Consultative Committee for Length – CCL

WORKING GROUP ON FREQUENCY STANDARDS - WGFS

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CMCs on frequency stabilized lasers – Guidelines

1 Scope

This document provides guidance on CMCs of the category "*frequency stabilized lasers*". It is intended for:

- NMIs with this CMC already approved, to decide whether it covers a requested calibration;
- applicant NMIs, to help in their applications of CMCs;
- CMC reviewers, to promote approval/disapproval in a consistent way worldwide.

2 Background

This document is designed to provide a technical basis for the review of CMCs in the field of optical frequency/ wavelength calibrations as far as CCL is concerned. Specifically, the service category 1.1.1 from the CMC classification scheme for length services, generally referred to as the DimVIM [1], is its topic. The category 1.1.1 deals with "frequency stabilized laser" as instruments and "vacuum wavelength; optical frequency" as the measurand. The applied calibration technique or maximum uncertainty is not regulated however.

Whereas in most calibrations services covered by CCL, the uncertainty claims of most NMI´s are quite homogeneous, this is not the case for service category 1.1.1. The scope of this category is deliberately rather broad. It is applicable for calibration of client's lasers at the 10^{-8} level but also to more demanding work with 10^{-13} relative uncertainty. Historically this category included (and still does so) the physical standards (MeP lasers [2], [3], [4]) used to perform a calibration. Consequently quite variable CMC entries ranging over many orders of magnitude are published in the KCDB [5] for this service. This originates partly from quite different calibration techniques and instruments, but also from misinterpretations.

Today the majority of NMIs operate iodine stabilized He-Ne laser as published in the MeP [2], [3] as the national standard for length. The actual calibration is performed by a heterodyne (or beat) measurement with the laser under test. Typically the measurement uncertainty of this technique is governed by the stability of the laser under test, whereas the uncertainty contribution from the beat measurement is often negligible small.

It is this fact which justifies claiming a CMC uncertainty which is equal to the standard laser uncertainty for this calibration technique. One must note that this simplification holds for the discussed example only, it can not be extrapolated for the high precision measurements discussed in the following.

To review a "traditional" CMC claim as discussed above, an artefact based comparison is perfectly adequate and the method of choice. The key comparison CCL-K11 [6] was introduced precisely for this reason in 2008. But being designed as an artefact-based comparison, CCL-K11 is not adequate to support all CMC claims under service category 1.1.1. NMIs interested in obtaining evidence for such services must find ways which are beyond artefact based comparisons. Some possibilities recognized by WGFS and CCL are presented in this document.

The possibility to claim low calibration uncertainties is vital (but not restricted to) for the so-called node laboratories of the CCL-K11 [6].

3 Types of Service

For a calibration service covered by category covered under 1.1.1 of the DimVIM, the measurand is well defined. Often the "Instrument Type or Method" dictates the actual "Measurand Level or Range" for this service and therefore requires separate CMC entries. To ease the approval process, a classification schema imposed on wavelength range, intended measurement uncertainty and method used is presented in this document.

For the time being, NMIs can provide laser optical frequency/vacuum wavelength calibration by two routes[1]: either by heterodyne beat frequency measurement against an optical frequency comb (formerly known as method b of [2])[2] or by beat frequency measurement against a stabilized laser from the list of recommended radiations for the realisation of the metre and other optical frequency standards (formerly known as method c). By using a frequency comb one can in principle calibrate devices under test operating in a wide wavelength range. In the second case one is restricted to a very narrow wavelength range near the standard's wavelength.

The optical frequency comb itself can be referenced to microwave time and frequency standards (RF, the common way) or to an optical frequency standard (currently not used as a standard service). In any case the comb provides a link between the optical frequency domain and the NMI's realisation of the SI second.

When performing a beat frequency measurement against a standard, the traceability chain either ends at this laser (the standard being a stabilized laser from the list of recommended radiations for the realisation of the metre) or at the realization of the second (the standard being calibrated using a comb).

4 CMC entries – Classification

This document addresses four typical situations which are classified according the target uncertainty and method used. Those situations are presented in the following together with examples which are copied from the public JCRB page.

It is specific in the field of laser metrology within the CCL, that the measurand for a single calibration service is either an absolute optical frequency or a vacuum wavelength. For historical reasons the very same service is often presented in both ways, thus doubling the CMC entry. Both quantities are of course physically equivalent but stating values (e.g. uncertainties) to a given place value can cause significant discrepancies. This problem is discussed in more detail in section 6.

