CCM – IAG Strategy for Metrology in Absolute Gravimetry: Role of CCM and IAG

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1 Introduction

The President of the Consultative Committee for Mass and related quantities (CCM)[1] and the President of the International Association of Geodesy (IAG)[2] Commission 2 «Gravity Field»[3] met on March 21, 2013 with the objective to better coordinate the work at the level of both organizations. It was decided to prepare a common strategic document to be used by their respective Working Groups (WG), Sub-commission (SC) and Joint Working Groups (JWG) to clarify future activities and to develop an action plan.

The main objective is to define and to harmonize the activities in order to ensure traceability to the SI[4] for gravity measurements at the highest level for metrology and geodesy within the framework of the CIPM[5] Mutual Recognition Arrangement (CIPM MRA[6]).

2 General principles

2.1 Vision

The CCM and IAG want to ensure scientific excellence and measurement of the gravity acceleration traceable to the SI at the level of uncertainty of few microgals (1 µGal = 1 x 10^{-8} m/s^2) or better according to the principles of the CIPM MRA, for metrology (in particular for the realization of the new definition of the kilogram) and geodetic science (in particular for time variable gravity and gravity networks). The present strategy shall support

[1] http://www.bipm.org/en/committees/cc/ccm/
[2] http://www.iag-aig.org/
[3] http://www.iag-aig.org/index.php?tpl=text&id_c=7&id_t=553
[4] http://www.bipm.org/en/si/
[5] http://www.bipm.org/en/committees/cipm/
[6] http://www.bipm.org/en/cipm-mra/

the Global Geodetic Observing System (GGOS)[7], International Gravity Field Service (IGFS)[8], IAG Commission 2 "Gravity Field" and CCM activities.

2.2 Role and mission of CCM

In addition to all matters related to the comparisons of mass standards with the international prototype of the kilogram and the considerations that affect the definition and realization of the unit of mass, the **CCM is responsible for the establishment of international equivalence between national laboratories** for mass and a number of related quantities, such as gravity acceleration, and advises the CIPM on these matters.

Briefly: realization and dissemination (at the highest accuracy level) of the unit and international equivalence of primary standards validated through appropriate comparisons.

2.3 Role and mission of IAG Commission 2, IGFS and GGOS

The main role of IAG Commission 2 "Gravity Field" is the **accurate determination of the gravity field** and its temporal variations promoting, supporting and stimulating the advancement of knowledge, technology and international cooperation in the geodetic domain associated with Earth's gravity field.

The main goal of IGFS is to coordinate the servicing of the geodetic and geophysical community with gravity data, software and information.

The main goal of GGOS is to work with the IAG components to provide the geodetic infrastructures necessary for monitoring the Earth system and for global change research.

Briefly: practical application of gravity measurements in compliance with the IERS conventions[9] for the accurate determination of the gravity field in geodesy.

2.4 Level of collaboration

The scopes of CCM and IAG in the field of absolute gravimetry are complementary. The objective of this strategy is to harmonize the activities.
The CCM provides traceability to the SI for gravimetry. IAG represents one of the main stakeholders and user community in the field of gravimetry. The second main stakeholder is the metrology community.

Finally, mutual sharing of information is ensured through regular meetings at the management level between the CCM President and the President of IAG Commission 2. The technical contact at the operational level is established by systematically inviting observers from the other community to the working group meetings as well as by contact between the chairperson of the CCM WGG (see §3.1) and the chairperson of the IAG SC 2.1 (see §3.2).

3 Terms of Reference

3.1 CCM WGG

The Terms of Reference of the CCM Working Group on Gravimetry (WGG)[10] are:

- to propose key comparisons to the CCM;
- to maintain contact to international organizations and stakeholders active in absolute gravimetry;
- to support stakeholders to ensure and promote the traceability of gravity measurement to the SI;
- to follow the main research activities in absolute gravimetry.

[7] http://www.ggos.org/
[8] http://www.igfs.net/
[9] http://www.iers.org/nn_11216/SharedDocs/Publikationen/EN/IERS/Publications/tn/TechnNote36/tn36,templateId=raw,property=publicationFile.pdf/tn36.pdf
[10] http://www.bipm.org/en/committees/cc/ccm/working_groups.html#wgg

Remark: The main objective is the establishment of equivalence for absolute gravimeters belonging to National Metrology Institutes (NMIs) or Designated Institutes (DIs) in full accordance with the rules of the CIPM MRA.
Correct traceability according to the CIPM MRA ensures equivalent measurement results necessary for applications in metrology and geodesy.

