CO_2 4.3 µm fluorescence saturation lines (of width > 1 MHz). Later precision measurements of the 29 THz frequency revealed a systematic shift of 80 kHz in this earlier value. Over a seven-month period a series of five single-ion measurements, in which a number of experimental parameters were varied, yielded a value of:

$$f_{\mathrm{Sr+}} = 444\ 779\ 043\ 963\ (1 \pm 6.7 \times 10^{-11})\ \mathrm{kHz}.$$

The accuracy was limited by the 29 THz reference laser. Later improved measurements for the 29 THz laser frequency gave a correction to the ion frequency as given in [1.9-2].

1.10-1 Touahri D., Acef O., Clairon A., Zondy J.-J., Felder R., Hilico L., De Beauvoir B., Biraben F., Nez F., Frequency Measurement of the $5S_{1/2}$ (F = 3) –$5D_{5/2}$ (F = 5) Two-photon Transition in Rubidium, *Opt. Commun.*, 1997, **133**, 471-478.

These authors measured frequencies of three diode lasers stabilized on the $5S_{1/2}$ (F = 3) –$5D_{5/2}$ (F = 5) two-photon transition in rubidium, with an uncertainty of 1 kHz, using the BNM-LPTF frequency synthesis chain starting from a CO_2/OsO_4 reference laser at $\lambda \approx 10.3$ µm.

This paper gives:

$$f_{(5S_{1/2} - €5D_{5/2})} = (385\ 285\ 142\ 378.28 \pm 2)\ \mathrm{kHz}.$$

1.11.2-1 Zakharyash V.F., Klementyev V.M., Nikitin M.V., Timchenko B.A., Chebotayev V.P., Absolute Measurement of the Frequency of the E-Line of Methane, *Sov. Phys. Tech. Phys.*, 1983, **23**, 11, 1374-1375.

1.11.2-2 Chebotayev V.P., Klementyev V.M., Nikitin M.V., Timchenko B.A., Zakharyash V.F., Comparison of Frequency Stabilities of the Rb Standard and of the He-Ne/CH_4 Laser Stabilized to the E Line in Methane, *Appl. Phys.*, 1985, **B36**, 59-61.

1.11.2-3 Bagayev S.N., Borisov B.D., Gol'Dort V.G., Gusev A. Yu. *et al.*, An Optical Standard of Time, *Avtometrya*, 1983, **3**, 37-58.

1.11.2-4 Felder R., A Decade of Work on the Determination of the

Frequency of $F_2^{(2)}$ Methane transition at $\lambda \approx 3.39$ µm, *Rapport BIPM*-92/8.

1.11.2-5 Weiss C.O., Kramer G., Lipphardt B., Garcia E., Frequency Measurement of a CH_4 Hyperfine Line at 88 THz/"Optical Clock", *IEEE J. Quant. Electron*., 1988, **24**, 10, 1970-1972.

1.11.2-6 Felder R., Robertsson L., Report on the 1989 PTB Experiment, *Rapport BIPM*-92/7.

1.11.2-7 *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1983, **51**, 25-28, and Documents Concerning the New Definition of the Metre, *Metrologia*, 1984, **19**, 165-166.

1.12-1 Clairon A., Dahmani B., Filimon A., Rutman J., Precise Frequency Measurements of CO_2/OsO_4 and He-Ne/CH_4-Stabilized Lasers, *IEEE Trans. Instrum. Meas.*, 1985, **IM34**, 265-268.

This paper gives:

$f_{(CO_2,\ R(10)/OsO_4)} = (29\ 054\ 057\ 446\ 660 \pm 50)$ Hz and

$f_{(CO_2,\ R(12)/OsO_4)} - f_{(CO2,\ R(10)/OsO4)} = (42\ 217\ 506 \pm 1)$ kHz.

1.12-2 Clairon A., Dahmani B., Acef O., Granveaud M., Domnin Yu.S., Pouchkine S.B., Tatarenkov V.M., Felder R., Recent Experiments Leading to the Characterization of the Performance of Portable (He-Ne)/CH_4 Lasers, Part II: Results of the 1986 LPTF Absolute Frequency Measurements, *Metrologia*, 1988, **25**, 9-16.

This paper gives:

$f_{(CO_2,\ R(10)/OsO_4)} = (29\ 054\ 057\ 446.66 \pm 0.05)$ kHz,

$f_{(CO_2,\ R(12)/OsO_4)} - f_{(CO2,\ R(10)/OsO4)} = (42\ 217\ 505.68 \pm 0.05)$ kHz and

$f_{(CO_2,\ R(12)/OsO_4)} = (29\ 096\ 274\ 952.34 \pm 0.07\ )$ kHz.

1.12.3 Acef O., Metrological Properties of CO_2/OsO_4 Optical Frequency Standard, *Opt. Commun*., 1997, **134**, 479-486.

This paper gives:

$f_{(CO_2,\ R(12)/OsO_4)} = (29\ 096\ 274\ 952.34 \pm 0.07)$ kHz.

1.12-4 Bernard V., Nogues G., Daussy Ch., Constantin L., Chardonnet Ch.,

CO_2 Laser Stabilized on Narrow Saturated Absorption Resonances of CO_2; Improved Absolute Frequency Measurements, *Metrologia*, 1997, **34**, 313-318.

This paper gives:

$f_{(CO_2,\ R(12)/OsO_4)}$ = (29 096 274 952.343 ± 0.060) kHz.

2.1-1 *BIPM Com. Cons. Déf. Mètre*, 1982, **7**, M 58 and Documents Concerning the New Definition of the Metre, *Metrologia*, 1984, **19**, 168.

f_{Kr+}/f_i = 1.044 919 242 05 ($1 \pm 1.3 \times 10^{-9}$).

2.2-1 BIPM Com. Cons. Déf. Mètre, 1962, **3**, 18-19.

2.2-2 BIPM Proc. Verb. Com. Int. Poids et Mesures, 1963, **52**, 26-27.

2.3-1 NBS measurement of frequencies in the visible and near IR [Document CCDM/82-30].

This document gave the value 520 206 808 547 ($1 \pm 1.5 \times 10^{-10}$) kHz, which was reduced by 12 kHz at the request of the delegate at the 7th meeting of the CCDM. The value must now also be multiplied by the ratio (88 376 181 600.5/88 376 181 608) to account for the 1992 reference value of the methane frequency (Section 1.11-2) giving:

f_{a_1} = 520 206 808 491 ($1 \pm 1.5 \times 10^{-10}$) kHz.

2.3-2 Barwood G.P., Rowley W.R.C., Characteristics of a $^{127}I_2$-Stabilized Dye Laser at 576 nm, *Metrologia*, 1984, **20**, 19-23 [Document CCDM/92-12*c*].

This publication supersedes Document CCDM/82-34.

This paper gives:

$f_{a_1}/f_{a_{13}}$ = 1.098 381 317 29 ($1 \pm 1 \times 10^{-10}$).

With the recommended value (Section 1.6) of

$f_{a_{13}}$ = 473 612 214 705 ($1 \pm 2.5 \times 10^{-11}$) kHz,

one calculates:

f_{a_1} = 520 206 808 272 ($1 \pm 1 \times 10^{-10}$) kHz.

APPENDIX M 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 65-M 75 and *Metrologia*, 1984, **19**, 170-178, and in *BIPM Com. Cons. Déf. Mètre*, 1992, **8**, M 51-M 61 and *Metrologia*, 1993/94, **30**, 523-541.

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

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

For the uncertainties, account has been taken of:

- the uncertainties given by the authors;
- the spread in the different determinations of a single component;
- the effect of any perturbing components;
- the difference between the calculated and the measured values.