4.1 High accuracy comb based calibration service

- Fractional frequency uncertainty significantly lower than 10^{-11};
- Calibration using an optical frequency comb with a suitable frequency reference;
- The comb is directly used for this calibration service;
- The value of the measurand can often cover a wide wavelength range.

One of the services with smallest uncertainty in the KCDB is shown in the following table.

Calibration or Measurement Service			Measurand Level or Range			Measurement Conditions/Independent Variable		Expanded Uncertainty					Reference Standard used in calibration		List of Comparisons supporting this measurement/ calibration service
Class	Instrument or Artifact: Measurand	Instrument Type or Method	Minimum value	Maximum value	Units	Parameter	Specifications	Value	Units	Coverage Factor	Level of Confidence	Is the expanded uncertainty a relative one?	Standard	Source of traceability	
Laser radiations	Frequency stabilized laser: vacuum wavelength	Optical beat frequency	1530	1560	nm	Optical power	> 1 mW	3E-14		2	95%	Yes	Optical frequency comb linked to the SI second as realized at NRC (frequency doubling and counting of rf beat signal)	NRC	See the Mise en pratique for the definition of the metre (Ref. 14) See references 2, 3, 7
Laser radiations	Frequency stabilized laser: absolute frequency	Optical beat frequency	192	196	THz	Optical power	> 1 mW	3E-14		2	95%	Yes	Optical frequency comb linked to the SI second as realized at NRC (frequency doubling and counting of rf beat signal)	NRC	See the Mise en pratique for the definition of the metre (Ref. 14) See references 2, 3, 7

[1] Wavelength standards can also be calibrated by interferometric techniques. A wavemeter is commonly used to calibrate artefacts like spectral lamps (DimVIM category 1.2.1). This technique is outside the scope of this document.

[2] The current MeP [4] uses a different classification.

4.2 Medium accuracy comb based calibration service

- Fractional frequency uncertainty around 10^{-11} (comparable with those obtainable using stabilized lasers);
- Calibration using an optical frequency comb with a suitable frequency reference;
- The comb is directly used for this calibration service;
- The value of the measurand can often cover a wide wavelength range.

The main difference to case 4.1 is the significantly higher measurement uncertainty which is based on the procedure itself. In the example below this is caused by the determination of the beat frequency using a spectrum analyser instead of a frequency counter.

Calibration or Measurement Service			Measurand Level or Range			Measurement Conditions/Independent Variable		Expanded Uncertainty					Reference Standard used in calibration		List of Comparisons supporting this measurement/ calibration service
Class	Instrument or Artifact: Measurand	Instrument Type or Method	Minimum value	Maximum value	Units	Parameter	Specifications	Value	Units	Coverage Factor	Level of Confidence	Is the expanded uncertainty a relative one?	Standard	Source of traceability	
Laser radiations	Frequency stabilized laser: vacuum wavelength	Optical beat frequency	530	1200	nm	Optical power	> 1 µW	0.6 to 3	fm	2	95%	No	Optical frequency comb linked to the SI second as realized at NRC (measurement of beat signals with a rf spectrum analyzer)	NRC	See the Mise en pratique for the definition of the metre (Ref. 15) See references 5, 6, and 8
Laser radiations	Frequency stabilized laser: absolute frequency	Optical beat frequency	250	560	THz	Optical power	> 1 µW	600	kHz	2	95%	No	Optical frequency comb linked to the SI second as realized at NRC (measurement of beat signals with a rf spectrum analyzer)	NRC	See the Mise en pratique for the definition of the metre (Ref. 15) See references 5, 6, and 8

4.3 Comb assisted standard laser based calibration service

- Fractional frequency uncertainty around 10^{-11} (comparable with those obtainable using stabilized lasers);
- Calibration using stabilized lasers;
- The lasers are regularly validated by calibration using an optical frequency comb and a suitable frequency reference as in cases 4.1 or 4.2;
- The stabilized lasers are directly used for the calibration service;
- The value of the measurand covers only a few discrete, very narrow ranges around the standard laser frequencies.

The traceability to the comb-based service is the main difference to case 4.4.

The following table shows an example where acetylene-stabilized diode lasers are measured by a comb. In this case a relatively wide range of 4.5 THz can be accessed. Wavelengths and frequencies and relative uncertainties are stated.