3.2 IAG Sub-Commission 2.1

The main objective of the IAG SC 2.1 “Gravimetry and gravity networks”[11] is to promote scientific studies of methods and instruments for terrestrial, airborne, shipborne and satellite gravity measurement and establishment of gravity networks.

The Joint Working Group 2.1[12] (Techniques and Metrology in Absolute Gravimetry) can support the CCM WGG for the organisation of Key Comparisons (KC) (see §4.1.1, §4.1.2 and §4.1.3) and can organise additional comparisons (see §4.1.4) as defined by the geodetic needs.

The Joint Working Group 2.2[13] (Absolute Gravimetry and Absolute Gravity Reference System) makes use of all comparison data available to ensure traceable gravity values and maintains stable reference gravity stations for the practical work in geodesy.

4 The traceability chain in gravimetry

There are two distinct traceability paths for the measurements performed by absolute gravimeters:

A) Independent traceability to the SI units of time and frequency.
B) Calibration by comparison (against a reference).

Some schematic traceability chains are given in Fig. 1.

4.1 Independent traceability to the SI units of time and frequency

The absolute gravimeter has independent traceability to the SI unit of time (frequency) through the calibration of the frequencies of the laser and reference clock.

The uncertainty of the absolute gravimeter (Calibration Measurement Capability - CMC) is calculated combining the contributions of uncertainty associated with these references, together with all other contributions of uncertainty.

It is necessary also to perform comparisons between the absolute gravimeter and an appropriate reference in order to validate the associated uncertainty. References are absolute gravimeters as primary standards maintained by NMIs or DIs with declared Calibration Measurement Capabilities (CMCs)[14] in the CIPM MRA or a gravity value of a reference station characterized with the highest accuracy (see §4.2). The results need to be analysed as a comparison rather than a calibration. The analysis just needs to demonstrate whether or not the results are metrologically equivalent[15,16].

Absolute gravimeters of NMIs or DIs, recognized as primary standards, that have CMCs declared in the CIPM MRA shall participate in Key Comparisons (KC) in order to confirm their CMCs.