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

Table 1

$\lambda \approx$ 389 nm; hydrogen: frequencies of the 2S–8S/D two-photon transitions

Transition	Frequency/MHz	u_c/MHz
$2S_{1/2} - 8D_{5/2}$	770 649 561.587	0.006
$2S_{1/2} - 8D_{3/2}$	770 649 504.454	0.007
$2S_{1/2} - 8D_{1/2}$	770 649 350.016	0.008
$2S_{1/2} - 8D_{5/2}$	770 649 561.589	0.005
Deduced mean value for the $2S_{1/2} - 8D_{5/2}$ measurements:	770 649 561.585	0.005

Ref. [1]

Table 2

$\lambda \approx$ 389 nm; deuterium: frequencies of the 2S–8S/D two-photon transitions		
Transition	Frequency/MHz	u_c/MHz
$2S_{1/2} - 8D_{5/2}$	770 859 252.852	0.003
$2S_{1/2} - 8D_{3/2}$	770 859 195.704	0.004
$2S_{1/2} - 8D_{1/2}$	770 859 041.251	0.005
Deduced mean value for the $2S_{1/2} - 8D_{5/2}$ measurements:	770 859 252.852	0.004

Ref. [1]

Table 3

$\lambda \approx$ 515 nm; $^{127}I_2$, transition 43-0, P(13)					
Reference: component a_3 (or s), f = 582 490 603.37 MHz [2]					
Component	$[f(a_n) - f(a_3)]$/MHz	u_c/MHz	Component	$[f(a_n) - f(a_3)]$/MHz	u_c/MHz
a_1	−131.770	0.001	a_{11}	393.962	0.002
a_2	−59.905	0.001	a_{12}	435.599	0.003
a_3	0	–	a_{13}	499.712	0.005
a_4	76.049 1	0.002	a_{14}	518	
a_5	203.229	0.005	a_{15}	587.396	0.002
a_6	240.774	0.005	a_{16}	616.756	0.005
a_7	255.005	0.001	a_{17}	660.932	0.005
a_8	338.699 1	0.005	a_{18}	740	
a_9	349.717 1	0.005	a_{19}	742	
a_{10}	369	1	a_{20}	757.631	0.010
			a_{21}	817.337	0.005

Ref. [3–6]

Table 4

$\lambda \approx 515$ nm; $^{127}I_2$, transition 43-0, R(15)					
References	• component a_3, 43-0, P(13), $^{127}I_2$, f = 582 490 603.37 MHz [2] • $f(a_1) - f(a_3)$ = [−131.770 ± 0.001] MHz (Table 3) • $f(b_1) - f(a_1)$ = [283.835 ± 0.005] MHz [4,7]				
Component	$[f(b_n) - f(b_1)]$/MHz	u_c/MHz	Component	$[f(b_n) - f(b_1)]$/MHz	u_c/MHz
b_1	0	0.005	b_{11}	525.207	0.005
b_2	69.739	0.005	b_{12}	566.287	0.005
b_3	129.155	0.005	b_{13}	630.782	0.005
b_4	217	1	b_{14}	658.178	0.005
b_5	335.828	0.005	b_{15}	725.166	0.005
b_6	368	1	b_{16}	739.394	0.005
b_7	396.442	0.005	b_{17}	791.673	0.005
b_8	471	1	b_{18}	865.523	0.005
b_9	472	1	b_{19}	874.840	0.005
b_{10}	500.627	0.005	b_{20}	892.895	0.010
			b_{21}	947.278	0.010

Ref. [4, 5, 7]

Table 5

$\lambda \approx 515$ nm; $^{127}I_2$, transition 58-1, R(98)							
References	• component a_3, 43-0, P(13), $^{127}I_2$, f = 582 490 603.37 MHz [2] • $f(d_6) - f(a_3)$ = [−2100 ± 1] MHz [8]						
Component		$[f(d_n) - f(d_6)]$/MHz	u_c/MHz	Component		$[f(d_n) - f(d_6)]$/MHz	u_c/MHz
d_1	1	−413.488	0.005	d_8	8	200.478	0.005
d_2	2	−359.553	0.005	d_9	9	225.980	0.005
d_3	3	−194.521	0.005	d_{10}	10	253	1
d_4	4	−159.158	0.005	d_{11}	11	254	1
d_5	5	−105.769	0.005	d_{12}	12	314.131	0.005
d_6	6	0	–	d_{13}	13	426.691	0.005
d_7	7	172.200	0.005	d_{14}	14	481.574	0.005
				d_{15}	15	510.246	0.005

Ref. [5, 7, 8]

Table 6

$\lambda \approx 532$ nm; $^{127}I_2$, transition 32-0, R(57) (or 1104)		
References	• component a_{10}, 32-0, R(56), $^{127}I_2$, f = 563 260 223.48 MHz [2] • $f(a_1$, 32-0, R(57)) – $f(a_{10}$, 32-0, R(56)) = [–50 946.880 ± 0.002] MHz [2]	
Component	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	–
a_2	39.372	0.001
a_3	76.828	0.001
a_4	273.042	0.001
a_7	375.284	0.001
a_8	438.243	0.001
a_9	456.183	0.001
a_{10}	479.201	0.001
a_{11}	492.915	0.001
a_{12}	573.917	0.001
a_{13}	610.925	0.001
a_{14}	650.805	0.001
a_{15}	715.550	0.001
a_{16}	741.175	0.001
a_{17}	764.716	0.001
a_{18}	789.777	0.001
a_{19}	881.116	0.001
a_{20}	895.016	0.001
a_{21}	911.901	0.001

Ref. [9, 10]

Table 7

$\lambda \approx 532$ nm; $^{127}I_2$, transition 32-0, P(54) (or 1105)		
References	• component a_{10}, 32-0, R(56), $^{127}I_2$, f = 563 260 223.48 MHz [2] • $f(a_1$, 32-0, P(54)) – $f(a_{10}$, 32-0, R(56)) = [–47 588.892 ± 0.002] MHz [2]	
Component	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz
a_1	0	–
a_2	260.992	0.001
a_3	285.008	0.001
a_4	286.726	0.001
a_5	310.066	0.001
a_6	402.249	0.001
a_7	417.668	0.001
a_8	438.919	0.001
a_9	454.563	0.001
a_{10}	571.536	0.001
a_{11}	698.614	0.001
a_{12}	702.935	0.001
a_{13}	725.834	0.001
a_{14}	731.688	0.001
a_{15}	857.961	0.001

Ref. [9, 10]

Table 8

$\lambda \approx 532$ nm; $^{127}I_2$, transition 32-0, R(56) (or 1110)					
Reference: component a_{10}, f = 563 260 223.48 MHz [2]					
Component	$[f(a_n) - f(a_{10})]$/MHz	u_c/MHz	Component	$[f(a_n) - f(a_{10})]$/MHz	u_c/MHz
a_1	−571.547	0.002	a_9	−116.199	0.002
a_2	−311.848	0.002	a_{10}	0	–
a_5	−260.177	0.002	a_{11}	+126.513	0.003
a_6	−170.066	0.002	a_{12}	+131.211	0.002
a_7	−154.551	0.003	a_{13}	+154.491	0.003
a_8	−132.916	0.002	a_{15}	+286.410	0.003

Ref. [11, 12, 14]

Table 9

$\lambda \approx 532$ nm; $^{127}I_2$, transition 35-0, P(119) (or 1106)					
References	• component a_{10}, 32-0, R(56), $^{127}I_2$, f = 563 260 223.48 MHz [2] • $f(a_1$, 35-0, P(119)) – $f(a_{10}$, 32-0, R(56)) = [–36 840.162 ± 0.002] MHz [2]				
Component	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	Component	$[f(a_n) - f(a_1)]$/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
a_7, a_8 and a_{12} do not fit well					

Ref. [12, 13]

Table 10

$\lambda \approx 532$ nm; $^{127}I_2$, transition 33-0, R(86) (or 1107)					
References	• component a_{10}, 32-0, R(56), $^{127}I_2$, f = 563 260 223.48 MHz [2] • $f(a_1$, 33-0, R(86)) – $f(a_{10}$, 32-0, R(56)) = [–32 190.404 ± 0.002] MHz [2]				
Component	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	Component	$[f(a_n) - f(a_1)]$/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			

Ref. [11, 13]

Table 11

$\lambda \approx 532$ nm; $^{127}I_2$, transition 34-0, R(106) (or 1108)					
References	• component a_{10}, 32-0, R(56), $^{127}I_2$, f = 563 260 223.48 MHz [2] • $f(a_1$, 34-0, R(106)) – $f(a_{10}$, 32-0, R(56)) = [–30 434.762 ± 0.002] MHz [2]				
Component	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	Component	$[f(a_n) - f(a_1)]$/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			

Ref. [11, 13, 15]