In this example the standard is an acetylene stabilized laser. The source of traceability is the regular calibration of this standard by a frequency comb (this is unfortunately not indicated in the respective columns).

Calibration or Measurement Service			Measurand Level or Range			Measurement Conditions/Independent Variable		Expanded Uncertainty					Reference Standard used in calibration		List of Comparisons supporting this measurement/ calibration service
Class	Instrument or Artifact: Measurand	Instrument Type or Method	Minimum value	Maximum value	Units	Parameter	Specifications	Value	Units	Coverage Factor	Level of Confidence	Is the expanded uncertainty a relative one?	Standard	Source of traceability	
Laser radiations	Frequency stabilized laser	Optical beat frequency	1530	1565	nm			1.0E-09		2	95%	Yes			absolute optical frequency measurements of acetylene-stabilized lasers by frequency combs referring to UTC(k)'s at NMIJ, NPL and NRC (2003,2004)
Laser radiations	Frequency stabilized laser	Optical beat frequency	191.5	196	THz			1.0E-09		2	95%	Yes			absolute optical frequency measurements of acetylene-stabilized lasers by frequency combs referring to UTC(k)'s at NMIJ, NPL and NRC (2003,2004)

4.4 Standard laser based calibration service

- Fractional frequency uncertainty around 10^{-11} level or significantly higher;
- Calibration using stabilized lasers;
- The lasers are operated according to the MeP or even under relaxed conditions.
- The stabilized lasers are directly used for the calibration service;
- The value of the measurand covers only a few discrete, very narrow ranges around the standard laser frequencies.

Both, wavelengths and frequencies and absolute uncertainties are stated. Note the last entry: obviously the same type of instrument is listed with an uncertainty 100 times larger.

This last example was for a long time the standard top level calibration service and the proof of traceability in the field of dimensional metrology. It served as a prototype for all current CMC entries regarding laser frequencies.

Calibration or Measurement Service			Measurand Level or Range			Measurement Conditions/Independent Variable		Expanded Uncertainty					Reference Standard used in calibration		List of Comparisons supporting this measurement/ calibration service
Class	Instrument or Artifact: Measurand	Instrument Type or Method	Minimum value	Maximum value	Units	Parameter	Specifications	Value	Units	Coverage Factor	Level of Confidence	Is the expanded uncertainty a relative one?	Standard	Source of traceability	
Laser radiations	Frequency stabilized laser: vacuum wavelength	Optical beat frequency	633	633	nm			0.04	fm	2	95%	No	mise en pratique iodine-stabilized He-Ne laser	BNM	BIPM.L-K10
Laser radiations	Frequency stabilized laser: absolute frequency	Optical beat frequency	474	474	THz			24	kHz	2	95%	No			
Laser radiations	Frequency stabilized laser: vacuum wavelength	Optical beat frequency	633	633	nm			3	fm	2	95%	No	mise en pratique iodine-stabilized laser	BNM	[BIPM.L-K10]

5 Supporting evidence for CMC

CMCs on frequency stabilized lasers are no exception as far as the JCRB rules imply. The basic rules for CMC approval must be applied. In particular, a calibration procedure under QS-control and a detailed uncertainty budget are required in any case.

The ideal evidence in primary metrology are results from comparisons and CCL has excellent guiding documents for the length field [7] [8]. Supporting evidence in the form of comparisons might however not be applicable in all cases as discussed before. Especially in the services with very low measurement uncertainties other ways must be found and the following sections will give guidance.

5.1 High accuracy comb based calibration service

This is the most critical service, needing considerable amount of work by both, the applicant and the reviewer. To date a confirmation of low measurement uncertainties is not trivial. In this document requirements from CCTF are used as guidance.

In line with the requirements of the CCTF for reporting data from primary frequency standards and of the CCL-CCTF Frequency Standards WG for reporting data from other (optical) frequency standards for inclusion in the list of recommended radiations for the realisation of the metre and other optical frequency standards [2], either as secondary representations of the second or otherwise, the primary requirement for an NMI wishing to claim the highest accuracy measurement capability using an optical frequency comb is that it shall have had published, in a peer-reviewed journal, a measurement of an atomic or molecular optical frequency with better uncertainty than that to be quoted in the CMC for the calibration service.

It is desirable that reliance should not be placed on a single published measurement but rather there should be evidence of reproducibility of measurement of the atomic or molecular optical frequency over time. It is also desirable that the atomic or molecular frequency should be one included in the list of recommended radiations for the realisation of the metre and other optical frequency standards. Ideally, the same atomic or molecular optical frequency shall have been measured by at least one other NMI or other institution, with agreement between the measurements.