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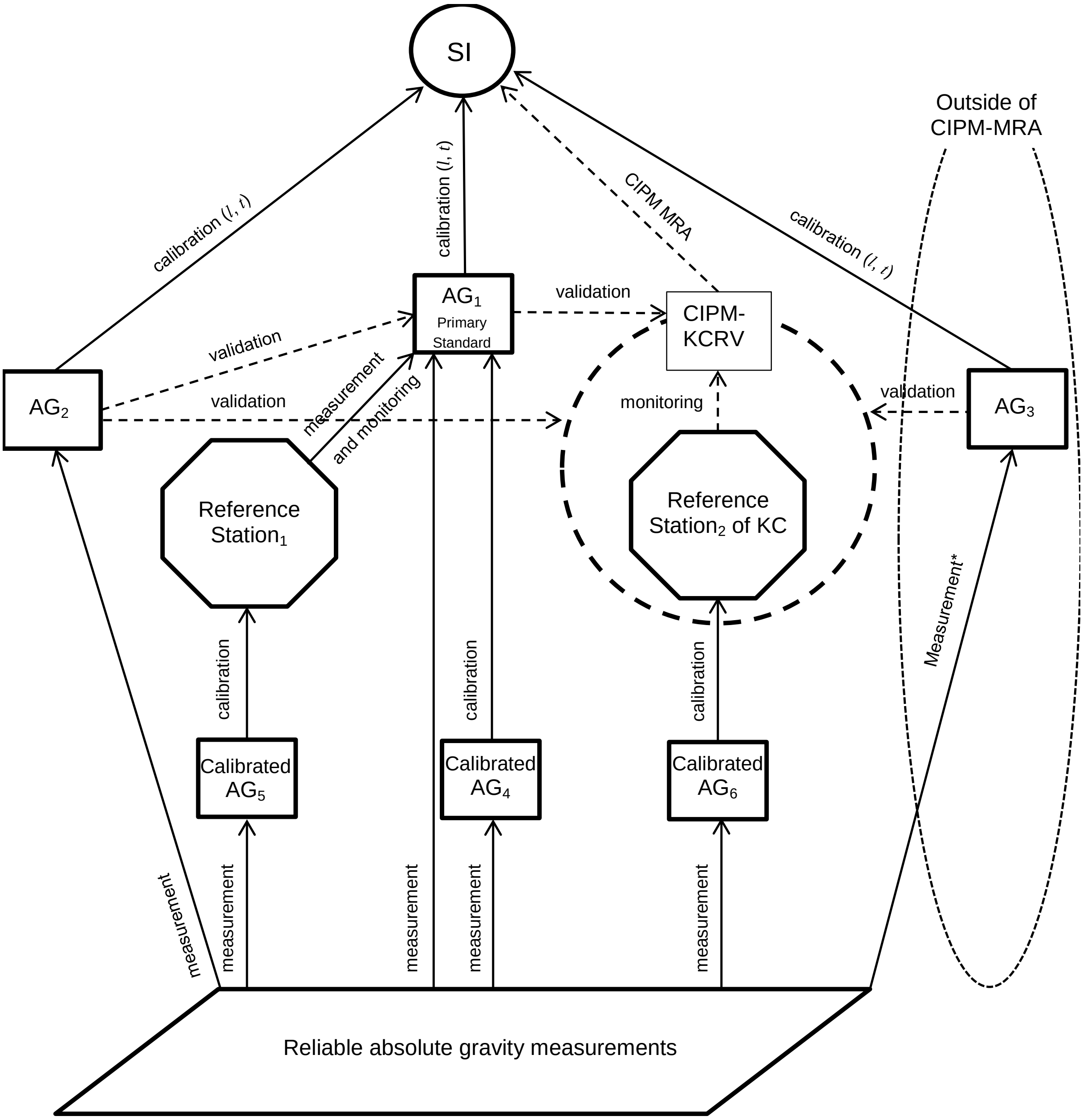
[11] http://www.iag-commission2.ch/SC21.pdf
[12] http://www.iag-commission2.ch/WG21.pdf
[13] http://www.iag-commission2.ch/WG22.pdf
[14] http://kcdb.bipm.org/AppendixC/default.asp
[15] K Beissner, 2002, Metrologia 39, 59. *On a measure of consistency in comparison measurements*
[16] A G Steele and R J Douglas, 2006, Metrologia 43, S235. *Extending E_n for measurement science*



AG_1:	Absolute Gravimeter (Primary Standard) with independent traceability to SI units (through calibration of laser and clock) (§4.1) validated with the KCRV of a KC (§4.1.1 - §4.1.3).
AG_2:	Absolute Gravimeter with independent traceability to SI units (§4.1) validated in comparison with a Primary Standard Absolute Gravimeter or with the CIPM-KCRV (§4.1.1 - §4.1.3).
AG_3:	Absolute Gravimeter with independent traceability to SI units (§4.1) validated with KCRV of an additional comparison outside the scope of CIPM MRA (§4.1.4).
AG_4:	Absolute Gravimeter calibrated against a reference gravimeter (AG_1) (§4.2.1).
AG_5:	Absolute Gravimeter calibrated against a gravity value of the Reference $Station_1$ (measured by AG_1 and carefully monitored) (§4.2.2).
AG_6:	Absolute Gravimeter calibrated against a gravity value of a Reference $Station_2$ (measured during a KC and carefully monitored) (§4.2.2).

Measurement In this case, measurements carried out by AG_3 cannot establish any measurement certificate for ensuring the traceability to the SI.*

Figure 1: Scheme of the traceability chain in gravimetry, according to §§4.1 – 4.2.

4.1.1 CIPM Key Comparisons (CIPM KC)

The main objective of a CIPM key comparison[17] is the **validation,** at the CIPM level, of the declared CMCs published in the Key Comparison Database (KCDB)[18] of the BIPM[19]. These comparisons serve as a technical basis for the CIPM MRA. See also Fig. 2 (CIPM KC).

Periodicity: according to the CCM strategy.

Responsibility[20]: CCM (approval) and the pilot laboratory (organization).

Participants: NMIs and DIs listed in Appendix A of the CIPM MRA, with preference given to NMIs and DIs of States Parties of the Metre Convention. If the total number of participants is limited for technical or budget reasons[21], participants are selected among CCM members preferably with declared CMCs and other WGG members in order to represent all regions and independent techniques.