Table 12

$\lambda \approx 532$ nm; $^{127}I_2$, transition 36-0, R(134)					
References	• component a_{10}, 32-0, R(56), $^{127}I_2$, f = 563 260 223.48 MHz [2] • $f(a_1$, 36-0, R(134)) – $f(a_{10}$, 32-0, R(56)) = [–17 173.680 ± 0.002] MHz [2]				
Component	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	Component	$[f(a_n) - f(a_1)]$/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			
a_{10} and a_{15} are too weak lines					

Ref. [11, 13]

Table 13

$\lambda \approx 532$ nm; $^{127}I_2$, transition 33-0, P(83) (or 1109)					
References	• component a_{10}, 32-0, R(56), $^{127}I_2$, f = 563 260 223.48 MHz [2] • $f(a_1$, 33-0, P(83)) − $f(a_{10}$, 32-0, R(56)) = [−16 602.549 ± 0.002] MHz [2]				
Component	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	Component	$[f(a_n) - f(a_1)]$/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

no data for a_{12}

Ref. [11, 13]

Table 14

$\lambda \approx 532$ nm; $^{127}I_2$, transition 32-0, P(53) (or 1111)					
References	• component a_{10}, 32-0, R(56), $^{127}I_2$, f = 563 260 223.48 MHz [2] • $f(a_1$, 32-0, P(53)) − $f(a_{10}$, 32-0, R(56)) = [2 599.708 ± 0.002] MHz [2]				
Component	$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	Component	$[f(a_n) - f(a_1)]$/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			

components a_5 through a_{14} are too weak for locking

Ref. [11, 13]

Table 15

$\lambda \approx 543.5$ nm; $^{127}I_2$, transition 26-0, R(2)					
Reference: component a_9, f = 551 579 482.96 MHz [2]					
Component	$[f(a_n) - f(a_9)]$/MHz	u_c/MHz	Component	$[f(a_n) - f(a_9)]$/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			

Ref. [16–23]

Table 16

$\lambda \approx 543.5$ nm; $^{127}I_2$, transition 28-0, R(106)					
Reference: component a_9, 26-0 R(12), $^{127}I_2$, f = 551 579 482.96 MHz [2]					
Component	$[f(b_n) - f(a_9)]$/MHz	u_c/MHz	Component	$[f(b_n) - f(a_9)]$/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			

Ref. [16-23]

Table 17

$\lambda \approx 612$ nm; $^{127}I_2$, transition 9-2, R(47)							
Reference: component a_7 (or o), f = 489 880 354.9 MHz [2]							
Component		$[f(a_n) - f(a_7)]$/MHz	u_c/MHz	Component		$[f(a_n) - f(a_7)]$/MHz	u_c/MHz
a_1	u	−357.16	0.02	a_{11}	k	119.045	0.006
a_2	t	−333.97	0.01	a_{12}	j	219.602	0.006
a_3	s	−312.46	0.02	a_{13}	i	249.60	0.01
a_4	r	−86.168	0.007	a_{14}	h	284.30	0.01
a_5	q	−47.274	0.004	a_{15}	g	358.37	0.03
a_6	p	−36.773	0.003	a_{16}	f	384.66	0.01
a_7	o	0	–	a_{17}	e	403.76	0.02
a_8	n	81.452	0.003	a_{18}	d	429.99	0.02
a_9	m	99.103	0.003	a_{19}	c	527.16	0.02
a_{10}	l	107.463	0.005	a_{20}	b	539.22	0.02
				a_{21}	a	555.09	0.02

Ref. [24, 26, 27, 29, 32]

Table 18

$\lambda \approx 612$ nm; $^{127}I_2$, transition 11–3, P(48)					
Reference: component a_7, 9-2, R(47), $^{127}I_2$, f = 489 880 354.9 MHz [2]					
Component	$[f(b_n) - f(a_7\,^{127}I_2)]$/MHz	u_c/MHz	Component	$[f(b_n) - f(a_7\,^{127}I_2)]$/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			

Ref. [24, 26, 27, 29, 32]

Table 19

$\lambda \approx 612$ nm; $^{127}I_2$, transition 15-5, R(48)		
Reference: component a_7, 9-2, R(47), $^{127}I_2$, f = 489 880 354.9 MHz [2]		
Component	$[f(c_n) - f(a_7, ^{127}I_2)]$/MHz	u_c/MHz
c_1	−513.83	0.03
c_2	−237.40	0.03
c_3	−228.08	0.03
c_4	−218.78	0.03
c_5	−209.96	0.03
c_6	−97.74	0.03
c_8	−73.92	0.03
c_9	−59.30	0.03

Ref. [24]

Table 20

$\lambda \approx 612$ nm; $^{129}I_2$, transition 10-2, P(110)							
Reference: component a_7, 9-2, R(47), $^{127}I_2$, f = 489 880 354.9 MHz [2]							
Component		$[f(a_n) - f(a_7, ^{127}I_2)]$/MHz	u_c/MHz	Component		$[f(a_n) - f(a_7, ^{127}I_2)]$/MHz	u_c/MHz
a_1	b′	−376.29	0.05	a_{15}	n	1.61	0.20
a_2	a′	−244.76	0.10	a_{16}	m	10.63	0.15
a_3	z	−230.79	0.20	a_{17}	l	15.82	0.20
a_4	y	−229.40	0.20	a_{18}	k	25.32	0.10
a_5	x	−216.10	0.05	a_{19}	j	49.44	0.15
a_6	w	−149.37	0.10	a_{20}	i	54.66	0.20
a_7	v	−134.68	0.10	a_{21}	h	69.02	0.10
a_8	u	−130.98	0.10	a_{22}	g	74.47	0.15
a_9	t	−116.67	0.05	a_{23}	f	110.60	0.10
a_{10}	s	−96.26	0.20	a_{24}	e	153.09	0.20
a_{11}	r	−90.70	0.20	a_{25}	d	154.70	0.20
a_{12}	q	−84.12	0.20	a_{26}	c	163.98	0.20
a_{13}	p	−77.79	0.20	a_{27}	b	166.22	0.20
a_{14}	o	−72.70	0.20	a_{28}	a	208.29	0.10

Ref. [30, 33, 34]

Table 21

$\lambda \approx 612$ nm; $^{129}I_2$, transition 14-4, R(113)							
Reference: component a_7, 9-2, R(47), $^{127}I_2$, f = 489 880 354.9 MHz [2]							
Component		$[f(b_n) - f(a_7, {}^{127}I_2)]$/MHz	u_c/MHz	Component		$[f(b_n) - f(a_7, {}^{127}I_2)]$/MHz	u_c/MHz
b_{19}	r	−410.4	0.3	b_{28}	i	−289.4	0.5
b_{20}	q	−390.0	0.3	b_{29}	h	−273.1	0.3
b_{21}	p	−383.9	0.5	b_{30}	g	−255.7	0.5
b_{22}	o	−362.8	0.3	b_{31}	f	−247	5
b_{23}	n	−352.9	0.3	b_{32}	e	−237	5
b_{24}	m	−346.4	0.3	b_{33}	d	−223	5
b_{25}	l	−330.0	0.3	b_{34}	c	−198.6	0.3
b_{26}	k	−324.9	0.3	b_{35}	b	−193.1	0.3
b_{27}	j	−304.7	0.3	b_{36}	a	−187.0	0.3

Ref. [33, 34]

Table 22

$\lambda \approx 633$ nm; $^{127}I_2$, transition 11-5, R(127)							
Reference: component a_{13} (or i), f = 473 612 214.705 MHz [2]							
Component		$[f(a_n) - f(a_{13})]$/MHz	u_c/MHz	Component		$[f(a_n) - f(a_{13})]$/MHz	u_c/MHz
a_2	t	−582.9	0.5	a_{12}	j	−21.565	0.005
a_3	s	−558.9	0.5	a_{13}	i	0	–
a_4	r	−320.73	0.01	a_{14}	h	21.939	0.005
a_5	q	−292.69	0.05	a_{15}	g	125.694	0.005
a_6	p	−290.29	0.05	a_{16}	f	138.892	0.005
a_7	o	−263.20	0.01	a_{17}	e	152.255	0.005
a_8	n	−162.814	0.005	a_{18}	d	165.116	0.005
a_9	m	−153.801	0.005	a_{19}	c	283.006	0.005
a_{10}	l	−137.994	0.005	a_{20}	b	291.100	0.005
a_{11}	k	−129.950	0.005	a_{21}	a	299.931	0.005

Ref. [34-47]

Table 23

$\lambda \approx 633$ nm; $^{127}I_2$, transition 6-3, P(33)							
References	• component a_{13}, 11-5, R(127), $^{127}I_2$, f = 473 612 214.705 MHz [2] • $f(b_{21}) - f(a_{13}$, 11-5, R(127)) = [−393.53 ± 0.02] MHz [48]						
Component		$[f(b_n) - f(b_{21})]$/MHz	u_c/MHz	Component		$[f(b_n) - f(b_{21})]$/MHz	u_c/MHz
b_1	u	−922.571	0.008	b_{11}	k	−439.01	0.01
b_2	t	−895.064	0.008	b_{12}	j	−347.354	0.007
b_3	s	−869.67	0.01	b_{13}	i	−310.30	0.01
b_4	r	−660.50	0.02	b_{14}	h	−263.588	0.009
b_5	q	−610.697	0.008	b_{15}	g	−214.53	0.02
b_6	p	−593.996	0.008	b_{16}	f	−179.312	0.005
b_7	o	−547.40	0.02	b_{17}	e	−153.942	0.005
b_8	n	−487.074	0.009	b_{18}	d	−118.228	0.007
b_9	m	−461.30	0.03	b_{19}	c	−36.73	0.01
b_{10}	l	−453.21	0.03	b_{20}	b	−21.980	0.007
				b_{21}	a	0	–

Ref. [43, 48-53]

Table 24

$\lambda \approx 633$ nm; $^{129}I_2$, transition 8-4, P(54)							
References	• component a_{13}, 11-5, R(127), $^{127}I_2$, f = 473 612 214.705 MHz [2] • $f(a_{28}$, 8-4, P(54)) − $f(a_{13}$, 11–5, R(127)) = [95.90 ± 0.04] MHz [54, 56]						
Component		$[f(a_n) - f(a_{28})]$/MHz	u_c/MHz	Component		$[f(a_n) - f(a_{28})]$/MHz	u_c/MHz
a_2	z′	−449	2	a_{15}	j′	−206.1	0.2
a_3	y′	−443	2	a_{16}	i′	−197.73	0.08
a_4	x′	−434	2	a_{17}	h′	−193.23	0.08
a_5	w′	−429	2	a_{18}	g′	−182.74	0.03
a_6	v′	−360.9	1	a_{19}	f′	−162.61	0.05
a_7	u′	−345.1	1	a_{20}	e′	−155.72	0.05
a_8	t′	−340.8	1	a_{21}	d′	−138.66	0.05
a_9	s′	−325.4	1	a_{22}	c′	−130.46	0.05
a_{10}	r′	−307.0	1	a_{23}	a′	−98.22	0.03
a_{11}	q′	−298.2	1	a_{24}	n_2 }	−55.6[a]	0.5
a_{12}	p′	−293.1	1	a_{25}	n_1 }		
a_{13}	o′	−289.7	1	a_{26}	m_2	−43.08	0.03
a_{14}	n′	−282.7	1	a_{27}	m_1	−41.24	0.05
				a_{28}	k	0	–

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

Ref. [57-62]

Table 25

$\lambda \approx 633$ nm; $^{129}I_2$, transition 12-6, P(69)							
References	• component a_{13}, 11-5, R(127), $^{127}I_2$, f = 473 612 214.705 MHz [2] • $f(a_{28}$, 8-4, P(54)) – $f(a_{13}$, 11-5, R(127)) = [95.90 ± 0.04] MHz [54-56]						
Component		$[f(b_n) - f(a_{28})]$/MHz	u_c/MHz	Component		$[f(b_n) - f(a_{28})]$/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[a]	0.05	b_{25}	l′	560.94	0.05
b_6	q′′	264.84[b]	0.05	b_{26}	k′	566.19	0.05
b_7	p′′	288.06	0.05	b_{27}	j′	586.27	0.03
b_8	k′′	337.75	0.1	b_{28}	i′	601.78	0.03
b_9	i''_1	358.8	0.5	b_{29}	h′	620.85	0.03
b_{10}	i''_2			b_{30}	g′	632.42	0.03
b_{11}	f′′	373.80	0.05	b_{31}	f′	644.09	0.03
b_{12}	d′′	387.24	0.05	b_{32}	e′	655.47	0.03
b_{13}	c′′	395.3	0.2	b_{33}	d′	666.81	0.10
b_{14}	b′′	402.45	0.05	b_{34}	c′	692.45	0.10
b_{15}	a′′	407	4	b_{35}	b′	697.96	0.10
b_{16}	z′	412.37	0.05	b_{36}	a′	705.43	0.10
b_{17}	y′	417	4				

[a]also component m_{28} of 6–3, P(33), $^{127}I^{129}I$
[b]also component m_{29} of 6–3, P(33), $^{127}I^{129}I$

Ref. [57, 60, 62]

Table 26

$\lambda \approx 633$ nm; $^{129}I_2$, transition 8-4, R(60)		
References	• component a_{13}, 11-5, R(127), $^{127}I_2$, f = 473 612 214.705 MHz [2] • $f(a_{28}$, 8-4, P(54)) – $f(a_{13}$, 11-5, R(127)) = [95.90 ± 0.04] MHz [54-56]	
Component	$[f(d_n) - f(a_{28})]$/MHz	u_c/MHz
d_{23} A′	–555	5
d_{24} N ⎫ d_{25} N ⎭	–511	2
d_{26} M ⎫ d_{27} M ⎭	–499	2
d_{28} K	–456	2

Ref. [57]

Table 27

$\lambda \approx 633$ nm; $^{129}I_2$, transition 6-3, P(33)					
References	• component a_{13}, 11-5, R(127), $^{127}I_2$, f = 473 612 214.705 MHz [2] • $f(e_2) - f(a_{13}$, 11-5, R(127)) = [988.3 ± 0.2] MHz [63, 65]				
Component	$[f(e_n) - f(e_2)]$/MHz	u_c/MHz	Component	$[f(e_n) - f(e_2)]$/MHz	u_c/MHz
e_1 A	−19.82	0.05	e_9 I	239	2
e_2 B	0	–	e_{10} J	249	2
e_3 C	17.83	0.03	e_{11} K	260	2
e_4 D	102.58	0.05	e_{12} L	269	3
e_5 E	141	2	e_{13} M	273	4
e_6 F	157	2	e_{14} N	287	4
e_7 G	191	2	e_{15} O	293	5
e_8 H	208	2	e_{16} P	295	5
			e_{17} Q	306	6

Ref. [57, 62–64]

Table 28

$\lambda \approx 633$ nm; $^{127}I^{129}I$, transition 6-3, P(33)								
References	• component a_{13}, 11-5, R(127), $^{127}I_2$, f = 473 612 214.705 MHz [2] • $f(a_{28}$, 8-4, P(54)) – $f(a_{13}$, 11-5, R(127)) = [95.90 ± 0.04] MHz [54–56]							
Component		$[f(m_n) - f(a_{28})]$/MHz	u_c/MHz	Component		$[f(m_n) - f(a_{28})]$/MHz	u_c/MHz	
m_1	m′	–254	3	m_{26}	u′′	212.80	0.05	
m_2	l′	–233.71	0.10	m_{27}	t′′	219.43	0.05	
m_3	k′	–226.14	0.10	m_{28}	r′′	256.90	0.10	
m_4	j′	–207	2	m_{29}	q′′	264.84	0.05	
m_5	b′	–117.79	0.10	m_{30}	o′′	299.22	0.05	
m_6	p	–87.83	0.15	m_{31}	n′′	312.43	0.05	
m_7	o	–78.2	0.5	m_{32}	m′′	324.52	0.03	
m_8	n	–56[a]	1	m_{33}	l′′	333.14	0.03	
m_9	l	–17.55	0.05	m_{34} m_{35}	k''_2 k''_1	337.7	0.5	
m_{10}	j	12.04	0.03					
m_{11}	i	15.60	0.03	m_{36}	j′′	345.05	0.05	
m_{12}	h	33.16	0.03	m_{37}	h′′	362.18	0.10	
m_{13}	g_2	39.9	0.2	m_{38}	g′′	369.78	0.03	
m_{14}	g_1	41.3	0.2	m_{39}	e′′	380.37	0.03	
m_{15}	f	50.72	0.03	m_{40}	d′′	385	4	
m_{16}	e	54.06	0.10	m_{41}	x′	431	4	
m_{17}	d	69.33	0.03	m_{42}	w′	445	4	
m_{18}	c	75.06	0.03	m_{43}	v′	456.7	0.5	
m_{19}	b	80.00	0.03	m_{44}	u′	477.17	0.05	
m_{20}	a	95.00	0.03	m_{45}	t′	486.43	0.05	
m_{21}	y′′	160.74	0.03	m_{46}	s′	495.16	0.05	
m_{22}	x′′	199.52	0.03	m_{47}	r′	503.55	0.05	
m_{23}	w′′	205.06	0.05	m_{48}	p′	515.11	0.05	
m_{24} m_{25}	v''_2 v''_1	207.9	0.5					

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

Ref. [42, 57, 60-62]

Table 29

$\lambda \approx 640$ nm; $^{127}I_2$, transition 8-5, P(10)					
Reference: component a_9 (or g), $f = 468\ 218\ 332.4$ MHz [2]					
Component	$[f(a_n) - f(a_9)]$/MHz	u_c/MHz	Component	$[f(a_n) - f(a_9)]$/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			

Ref. [17, 27, 66-73]

Table 30

$\lambda \approx 640$ nm; $^{127}I_2$, transition 8-5, R(16)		
Reference: component a_9, 8-5, P(10), $f = 468\ 218\ 332.4$ MHz [2]		
Component	$[f(b_n) - f(a_9)]$/MHz	u_c/MHz
b_1	62.83	0.01
b_2	329.8	0.2
b_3	335.99	0.02

Ref. [17, 27, 66-73]

Table 31

$\lambda \approx 778$ nm; ^{85}Rb, $5S_{1/2} - 5D_{3/2}$ two-photon transition		
Reference: transition $[5S_{1/2}(F_g = 3) - 5D_{5/2}(F_e = 5)]$, ^{85}Rb, $f = 385\ 285\ 142\ 378$ kHz [2]		
Transition	$[f(5S_{1/2}(F_g = n) - 5D_{3/2}(F_e = m)) - f_{ref}]$/kHz	u_c/kHz
$F_g = 3$, $F_e = 1$	−44 462 655	7
$F_g = 3$, $F_e = 2$	−44 459 151	7
$F_g = 3$, $F_e = 3$	−44 453 175	7
$F_g = 3$, $F_e = 4$	−44 443 871	7
$F_g = 2$, $F_e = 1$	−42 944 789	7
$F_g = 2$, $F_e = 2$	−42 941 283	7
$F_g = 2$, $F_e = 3$	−42 935 308	7
$F_g = 2$, $F_e = 4$	−42 926 004	7

Ref. [74]

Table 32

$\lambda \approx$ 778 nm; ^{85}Rb, $5S_{1/2} - 5D_{5/2}$ two-photon transition		
Reference: transition [$5S_{1/2}$ (F_g = 3) – $5D_{5/2}$ (F_e = 5)], ^{85}Rb, f = 385 285 142 378 kHz [2]		
Transition	[f($5S_{1/2}$ ($F_g = n$) – $5D_{5/2}$ ($F_e = m$)) – f_{ref}]/kHz	u_c/kHz
$F_g = 3, F_e = 5$	0	–
$F_g = 3, F_e = 4$	4 718	9
$F_g = 3, F_e = 3$	9 228	9
$F_g = 3, F_e = 2$	13 031	9
$F_g = 3, F_e = 1$	15 771	14
$F_g = 2, F_e = 4$	1 522 595	9
$F_g = 2, F_e = 3$	1 527 094	9
$F_g = 2, F_e = 2$	1 530 887	9
$F_g = 2, F_e = 1$	1 533 631	11
$F_g = 2, F_e = 0$	1 535 084	26

Ref. [74]

Table 33

$\lambda \approx$ 778 nm; ^{87}Rb, $5S_{1/2} - 5D_{3/2}$ two–photon transition		
Reference: transition [$5S_{1/2}$ (F_g = 3) – $5D_{5/2}$ (F_e = 5)], ^{85}Rb, f = 385 285 142 378 kHz [2]		
Transition	[f($5S_{1/2}$ ($F_g = n$) – $5D_{3/2}$ ($F_e = m$)(^{87}Rb) – f_{ref}]/kHz	u_c/kHz
$F_g = 2, F_e = 0$	–45 047 389	7
$F_g = 2, F_e = 1$	–45 040 639	7
$F_g = 2, F_e = 2$	–45 026 674	7
$F_g = 2, F_e = 3$	–45 004 563	7
$F_g = 1, F_e = 1$	–41 623 297	7
$F_g = 1, F_e = 2$	–41 609 335	7
$F_g = 1, F_e = 3$	–41 587 223	7

Ref. [74]

Table 34

$\lambda \approx$ 778 nm; ^{87}Rb, $5S_{1/2} - 5D_{5/2}$ two-photon transition		
Reference: transition [$5S_{1/2}$ (F_g = 3) – $5D_{5/2}$ (F_e = 5)], ^{85}Rb, f = 385 285 142 378 kHz [2]		
Transition	[f($5S_{1/2}$ ($F_g = n$) – $5D_{5/2}$ ($F_e = m$) (^{87}Rb) – f_{ref}]/kHz	u_c/kHz
$F_g = 2, F_e = 4$	–576 001	9
$F_g = 2, F_e = 3$	–561 589	9
$F_g = 2, F_e = 2$	–550 112	9
$F_g = 2, F_e = 1$	–542 142	9
$F_g = 1, F_e = 3$	2 855 755	9
$F_g = 1, F_e = 2$	2 867 233	9
$F_g = 1, F_e = 1$	2 875 200	9

Ref. [74]

Table 35

$\lambda \approx 10.3$ µm; OsO_4					
Reference: R(12), OsO_4, CO_2, f = 29 096 274 952.34 kHz [2]					
$^{12}C^{16}O_2$	OsO_4 Line [Isotope]	$[f_{(P_n)}$ or $f_{(R_n)} - f_{(R_{12})}]$/kHz	u_c/kHz	$[f(OsO_4) - f(CO_2)]$/kHz	u_c/kHz
P(22)	P(74)A1(5) [192]	−844 345 436.65	0.09	−12 149.5	0.2
P(20)		−790 040 830.98	0.09	+9 229.6	0.2
P(18)		−736 516 128.03	0.08	−14 992	5
		−736 504 995.82	0.08	−3 855.2	0.1
	P(64)A1(2) [188]	−736 445 985.41	0.08	+5 515	5
	P(64)A1(2) [188]	−736 439 540.97	0.08	+61 594	5
P(16)		−683 728 418.00	0.08	−43 197	5
		−683 651 841.20	0.08	+33 384.6	0.1
P(14)		−631 598 013.29	0.08	+3 219.6	0.2
P(12)	P(39)A1(3) [192]	−580 222 963.99	0.08	+25 330.6	0.1
	P(39)A1(2) [192]	−580 222 506.81	0.08	+25 782	5
P(10)		−529 644 580.34	0.08	−18 821.1	0.1
P(8)	P(30)A1(1) [188]	−479 721 322.72	0.08	+11 864.7	0.1
P(6)		−430 592 349.89	0.08	−22 003	5
P(4)		−382 162 528.10	0.08	−25 299	5
		−382 155 194.99	0.08	−17 966	5
		−382 146 973.19	0.08	9 744	5
R(2)		−218 362 555.41	0.08	+9 955	5
R(4)		−173 244 278.93	0.08	−15 760	5
R(6)		−128 851 761.11	0.08	−33 873.0	0.1
R(8)		−85 158 088.16	0.08	−16 145	5
		−85 137 586	1	+4 368	1
		−85 115 539.96	0.08	+26 402	5
		−85 111 960.61	0.08	+29 982	5
	R(26)A1(0) [189]	−85 094 327.35	0.08	+47 615	5
		−85 094 189.27	0.08	+47 753	5
		−85 092 807.12	0.08	+49 135	5
		−85 092 705.66	0.08	+49 237	5
R(10)		−42 217 505.68	0.07	−15 252.7	0.6
R(12)		0		+558.1	0.1
R(14)		+41 472 081.08	0.08	+10 919.1	0.1
R(16)	R(49)A1(2) [187]	+82 193 963.38	0.08	+13 237.9	0.1
R(18)		+122 132 337.85	0.08	−23 400	5
		+122 175 077.75	0.08	+19 342.6	0.1
		+122 177 136.57	0.08	+21 398	5
R(20)	R(67) [192]	+161 358 870.72	0.08	−24 706.6	0.2
R(22)	R(73)A1(0) [192]	+199 854 633.12	0.08	−6 788	5
		+199 871 404.82	0.08	+9 986.0	0.2
R(24)		+237 601 310.30	0.09	+15 102.1	0.1
R(26)		+274 539 126.07	0.09	−15 542.5	0.1

Ref. [75-82]

Table 36

$\lambda \approx 576$ nm; $^{127}I_2$, transition 17–1, P(62)							
Reference: component a_1 (or o), f = 520 206 808.4 MHz [2]							
Component		$[f(a_n) - f(a_1)]$/MHz	u_c/MHz	Component		$[f(a_n) - f(a_1)]$/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_6	j	416.67	0.02	a_{15}	a	869.53	0.03

Ref. [83-84]

Bibliography

1 De Beauvoir B., Nez F., Julien L., Cagnac B., Biraben F, Touahri D., Hilico L., Acef O., Clairon A., Zondy J.-J., Absolute Frequency Measurement of the *2S–8S/D* Transitions in Hydrogen and Deuterium: New Determination of the Rydberg Constant, *Phys. Rev. Lett.*, 1997, **78**, No. 3, 440-443.

2 Recommendation M 1 (*BIPM Com. Cons. Déf. Mètre*, 9th meeting, 1997) adopted by the Comité International des Poids et Mesures at its 86th Meeting as Recommendation 1 (CI-1997).

3 Hackel L.A., Casleton K.H., Kukolich S.G., Ezekiel S., Observation of Magnetic Octupole and Scalar Spin-Spin Interactions in I_2 Using Laser Spectroscopy, *Phys. Rev. Lett.*, 1975, **35**, 568-571.

4 Camy G., *Thesis*, Université Paris-Nord, 1979.

5 Bordé C.J., Camy G., Decomps B., Descoubes J.-P., High Precision Saturation Spectroscopy of $^{127}I_2$ with Argon Lasers at 5145 Å and 5017 Å: Main Resonances, *J. Phys.*, 1981, **42**, 1393-1411.

6 Spieweck F., Gläser M., Foth H.J., Hyperfine Structure of the P(13), 43-0 Line of $^{127}I_2$ at 514.5 nm, European Conference on Atomic Physics, Apr. 6-10, 1981, Heidelberg. In *Europhysics Conference Abstracts*, **5A**, Part **I**, 325-326.

7 Spieweck F., *personal communication*.

8 Foth H.J., Spieweck F., Hyperfine Structure of the R(98), 58-1 Line of $^{127}I_2$ at 514.5 nm, *Chem. Phys. Lett.*, 1979, **65**, 347-352.

9 Ye J., Robertsson L., Picard S., Ma L.S., Hall J.L., Absolute Frequency Atlas of Molecular I_2 Lines at 532 nm, *IEEE Trans. Instrum. Meas.*, 1999, **48**, 544-549.

10 Macfarlane G.M., Barwood G.P., Rowley W.R.C., Gill P., Interferometric Frequency Measurements of an Iodine Stabilized Nd:YAG Laser, *IEEE Trans. Instrum. Meas.*, 1999, **48**, 600-603.

11 Arie A., Byer R.L., Laser Heterodyne Spectroscopy of $^{127}I_2$ Hyperfine Structure Near 532 nm, *J. Opt. Soc. Am. B,* 1993, **10**, 1990-1997 and errata.

12 Arie A., Byer R.L., The Hyperfine Structure of the $^{127}I_2$ P(119) 35-0 Transition, *Opt. Commun.*, 1994, **111**, 253-258 and errata.

13 Eickhoff M.L., *Thesis*, University of Colorado, 1994.

14 Jungner P., Eickhoff M.L., Swartz S.D., Ye Jun, Hall J.L., Waltman S., Stability and Absolute Frequency of Molecular Iodine Transitions Near 532 nm, *Laser Frequency Stabilization and Noise Reduction*, SPIE, 1995, **2378**, 22-34.

15 Eickhoff M.L., Hall J.L., Optical Frequency Standard at 532 nm, *IEEE Trans. Instrum. Meas.*, 1995, **44**, No. 2, 155-158.

16 Chartier J.-M., Hall J.L., Gläser M., Identification of the I_2-Saturated Absorption Lines Excited at 543 nm with the External Beam of the Green He-Ne Laser, *Proc. CPEM'86*, 1986, ISBN 86-CH2267-3, 323.

17 Gläser M., Hyperfine Components of Iodine for Optical Frequency Standards *PTB-Bericht*, 1987, **PTB-Opt-25**.

18 Chartier J.-M., Fredin-Picard S., Robertsson L., Frequency-Stabilized 543 nm He-Ne Laser Systems: a New Candidate for the Realization of the Metre ?, *Opt. Commun.*, 1989, **74**, 87-92.

19 Brand U., Ein iodstabilisiertes He-Ne Laser Wellenlägennormal grüner Strahlung, *PTB-Bericht*, 1991, **PTB-Opt-34**.

20 Simonsen H., Poulsen O., Frequency Stabilization of an Internal Mirror He-Ne Laser at 543.4 nm to I_2-Saturated Absorptions, *Appl. Phys. B*, 1990, **50**, 7-12.

21 Fredin-Picard S., Razet A., On the Hyperfine Structure of $^{127}I_2$ Lines at the 543 nm Wavelength of the He-Ne Laser, *Opt. Commun.*, 1990, **78**, 149-152.

22 Lin T., Liu Y.-W., Cheng W.-Y., Shy J.-T., Iodine-Stabilized 543 nm He-Ne Lasers, *Opt. Commun.*, 1994, **107**, 389-394.

23 Simonsen H.R., Brand U., Riehle F., International Comparison of Two Iodine-Stabilized He-Ne Lasers at $\lambda \approx 543$ nm, *Metrologia*, 1994/95, **31**, 341-347.

24 Razet A., Millerioux Y., Juncar P., Hyperfine Structure of the 47R(9-2), 48P(11-3) and 48R(15-5) Lines of $^{127}I_2$ at 612 nm as Secondary Standards of Optical Frequency, *Metrologia*, 1991, **28**, 309-316.

25 Cérez P., Bennett S.J., Helium-Neon Laser Stabilized by Saturated Absorption in Iodine at 612 nm, *Appl. Opt.*,1979, **18**, 1079-1083.

26 Gläser M., Properties of a He-Ne Laser at $\lambda \approx 612$ nm, Stabilized by Means of an External Iodine Absorption Cell, *IEEE Trans. Instrum. Meas.*, 1987, **IM-36**, 604-608.

27 Bertinetto F., Cordiale P., Fontana S., Picotto G.B., Recent Progresses in He-Ne Lasers Stabilized to $^{127}I_2$, *IEEE Trans. Instrum. Meas.*, 1985, **IM-34**, 256-261.

28 Bertinetto F., Cordiale P., Picotto G.B., Chartier J.-M., Felder R., Gläser M., Comparison Between the $^{127}I_2$-Stabilized He-Ne Lasers at 633 nm and at 612 nm of the BIPM and the IMGC, *IEEE Trans. Instrum. Meas.*, 1983, **IM-32**, 72-76.

29 Gläser M., Hyperfine Components of Iodine for Optical Frequency Standards, *PTB-Bericht*, 1987, **PTB-Opt-25.**

30 Dschao K., Gläser M., Helmcke J., I_2-Stabilized He-Ne Lasers at 612 nm, *IEEE Trans. Instrum. Meas.*, 1980, **IM-29**, 354-357.

31 Bertinetto F., *Personal communication*, poster presented at the CPEM'84, Delft, 1984.

32 Robertsson L., Iodine-stabilized He-Ne Lasers at $\lambda = 612$ nm Using Internal and External Cells, *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1992, **60**, 160-162 and Document CCDM/92-20*a* (BIPM).

33 Ciddor P.E., Brown N., Hyperfine Spectra in Iodine 129 at 612 nm, *Opt. Commun.*, 1980, **34**, 53-56.

34 Gläser M., Dschao K., Foth H.J., Hyperfine Structure and Fluorescence Analysis of Enriched $^{129}I_2$ at the 612 nm Wavelength of the He-Ne Laser, *Opt. Commun.*, 1981, **38**, 119-123.

35 Rowley W.R.C., Wallard A.J., Wavelength Values of the 633 nm Laser, Stabilized with $^{127}I_2$-Saturated Absorption, *J. Phys. E*, 1973, **6**, 647-651.

36 Hanes G.R., Baird K.M., De Remigis J., Stability, Reproducibility, and Absolute Wavelength of a 633 nm He-Ne Laser Stabilized to an Iodine Hyperfine Component, *Appl. Opt.,* 1973, **12**, 1600-1605.

37 Cérez P., Brillet A., Hartmann F., Metrological Properties of the R(127) Line of Iodine Studied by Laser Saturated Absorption, *IEEE Trans. Instrum. Meas*. 1974, **IM-23**, 526-528.

38 Bayer-Helms F., Chartier J.-M., Helmcke J., Wallard A.J., Evaluation of the International Intercomparison Measurements (March 1976) with $^{127}I_2$-Stabilized He-Ne Lasers, *PTB-Bericht*, 1977, **Me-17**, 139-146.

39 Bertinetto F., Rebaglia B.I., Performances of IMGC He-Ne ($^{127}I_2$) Lasers, *Euromeas'77,* IEEE, 1977, **152**, 38-39.

40 Tanaka K., Sakurai T., Kurosawa T., Frequency Stability and Reproducibility of an Iodine Stabilized He-Ne Laser, *Jap. J. Appl. Phys.*, 1977, **16**, 2071-2072.

41 Blabla J., Smydke J., Chartier J.-M., Gläser M., Comparison of the $^{127}I_2$-Stabilized He-Ne Lasers at 633 nm Wavelength of the Czechoslovak Institute of Metrology and the Bureau International des Poids et Mesures, *Metrologia*, 1983, **19**, 73-75 and Document CCDM/82-26.

42 Document CCDM/82-19*a* [Means of measurements made during the international comparisons between the BIPM and LHA, NPL, PTB, IMGC, INM, NBS, NIM, CSMU, 1974-1981].

43 Morinaga A., Tanaka K., Hyperfine Structure in the Electronic Spectrum of $^{127}I_2$ by Saturated Absorption Spectroscopy at 633 nm, *Appl. Phys. Lett.*, 1978, **32**, 114-116.

44 Blabla J., Bartôs M., Smydke J., Weber T., Hantke D., Phillip H., Sommer M., Tschirnich J., Frequency Intervals of HFS Components of an $^{127}I_2$-Stabilized He-Ne Laser at 633 nm Wavelength, *ASMW Metrologische Abhandlungen*, 1983, **3**, 4.

45 Chartier J.-M., Results of International Comparisons Using Methane-Stabilized He-Ne Lasers at 3.39 µm and Iodine Stabilized He-Ne Lasers at 633 nm, *IEEE Trans. Instrum. Meas.*, 1983, **IM-32**, 81-83.

46 Chartier J.-M., Robertsson L., Fredin-Picard S., Recent Activities at BIPM in the Field of Stabilized Lasers − Radiations Recommended for the Definition of the Meter, *IEEE Trans. Instrum. Meas.*, 1991, **40**, 181-184.

47 Petru F., Popela B., Vesela Z., Iodine Stabilized He-Ne Lasers at $\lambda = 633$ nm of a Compact Construction, *Metrologia*, 1992, **29**, 301-307.

48 Razet A., Gagnière J., Juncar P., Hyperfine Structure Analysis of the 33P(6-3) Line of $^{127}I_2$ at 633 nm Using a Continuous-Wave Tunable Dye Laser, *Metrologia*, 1993, **30**, 61-65.

[This paper gives $f_{b_{21}} - f_{a_{16}}$ (or f) = (−532.425 ± 0.015) MHz. Using the frequency difference $f_{a_{16}} - f_{a_{13}}$ = (138.892 ± 0.005) MHz (Table 22), one calculates: $f_{b_{21}} - f_{a_{13}}$ = (−393.533 ± 0.016) MHz.]

49 Hanes G.R., Lapierre J., Bunker P.R., Schotton K.C., Nuclear Hyperfine Structure in the Electronic Spectrum of $^{127}I_2$ by Saturated Absorption Spectroscopy, and Comparison with Theory, *J. Mol. Spectrosc.*, 1971, **39**, 506-515.

50 Bergquist J.C., Daniel H.U., A Wideband Frequency-Offset Locked Dye Laser Spectrometer Using a Schottky Barrier Mixer, *Opt. Commun.*, 1984, **48**, 327-333.

51 Simonsen H.R., Iodine-Stabilized Extended Cavity Diode Laser at $\lambda \approx$ 633 nm, *IEEE Trans. Instrum. Meas.*, 1997, **46**, 141-144.

52 Edwards C.S., Barwood G.P., Gill P., Rowley W.R.C., A 633 nm Iodine-Stabilized Diode Laser Frequency Standard, *Metrologia*, 1999, **36,** to be published.

53 Millerioux Y., Wallerand J.P., Chagniot D., Zarka A., Chartier J.-M., Measurement and Analysis of the Hyperfine Structure of 6-3, P(33) Transition [Measurements made at the BIPM, not yet published].

54 Rowley W.R.C., Document CCDM/82-2 [Measurements made at $t(^{129}I_2) = t(^{127}I_2)$ = 8 °C)].

55 Chartier J.-M., Détermination et reproductibilité de l'intervalle de fréquence ($^{129}I_2$, k) – ($^{127}I_2$, i), *Rapport BIPM*-82/10 [Measurements made at $t(^{129}I_2) = t(^{127}I_2)$ = 8 °C].

56 Chartier J.-M., Lasers à He-Ne asservis sur l'absorption saturée de l'iode en cuve interne à λ = 633 nm, *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1984, **52**, 44.

57 Gerlach R.W., *Thesis*, University Cleveland, 1975.

58 Knox J.D., Yoh-Han Pao, High-Resolution Saturation Spectra of the Iodine Isotope $^{129}I_2$ in the 633 nm Wavelength Region, *Appl. Phys. Lett.*, 1971, **18**, 360-362.

59 Tesic M., Yoh-Han Pao, Theoretical Assignment of the Observed Hyperfine Structure in the Saturated Absorption Spectra of $^{129}I_2$ and $^{127}I^{129}I$ Vapors in the 633 nm Wavelength Region, *J. Mol. Spectrosc.*, 1975, **57**, 75-96.

60 Magyar J.A., Brown N., High Resolution Saturated Absorption Spectra of Iodine Molecules $^{129}I_2$, $^{129}I^{127}I$, and $^{127}I_2$ at 633 nm, *Metrologia*, 1980, **16**, 63-68.

61 Chartier J.-M., Mesures d'intervalles entre composantes hyperfines de I_2, *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1978, **46**, 32-33.

62 Chartier J.-M., Mesures d'intervalles de fréquence entre composantes hyperfines des transitions 8-4, P(54) ; 12-6, P(69) ; 6-3, P(33) de $^{129}I_2$ et 6-3, P(33) de $^{127}I^{129}I$, *Rapport BIPM*-93/3 and Document CCDM/92-20*a* (BIPM).

63 Schweitzer W.G. Jr, Kessler E.G. Jr, Deslattes R.D., Layer H.P., Whetstone J.R., Description, Performances, and Wavelengths of Iodine Stabilized Lasers, *Appl. Opt.*, 1973, **12**, 2927-2938.

64 Helmcke J., Bayer-Helms F., He-Ne Laser Stabilized by Saturated Absorption in I_2, *IEEE Trans. Instrum. Meas.*, 1974, **IM-23**, 529-531 [Measurements reduced to $t(^{129}I_2) = t(^{127}I_2) = 2$ °C].

65 Chartier J.-M., Lasers à He-Ne asservis sur l'absorption saturée de l'iode en cuve interne ($\lambda = 633$ nm), *BIPM Proc.-Verb. Com. Int. Poids et Mesures*, 1985, **53**, 50.

66 Bennett S.J., Cérez P., Hyperfine Structure in Iodine at the 612 nm and 640 nm Helium-Neon Wavelengths, *Opt. Commun.*, 1978, **25**, 343-347.

67 Dschao K., Jie X., Chen-Yang L., Han-Tian L., Hyperfine Structure in Iodine Observed at the 612 nm and 640 nm ^3He-^{22}Ne Laser Wavelengths, *Acta Metrologica Sinica*, 1982, **3**, 322-323 and Document CCDM/92-10-2*a* (NIM).

68 Zhao K., Hua L., Hyperfine Structure of Iodine at 640 nm ^3He-^{22}Ne Laser Wavelength and Identification, *Acta Metrologica Sinica*, 1983, **3**, 673-677 and Document CCDM/92-10-2*d* (NIM).

69 Bennett S.J., Mills-Baker P., He-Ne Stabilized 640 nm Helium-neon, *Opt. Commun.* 1984, **51**, 322-324.

70 Zhao K.G., Blabla J., Helmcke J., $^{127}I_2$-Stabilized ^3He-^{22}Ne Laser at 640 nm Wavelength, *IEEE Trans. Instrum. Meas.*, 1985, **IM-34**, 252-256 and Documents CCDM/92-10*a* and 10-2*c* (NIM).

71 Zhao K., Hua L., Analysis and Calculation of Hyperfine Lines of Iodine Molecule, *Acta Metrologica Sinica*, 1985, **6**, 83-88 and Document CCDM/92-10-2*c* (NIM).

72 Gläser M., Identification of Hyperfine Structure Components of Iodine Molecule at 640 nm Wavelength, *Opt. Commun.*, 1985, **54**, 335-342.

73 Zhao K., Cheng-Yang L., Hua L., Jie X., He W., Investigations of $^{127}I_2$-Stabilized He-Ne Laser at 640 nm, *Acta Metrologica Sinica*, 1987, **8**, 88-95 and Document CCDM/92-10-2*f* (NIM).

74 Nez F., Biraben F., Felder R., Millerioux Y., Optical Frequency Determination of the Hyperfine Components of the $5S_{1/2}$-$5D_{3/2}$ Two Photon Transitions in Rubidium, *Opt. Commun*., 1993, **102**, 432-438.

75 Clairon A., Van Lerberghe A., Salomon C., Ouhayoun M., Bordé Ch.J., Towards a New Absolute Frequency Reference Grid in the 28 THz Range, *Opt. Commun*., 1980, **35**, 368-372.

76 Clairon A., Van Lerberghe A., Bréant Ch., Salomon Ch., Camy G., Bordé Ch.J., A New Absolute Frequency Reference Grid in the 28 THz Range: Troisième symposium sur les étalons de fréquence et la métrologie (Aussois, 1981), *J. Phys.* (Paris), Colloque C8, Suppl. to No. 12, **42**, C8 127-135.

77 Chardonnet Ch., Van Lerberghe A., Bordé Ch.J., Absolute Frequency Determination of Super-Narrow CO_2 Saturation Peaks Observed in an External Absorption Cell, *Opt. Commun.*, 1986, **58**, 333-337.

78 Clairon A., Acef O., Chardonnet Ch., Bordé Ch.J., State of the Art for High Accuracy Frequency Standards in the 28 THz Range Using Saturated Absorption Resonances of OsO_4 and CO_2, *Frequency Standards and Metrology: Proceedings*, De Marchi A. ed., Springer-Verlag, 1989, 212-221.

79 Chardonnet Ch., Bordé CH.J., Hyperfine Interactions in the ν_3 Band of Osmium Tetroxide: Accurate Determination of the Spin-Rotation Constant by Crossover Resonance Spectroscopy, *J. Mol. Spectrosc.*, 1994, **167,** 71-98.

This paper gives also absolute frequencies of assigned $Os^{16}O_4$ lines belonging to the ν_3 band.

80 Bernard V., Nogues G., Daussy Ch., Constantin L., Chardonnet Ch., CO_2 Laser Stabilized on Narrow Saturated Absorption Resonances of CO_2; Improved Absolute Frequency Measurements, *Metrologia*, 1997, **34**, 313-318.

81 Frech B., Constantin L.F., Amy-Klein A., Phavorin O., Daussy C., Chardonnet Ch., Mürtz M., Frequency Measurements of Saturated-fluorescence-stabilized CO_2 Laser Lines: Comparison with an OsO_4-stabilized CO_2 Laser Standard, *Appl. Phys. B*, 1998, **67**, 217-221.

82 Acef O., Michaud F., Rovera G.D., Accurate Determination of OsO_4 Absolute Frequency Grid at 28/29 THz, *IEEE Trans. Instrum. Meas.*, 1999, **48**, 567-570.

83 Baird K.M., Evenson K.M., Hanes G.R., Jennings D.A., Petersen F.R., Extension of Absolute Frequency Measurements to the Visible: Frequency of Ten Hyperfine Components of Iodine, *Opt. Lett.*, 1979, **4**, 263-264.

84 Barwood G.P., Rowley W.R.C., Characteristics of a $^{127}I_2$-Stabilized Dye Laser at 576 nm, *Metrologia*, 1984, **20**, 19-23.

LIST OF ACRONYMS
USED IN THE PRESENT VOLUME

1 Acronyms for laboratories, committees and conferences

BIPM	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, see CCL
CCDS*	Consultative Committee for the Definition of the Second, see CCTF
CCL	(formerly the CCDM) Consultative Committee for Length
CCTF	(formerly the CCDS) Consultative Committee for Time and Frequency
CENAM	Centro Nacional de Metrologia, Mexico (Mexico)
CGPM	Conférence Générale des Poids et Mesures
CIPM	Comité International des Poids et Mesures
CMI	Český Metrologický Institut/Czech Metrological Institute, Prague and Brno (Czech Rep.)
CPEM	Conference on Precision Electromagnetic Measurements
CSELT	Centro Studi e Laboratori Telecomunicazioni, Turin (Italy)
CSIR-NML	Council for Scientific and Industrial Research, National Metrology Laboratory, Pretoria (South Africa)
CSIRO-NML	Commonwealth Scientific and Industrial Research Organization, National Measurement Laboratory, Lindfield (Australia)
CSMU*	Československý Metrologický Ústav, Bratislava and Prague (former Czechoslovakia), see SMU
ETCA	Établissement Technique Central de l'Armement, Arcueil (France)
EUROMET	European Collaboration in Measurement Standards

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

IEEE	Institute of Electrical and Electronics Engineers, Piscataway NJ (United States)
IMGC	Istituto di Metrologia G. Colonnetti, Turin (Italy)
INM*	Institut National de Métrologie, Paris (France), see BNM-INM
INMETRO	Instituto Nacional de Metrologia, Normalizaçao e Qualidade Industrial, Rio de Janeiro (Brazil)
IPL	Institute of Laser Physics, Novosibirsk (Russian Fed.)
ISO	International Organization for Standardization
JILA	Joint Institute for Laboratory Astrophysics, Boulder CO (United States)
KRISS	Korea Research Institute of Standards and Science, Taejon (Rep. of Korea)
LENS	European Laboratory for Nonlinear Spectroscopy, Firenze (Italy)
LPTF*	Laboratoire Primaire du Temps et des Fréquences, Paris (France), see BNM-LPTF
MPQ	Max Planck Institut für Quantenoptik, Garching (Germany)
NBS*	National Bureau of Standards, Gaithersburg MD (United States), see NIST
NIM	National Institute of Metrology, Beijing (China)
NIST	(formerly the NBS) National Institute of Standards and Technology, Gaithersburg MD (United States)
NMi-VSL	Nederlands Meetinstituut, Van Swinden Laboratorium, Delft (The Netherlands)
NML	see CSIR
NML	see CSIRO
NPL	National Physical Laboratory, Teddington (United Kingdom)
NRC	National Research Council of Canada, Ottawa (Canada)
NRLM	National Research Laboratory of Metrology, Tsukuba (Japan)
OFMET	Office Fédéral de Métrologie/Eidgenössisches Amt für Messwesen, Wabern (Switzerland)
PTB	Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin (Germany)
SMU	(formerly the CSMU) Slovenský Metrologický Ústav/ Slovak Institute of Metrology, Bratislava (Slovakia)

VNIIFTRI	All-Russian Research Institute for Physical, Technical and Radiophysical Measurements, Moscow (Russian Fed.)
VNIIM	D.I. Mendeleyev Institute for Metrology, St Petersburg (Russian Fed.)
WGDM	Working group on dimensional metrology

2 Acronyms for scientific terms

CMM	Coordinate Measuring Machine
SI	International System of Units