This measurement can be a remote measurement of an atomic or molecular optical standard at another NMI by means of an optical fibre link or other high-accuracy frequency transfer technique, subject to demonstration of the performance of the link at an adequate uncertainty level. At the present state of the art, publication in a peer-reviewed journal will provide adequate validation.

Supplemental supporting evidence can be provided from the consistency of measurements of the same optical frequency made using two or more optical frequency comb systems, preferably ones based on different mode-locked lasers, e.g. Ti:sapphire and Er:fibre, or using substantially different locking and frequency counting electronics. Evidence of this equivalence is essential if the comb system to be used for calibration is not the comb system used for the published optical frequency measurement underpinning the CMC. Further supporting evidence can come from the analysis of the noise characteristics and stability of locking error signals etc. but this should not be considered sufficient in itself in order to claim the highest accuracy. However, taken together with an analysis of the uncertainty of the frequency reference, this can be adequate evidence to support a measurement uncertainty of up to a few parts in 10^{13}.

The comb can be referenced either to local RF/microwave frequency standards, i.e. to the NMI's realisation of the SI second (compared via CCTF-K001.UTC), or to an atomic or molecular frequency from the list of recommended radiations for the realisation of the metre and other optical frequency standards; preferably that used in support of the CMC but in any case one for which a frequency measurement has been published in a peer-reviewed journal , so long as its uncertainty is better than that quoted in the CMC. Note that in this case, with the comb being used to compare optical frequencies, calibration is effectively by method (c) of ref [3], i.e. by means of a stabilised laser from the list of recommended radiations for the realisation of the metre and other optical frequency standards.

The comb may alternatively be referenced to an RF oscillator disciplined by timing signals from a global navigational satellite system (GNSS) such as GPS, Galileo, BeiDou, or GLONASS. The GNSS timing signal is traceable to the SI second and hertz via the system's primary timing facility, e.g. for GPS, via UTC(USNO), but the uncertainty in the derived frequency must be evaluated by comparison with the NMI's realisation of the SI second. In this case the uncertainty quoted in the CMC must reflect the use of this reference.

Operating procedures for the comb system should be in place; these procedures should be those used for measurement of the atomic or molecular optical frequency. Where this measurement made use of a frequency reference of better uncertainty than that routinely used for laser calibration (e.g. a primary caesium frequency standard, where a hydrogen maser is used for the laser calibration), procedures appropriate to the use of the latter reference should be used.

There is sufficient published evidence that the modes of an optical frequency comb, properly set up and operated, have the same fractional frequency accuracy across the whole optical bandwidth of the comb. Therefore if the above conditions are met, the measurement capability at the frequency/wavelength of the reference atomic or molecular optical frequency can be quoted at any frequency/wavelength within the accessible bandwidth of the comb; however it may be considered prudent to degrade the uncertainty to be quoted in a CMC.

The above conditions are sufficient for an NMI to publish a CMC without reference to participation in any key comparison other than CCTF-K001.UTC. However, it is desirable that an NMI meeting these conditions should either be a CCL-K11 node lab or at least be willing to act as a host lab. A CCL-K11 node lab should meet the conditions above.

It is generally accepted that NMIs having reviewed and published CMCs in this category, can offer services of the following, lower level categories without further participating in key comparisons.

5.2 Medium accuracy comb based calibration service

A number of NMIs have chosen to move to providing optical frequency/vacuum wavelength calibration by absolute frequency measurement using a comb. If the uncertainty capability to be quoted in a CMC is at the level of uncertainty obtained using e.g. an iodine-stabilised 633 nm helium-neon laser, then the applicant might choose one of two options to provide supporting evidence for this service.

Option 1: The applicant proceeds like in the preceding case 5.1. Due to the relaxed uncertainty constrains as compared to the previous case, some requirements might be dropped also. It is at the discretion of both, the applicant and the reviewer, to find a suitable compromise between workload and necessary evidence.

Option 2: The applicant proceeds like in the following case of 5.3. Many challenges in the review process can thus be avoided. Basically taking part in an artefact based comparison can support valuable evidence.

5.3 Comb assisted standard laser based calibration service

In this case the comb is not used for customer's calibrations (covered by the respective CMC), but to provide primary traceability for the stabilized laser used as the working standard.

The applicant has to document the internal calibration procedure for the working standard. This may include working procedures, uncertainty budgets, recalibration intervals etc.

For the application of this CMC type it is not necessary to provide also comb based calibrations services. Apart from the documented traceability leading to the comb, the ultimate supporting evidence for this service can be gained exactly as in the following case 5.4.

5.4 Standard laser based calibration service

For this type of service an artefact based comparison is certainly the most direct way to prove competence. The key comparison CCL-K11 is the matter of choice in this case. Details on participation and reporting can be found in the technical protocol for CCL-K11 [6]. In the final report for this comparison there is usually a section on CMC claims vs. result. This eases the workload of the reviewer considerably.

There might be a problem with "exotic" types of laser standards for which the node labs of [6] cannot provide adequate service (e.g. the laser operates at a wavelength not covered by the node lab's setup). Up to now this did not happen.

6 Stating Uncertainties in CMC

Beside the scientific prudence to state meaningful results, one must have in mind that stated uncertainties will eventually be checked against experimental evidence (i.e. reference value of a comparison). One should minimize the danger of ambiguity.

6.1 Wavelength vs. Frequency

It is a specific in the field of laser metrology within CCL, that the measurand for a single calibration service is stated as an absolute optical frequency or as a vacuum wavelength. The stabilized laser sources where often developed by frequency metrologists but eventually used within dimensional metrology as standards of length. For such historical reasons the very same service is often presented in both ways, thus doubling the CMC entry. Both quantities are of course physically equivalent[3] but stating values (e.g. uncertainties) to a given place value can cause significant discrepancies. A typical example in the KCDB is for the iodine stabilized He-Ne laser at 633 nm as shown below.

Measurand Range	Expanded Uncertainty	Relative Uncertainty (calculated)
633 nm	0.04 fm	$6.3 \cdot 10^{-11}$
474 THz	24 kHz	$5.1 \cdot 10^{-11}$

The number of digits given for the expanded uncertainty is in accordance with normative regulations [9]. However the two values differ by about 20 %! This can make a big difference between fail/no fail in performance tests. For a typical user of the KCDB the quantity “vacuum wavelength” is often more familiar, to avoid ambiguities the CMC should state relative uncertainties.

6.2 Absolute Uncertainty vs. Relative Uncertainty

For a given measurement result the relative uncertainty is defined in [9] as the uncertainty divided by the value of the measurand. It is a dimensionless quantity by definition. In the field of laser frequency metrology the relative uncertainty often has a constant value for the given measurand range. Relative uncertainties are thus the preferred way to state CMCs in this case. Otherwise one would have to a quantity equation for the absolute uncertainty, which is cumbersome.

For the case of a single valued measurement range (as in standard laser based calibration 4.4) it is common to state absolute[4] uncertainties. This practice originates from a direct reference to the published absolute uncertainties in the MeP [3]. As long as there is no discrepancy with the actual numerical values, no recommendation for either case can be given in this document.

It is worth noting that the numerical value of the relative uncertainty is the same for frequency and for vacuum wavelength, respectively.

7 Literature

[1] CCL Length Services Classification (DimVIM). www.BIPM.org

[2] N. N. Metrologia 19, 163-178, “Documents Concerning the New Definition of the Metre”, 1984

[3] Quinn T. J. Metrologia 40 103-133, 2001 and Felder R. Metrologia 42, 323-325, 2003

[4] SI Brochure – 9th edition – Appendix 2 “Mise en pratique for the definition of the metre in the SI”, 2019. www.BIPM.org

[5] The BIPM key comparison database. www.BIPM.org/kcdb

[6] Matus M., Seppä J., Inaba H., Margolis H., Bernard J. “Comparison of optical frequency and wavelength standards”, Technical protocol, 2020. www.BIPM.org

[7] CCL/WG-MRA/GD-1 “Running of MRA comparisons in length metrology and monitoring their impact on CMCs”, 2018. www.BIPM.org

[8] CCL/WG-MRA/GD-3 “Guide to preparation of Key Comparison Reports in Dimensional Metrology”, 2015. www.BIPM.org

[9] JCGM 100:2008, “Evaluation of measurement data — Guide to the expression of uncertainty in measurement”, BIPM 2008. www.BIPM.org

[3] For an ideal electromagnetic plane wave.

[4] The term “absolute uncertainty“ is unusual and not normative. It is used here to avoid confusion with the term “relative uncertainty”.