Terminology: CCM.G-K1, CCM.G-K2,[21]

Remark: the terminology "International comparison of absolute gravimeters" (ICAG) related to the comparison system established before the CIPM MRA is replaced by the CIPM terminology for KCs.

4.1.2 Regional Key comparisons (RMO KC)

The main objective of a regional key comparison is the **validation** of the CMCs published in the KCDB of the BIPM through links to the CIPM KC. This is especially important for participants who could not be accommodated in the CIPM KC.

The RMO KCs must be linked to the corresponding CIPM key comparisons by means of common participants. This is mandatory to demonstrate global equivalence. To achieve this, it is recommended that at least two of the participants in the preceding CIPM KC participate also in the RMO KC[21]. See also Fig. 2 (RMO KC). Therefore the RMO must adopt essentially the same protocol as the CIPM KC and must consider carefully how to link their results to the CIPM KC[21].

Periodicity: subsequent to CIPM KCs.

Responsibility: The RMO, the CCM (approval) and the pilot laboratory (organization).

Participants: NMIs and DIs of the Regional Metrology Organizations (RMO)[21].

Terminology: EURAMET.M.G-K1, APMP.M.G-S1,[21]

Remark: the terminology Regional comparison of absolute gravimeters (RCAG) related to the comparison system before the CIPM MRA is replaced by the CIPM terminology for KCs.

4.1.3 Subsequent bilateral key comparisons

The main objective of a bilateral key comparison is the **validation** of the declared CMCs published in the KCDB of the BIPM through links to the CIPM KC or RMO KC. These comparisons serve as a technical basis for the CIPM MRA. See also Fig. 2 (Bilateral KC)

Periodicity: on demand of a participant.

Responsibility: CCM (approval) and the pilot laboratory (organization).

Participants: two, one of them shall have participated in the preceding CIPM or RMO KC.

Terminology: The results of subsequent key comparisons may be assigned by a separate identifier. This identifier will usually be the name of the previous comparison plus a suffix[22].

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[17] http://www.bipm.org/en/cipm-mra/key_comparisons/
[18] http://kcdb.bipm.org/AppendixB/KCDB_ApB_search.asp
[19] http://www.bipm.org/
[20] CIPM MRA-D-05. *Measurement comparisons in the CIPM MRA*, Version 1.4. (http://www.bipm.org/utils/common/CIPM_MRA/CIPM_MRA-D-05.pdf) and Technical supplement to the arrangement (CIPM revision 2003) (http://www.bipm.org/utils/en/pdf/mra_techsuppl2003.pdf)
[21] http://kcdb.bipm.org/appendixB/KCDB_ApB_search_result.asp?search=1&met_idy=6&bra_idy=50&cmt_idy=0&ett_idy_org=0&epo_idy=0&cou_cod=0
[22] Bilateral Key Comparisons are no longer assigned the special identifier “BK” for registration in the KCDB. This allows potential additional participants to join in the comparison without the need to modify the identifier.

The approval process for CIPM KCs carried out within the CCM and subsequent RMO KCs is described in CCM Guidelines[23].

4.1.4 Additional comparisons

Additional comparisons outside the scope of the CIPM MRA could be organized by anyone at any time; the participation is open.

In order to guarantee traceability to the SI, the additional comparison must be linked to the corresponding CIPM or RMO KC by means of joint participants. This is mandatory to demonstrate global equivalence. To achieve this, it is recommended that at least two of the participants in the preceding CIPM or RMO KC participate also in the additional comparison. See also Fig. 2 (additional comparison).

Additional comparisons could be organized simultaneously with CIPM or RMO KCs if the pilot laboratory agrees. In this case, the results of the participants outside the CIPM MRA are not included in the final KC report. A separate report should be established and put into the IAG-AGrav database[24].

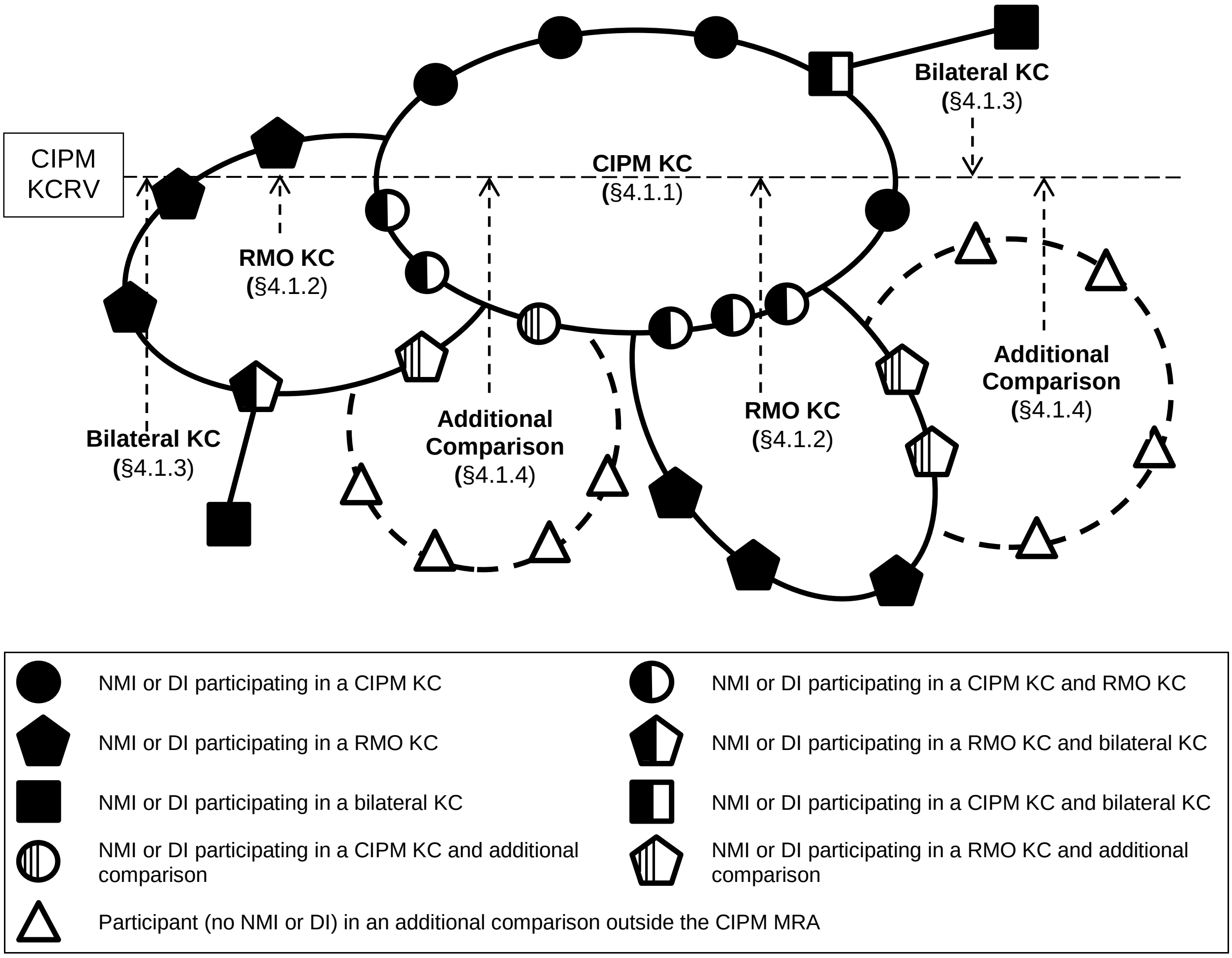

Figure 2: Scheme of some example of structure for Key Comparisons and other comparisons, according to §§4.1.1 - 4.1.4. To be noted that all comparisons have the same reference value, that is the CIPM-KCRV (through the links between comparisons).

[23] http://www.bipm.org/utils/en/pdf/CCM_Guidelines_on_Final_Reports.pdf

[24] http://agrav.bkg.bund.de/agrav-meta/ and http://bgi.omp.obs-mip.fr/data-products/Gravity-Databases/Absolute-Gravity-data

4.2 Calibration by the comparison

The absolute gravimeter derives its traceability directly from a comparison with the gravimeter of a NMI or a DI having declared CMCs in the CIPM MRA or using a gravity value of a reference station (characterized and monitored by appropriate methods).

The recommended method to determine the uncertainty of the calibrated absolute gravimeter includes, in this case, the corresponding contributions of uncertainty[25] and the bias[26] obtained in the comparison.

4.2.1 Comparison against a reference gravimeter

It is a typical calibration where the Device-Under-Test (DUT) is compared to the reference instrument. In our case, the DUT is the absolute gravimeter of a customer and the reference instrument (absolute gravimeter as primary national standard) of a NMI or a DI with declared CMCs.

4.2.2 Comparison against a gravity value of a reference station

The DUT is calibrated using the value of a reference station that has been characterized with the highest accuracy (for example during a KC) and that is carefully monitored since then (for example with combined measurements of absolute and superconducting gravimeter). In this case, the uncertainty of the DUT has to include also the uncertainty of estimated gravity variations at a reference station.

4.3 Measurement certificate for the characterization of a gravity site

The need of traceability to the SI for gravity measurement in metrology, geodesy etc. is defined by the customer and is closely related to its scientific objectives and to quality management. If traceability to the SI is needed, NMIs or DIs, as well an accredited laboratory in this field, with declared CMCs can measure gravity acceleration at a specified station and establish a measurement certificate.

4.4 Summary

<table>
<tr><th>Reference to section</th><th>Method</th><th>Report</th><th>Procedure</th></tr>
<tr><td>4.1</td><td>Independent traceability to the SI units of time and frequency</td><td></td><td rowspan="5">Validation</td></tr>
<tr><td>4.1.1</td><td>CIPM key comparison</td><td rowspan="3">Final report into KCDB</td></tr>
<tr><td>4.1.2</td><td>Regional key comparison</td></tr>
<tr><td>4.1.3</td><td>Bilateral key comparison</td></tr>
<tr><td>4.1.4</td><td>Additional comparisons linked to CIPM MRA</td><td>Final report into IAG AGrav DB</td></tr>
<tr><td>4.2</td><td>Calibration by the comparison (against a reference)</td><td></td><td rowspan="3">Calibration of a DUT</td></tr>
<tr><td>4.2.1</td><td>Comparison against a reference gravimeter</td><td>Calibration certificate</td></tr>
<tr><td>4.2.2</td><td>Comparison against a gravity value of a reference station</td><td>Calibration certificate</td></tr>
<tr><td>4.3</td><td>Measurement certificate for the characterization of a gravity site</td><td>Measurement certificate</td><td>Measurement</td></tr>
</table>

5 Scheduling of comparisons

The equivalence of results within the declared CMCs must be guaranteed according to the following typical scheduling:

[25] uncertainty of the primary standard, method of calibration, etc..

[26] JCGM 200:2012. *International Vocabulary of Metrology – Basic and General Concepts and Associated Terms.* http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf

Year 1	CIPM KC (according to section 4.1.1)
Year 1 + *x*	RMO KCs (according to section 4.1.2)
Year 1 + *y*	Next CIPM KC

The periodicity *x* is defined by the RMOs based on a recommendation of the RMO TC and the periodicity *y* is defined by the CCM on the recommendation of the CCM WGG.

Traceability to the SI according to the routes defined in §§4.1, 4.2 and 4.3 can be performed at any time according to the specific needs of the customers (for example for the validation of the instrument stability).

6 Common action plan

6.1 Short term

6.1.1 IAG

- Align the Terms of Reference of the Commission 2, its SC and JWGs with the present document.
- This document will be published in the appropriate websites and publications
- The CCM – IAG Strategy for gravimetry shall be presented at the next possible occasions (IAG meetings and conferences).
- IAG encourages stakeholders in geodesy community to intensify cooperation with their NMIs to reach the status of DIs.

6.1.2 CCM

- This document will be published in the CCM WGG website (open access).
- CCM encourages NMIs to intensify cooperation with stakeholders in geodesy community in order to be designated as DIs.
- CCM encourages the NMIs and DIs to increase the number of declared CMCs in gravimetry (presently only four). It is highly desirable that a minimum number of 8 NMIs or DIs have declared CMC before the end of 2014.
- CCM encourages to reduce the declared measurement uncertainty (according to the GUM[27]) of the majority of CMC entries according to the state of art (5 µGal or below).
- The CCM – IAG Strategy for gravimetry will be presented at the next possible occasions (KCs, CCM WGG meetings, and conferences).

6.2 Medium term (IAG and CCM)

- Plan future KCs and other comparisons according to the principles and responsibilities described in this document in order to efficiently fulfill the need of both metrology and geodesy.

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[27] JCGM 100:2008 *Evaluation of measurement data – Guide to the expression of uncertainty in measurement.* http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf