Hans-Jürgen von Martens
Representative of ISO TC 108 to BIPM/CCAUV

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(cf. Draft Agenda of 28/06/2010, item 13.3)

Recent progress of ISO TC 108/SC 3 towards key comparisons and traceability in the field of vibration and shock acceleration

1 Introduction

This report updates the information presented to the 2nd to 6th meetings of the CCAUV. In the documents CCAUV/99-12, CCAUV/01-05, CCAUV/02-08, CCAUV/04-06, CCAUV/06-05 and CCAUV/08/01 the International Organization for Standardization outlined the regulations for developing and adopting ISO standards, and presented the standards developed in ISO/TC 108/SC 3 (in Working Group WG 6: *Calibration* in particular). With the development of the ISO 16063/XX series of standards, ISO/TC 108 *Mechanical vibration, shock and condition monitoring* responded to the need for upgraded and new standard calibration methods applicable to

- CIPM key comparisons, RMO key comparisons and Supplementary comparisons in the field of vibration and shock measurements
- the reliable and uniform specification of the Calibration and Measurement Capabilities (CMCs) in the branch vibration, published in the BIPM key comparison database (cf. Appendix C of the Mutual Recognition Arrangement MRA) - all NMIs claim their CMCs in the field of vibration and shock acceleration to be in compliance with the relevant ISO standards
- the establishment of traceability chains in the field of vibration and shock (measurands: acceleration, velocity, displacement, angular acceleration, angular velocity and rotational angle).

ISO standards and standardization projects focusing on the specification of calibration methods needed at different levels of a traceability chain in the field of vibration and shock are presented. In the following, the information will be updated outlining the progress achieved since the 6th meeting of the CCAUV. The 29th meeting of ISO/TC 108/SC 3 held in St. Louis/ USA in November 2008 and the 30th meeting of ISO/TC 108/SC 3 held in London/ UK in September 2010 have marked further milestones in the ongoing process of developing standards significant for key comparisons and traceability.

NOTE: This CCAUV working document is intended to be included in the collection of CCAUV working documents of the 7th CCAUV Meeting (BIPM website for restricted access). Therefore, it had to be submitted to the BIPM before the 30th ISO TC 108/SC 3 Meeting. This working document is dated August 2010 and indicates, therefore, the state as of August 2010 of the ISO standardization projects under development, revision and review, respectively. Significant progress achieved in the 30th ISO/ TC 108/ SC 3 meeting (September 2010) will be taken into account in the updated presentation to be given during the 7th CCAUV meeting in October (see Draft Agenda of 28/06/2010, item 13.3).

2 The standard series ISO 16063 “Methods for the calibration of vibration and shock transducers”

Under the general title "Methods for the calibration of vibration and shock pick-ups", a standard series, ISO 5347, was issued in the period between 1987 and 1997. A revision of the ISO 5347 series, re-numbered to ISO 16063, was started in 1995, focusing on the specification of upgraded calibration methods needed at different levels of a traceability chain: methods for primary vibration calibration, secondary vibration calibration, primary shock calibration and secondary shock calibration. The re-numbering applies to those standards only which are under revision or are being newly developed. Therefore, the former numbering system (i.e. ISO 5347/XX) is still valid for the standards which have recently been reviewed and confirmed without revision. A survey of the state of the standards and standardization projects of the 16063 series is given in the following (see also references [1] to [9]).

(1) ISO 16063-1: Basic concepts
Issued as international standard in 1998, reviewed and confirmed in 2004 and 2009

(2) ISO 16063-11: Primary vibration calibration by laser interferometry
Issued as international standard in 1999, reviewed and confirmed in 2004 and 2009

(3) ISO 16063-12: Primary vibration calibration by the reciprocity method
Issued as international standard in 2002, reviewed and confirmed in 2007 with a Technical Corrigendum issued in 2008 (Cor.1:2008)

(4) ISO 16063-13: Primary shock calibration by laser interferometry
Issued as international standard in 2001, reviewed and confirmed in 2006

(5) ISO 16063-15: Primary angular vibration calibration by laser interferometry
Issued as international standard in 2006, reviewed and confirmed in 2009

(6) ISO 16063-21: Vibration calibration by comparison to a reference transducer
Issued as international standard in 2003, reviewed and confirmed in 2008 with a Technical Corrigendum issued in 2009 (Cor.1:2009)

(7) ISO 16063-22: Shock calibration by comparison to a reference transducer
Issued as international standard in 2005, reviewed and confirmed in 2008

(8) ISO 16063-23: Angular vibration calibration by comparison to reference transducers
Preliminary work item in the programme of work confirmed in 2008

(9) ISO 16063-31: Testing of transverse vibration sensitivity
Issued as international standard in 2009

(10) ISO 16063-32: Resonance testing
Revision of ISO 5347-14:1993 approved in 2004 and confirmed in 2007 as preliminary work item, 3rd preliminary working draft under preparation with extended scope for a combined revision of ISO 5347-14 and ISO 5347-22

(11) 16063-41: Calibration of laser vibrometers
New proposed work item approved in 2004, Draft International Standard approved in 2009

(12) ISO 16063-42 Calibration of seismometers

Preliminary work item in the programme of work, 2004, 2nd preliminary working draft in preparation

(13) PWI 21691 Dynamic force transducer calibration

Preliminary work item approved in 2004, confirmed in 2008 as zero stage project

(14) PWI Parameter identification of accelerometers by primary methods

Preliminary work item proposed and confirmed in 2008 as zero stage project

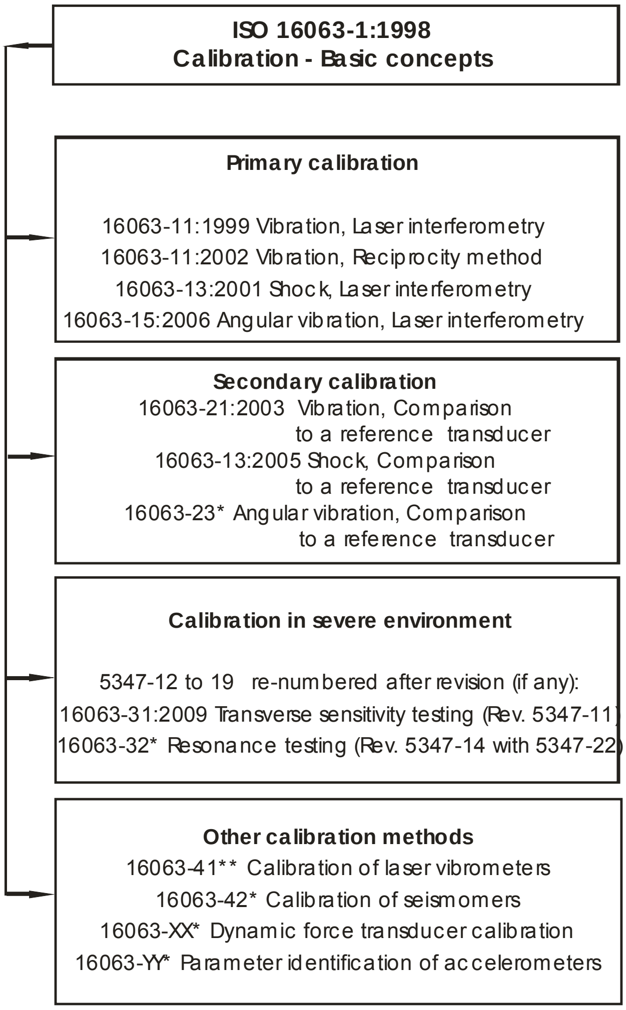

Figure 1: State of the standard series ISO 16063 “Methods for the calibration of vibration and shock transducers" (August 2010)

* Preliminary work item (zero-stage project), ** Draft International Standard (approved)

3 State of the standard series ISO 5347 “Calibration of vibration and shock pick-ups”

Table 1: Survey of standard series ISO 5347

ISO Part	Title	State
5347-0:1987	Basic concepts	revised → 16063-1:1998, the latter confirmed 2009
5347-1:1993	Primary vibration calibration by laser interferometry	revised → 16063-11:1999, the latter confirmed 2009
5347-2:1993	Primary shock calibration by light cutting	withdrawn, replaced with 16063-13:2001
5347-3:1993	Secondary vibration calibration	revised → 16063-21:2003, the latter confirmed 2008 with technical corrigendum Cor.1:2009
5347-4:1993	Secondary shock calibration	revised → 16063-22:2005, the latter confirmed 2008
ISO 5347-5:1993	Calibration by Earth's gravitation	confirmed 2009
ISO 5347-6:1993	Primary vibration calibration at low frequencies	withdrawn
ISO 5347-7:1993	Primary calibration by centrifuge	confirmed 2009 (need for amendment under consideration)
ISO 5347-8:1993	Primary calibration by dual centrifuge	confirmed 2009 (need for amendment under consideration)
ISO 5347-9:1993	Secondary vibration calibration by comparison of phase angles	withdrawn
ISO 5347-10:1993	Primary calibration by high impact shocks	confirmed 2004, new confirmation under consideration (SC 3 meeting Sept. 2010)
ISO 5347-11:1993	Testing of transverse vibration sensitivity	revised → 16063-31:2009
ISO 5347-12:1993	Testing of transverse shock sensitivity	confirmed 2009
ISO 5347-13:1993	Testing of base strain sensitivity	confirmed 2009
ISO 5347-14:1993	Resonance frequency testing of undamped accelerometers on a steel block	confirmed 2004, under revision, to be combined with ISO 5347-22:1997 (→ 16063-32)
ISO 5347-15:1993	Testing of acoustic sensitivity	confirmed 2009
ISO 5347-16:1993	Testing of torque sensitivity	confirmed 2009
ISO 5347-17:1993	Testing of fixed temperature sensitivity	confirmed 2009
ISO 5347-18:1993	Testing of transient temperature sensitivity	confirmed 2009

ISO Part	Title	State
ISO 5347-19:1993	Testing of magnetic field sensitivity	confirmed 2009
ISO 5347-20:1997	Primary vibration calibration by the reciprocity method	Revised → 16063-12:2002, the latter confirmed 2007 with technical corrigendum Cor.1:2008
ISO 5347-22:1997	Accelerometer resonance testing - General methods	confirmed 2009 to be combined with 5347-14 under revision (→ 16063-32)

4 Recent progress in development and application of ISO calibration standards

4.1 Survey on standards

ISO TC 108/SC 3 “Use and calibration of vibration and shock measuring instruments” (WG 6 “Calibration of vibration and shock transducers” in particular) has continued its activities to specify standard methods for the calibration of vibration and shock transducers and measuring instruments required to ensure international traceability to the SI units in the field of measurements of accelerations and derived motion quantities. The progress achieved since the 6th CCAUV meeting is reflected in the Sections 2 and 3 of this report.

Information on the development of the new standard series ISO 16063 will be updated, focusing mainly on the developments since the 6th CCAUV Meeting (BIPM; October 2008). Progress achieved later will be demonstrated only for those projects that have reached the stage of a Committee Draft or Draft International Standard stage, respectively. No specific information will be given on preliminary projects and working drafts discussed within working group WG 6 only. For preliminary work items (PWIs), see sections 2 and 3.

The task of ISO TC 108/SC 3/WG 6 is to develop international standards for the calibration of vibration and shock transducers. Various calibration methods have been specified to cover the different levels in the calibration hierarchy, from the highest accuracy level of primary calibration of a reference transducer in a national metrology institute (NMI) down to the lowest accuracy level of a check calibration of an accelerometer under field conditions. Calibration methods for nearly all kinds of vibration and shock transducers and measuring instruments have been specified.

The ISO standard 16063-1:1998, Methods for the calibration of vibration and shock transducers – Part 1: Basic concepts, was reviewed and confirmed in 2009.

For primary vibration calibration by laser interferometry at NMI level, ISO 16063-11: 1999 had extended the frequency range (0.4 Hz to 10 kHz) and included absolute phase shift measurement. This ISO standard was confirmed in 2009.

As an alternative primary methodology to laser interferometry, the reciprocity method for transducer calibration has been specified in ISO 16063-12:2002 (frequency range 40 Hz to 5 kHz). In 2007, this standard was confirmed with the decision to develop a technical corrigendum which was published in 2008 (Cor. 1:2008)

For modulus and phase calibration of rectilinear vibration transducers in the frequency range 0.4 Hz to 10 kHz at lower levels of the traceability chain ISO 16063-21:2003 had specified appropriate methods based on comparison with a reference transducer. This ISO standard was confirmed 2008 with the decision to develop a technical corrigendum which was published in 2009 (Cor. 1:2009).

The pair of ISO standards for primary and secondary shock calibration ISO 16063-13:2001 (laser interferometry) and ISO 16063-22:2005 (comparison to a reference transducer) has specified methods and techniques for shock-shaped accelerations of 100 m/s² up to 100 km/s² traceable to primary methodologies but proved to be applicable also at higher shock accelerations (e.g. 1000 km/s²).

ISO 16063-15:2006 specifies primary angular vibration calibration by laser interferometry (modulus and phase shift) in the frequency range from 0.4 Hz to 1.6 kHz. This ISO standard was confirmed in 2009. The corresponding project for angular vibration calibration by comparison to a reference transducer (to become ISO 16063-23) is still at the preliminary stage (PWI).

The ISO standard project "Testing of transverse vibration sensitivity" (Revision of ISO 5347-11:1993) was finished with the publication of ISO 16063-31:2009. This international standard specifies different methods using a single-axis vibration generator, a two-axis vibration generator or a triaxial vibration generator. Triaxial vibration excitation allows the transverse sensitivity to be determined with simultaneous excitation of a vibration in the sensitive axis of the transducer, thus simulating application conditions where the transducer is exposed to multi-axial vibration. To measure the motion components in up to three axes, primary methods (laser interferometry) and secondary methods (reference transducer) are specified.

The first international standard for the calibration of laser vibrometers (to become ISO 16063-41), has achieved the approved DIS stage in 2009. The project leader (author of this report) has prepared the Layout of the Final Draft International Standard (FDIS) of ISO 16063-41 taking into account the comments and proposals from the member bodies who had given their approval on the DIS. It is expected that the discussion during the ISO/TC 108/SC 3 meeting in London in September 2010 will lead to the confirmation as FDIS.

4.2 Measurement ranges and accuracy specified for standard techniques

For primary calibrations using laser interferometry, the following measurement ranges and expanded uncertainties (k = 2) are specified:

***Primary vibration calibration by laser interferometry* (ISO 16063-11):**
It is applicable to a frequency range from 1 Hz to 10 kHz and a dynamic range (amplitude) from 0.1 m/s^2 to 1 000 m/s^2 (frequency-dependent). The limits of the uncertainty of measurement shall be as follows.

For the modulus of sensitivity:

- 0.5 % of the measured value at reference conditions;
- 1 % of the measured value outside reference conditions.

For the phase shift of sensitivity:

- 0.5° of the measured value at reference conditions;
- 1° of the reading outside reference conditions.

***Primary shock calibration by laser interferometry* (ISO 16063-13):**

It is applicable in a shock pulse duration range 0.05 ms to 10 ms and a dynamic range (peak value) 10^2 m/s^2 to 10^5 m/s^2 (pulse duration-dependent). The limits of the uncertainty of shock sensitivity measurement shall be as follows:

- 1 % of reading at reference peak value of 1000 m/s^2 and reference shock pulse duration of 2 ms
- ≤ 2 % for all values of peak acceleration and shock pulse duration.

***Primary angular vibration calibration by laser interferometry* (ISO 16063-15):**

It is applicable to a frequency range from 1 Hz to 1.6 kHz and a dynamic range (amplitude) from 0.1 rad/s^2 to 1 000 rad/s^2 (frequency-dependent). The limits of the uncertainty of measurement shall be as follows:

For the modulus of sensitivity:

- 0.5 % of the measured value at reference conditions; ≤ 1 % outside reference conditions.

For the phase shift of sensitivity:

- 0.5° of the measured value at reference conditions; ≤1° outside reference conditions.

4.3 Accuracy (uncertainty of measurement) achievable with refined techniques

The international standards referred to in 4.2 allow special refined versions of the standard methods to be applied, which lead to even higher accuracy (smaller uncertainty of measurement) and/or wider parameter ranges than that specified for the standard methods.

Uncertainty evaluations (e.g. [11], [12]) and experimental investigations (e.g. [12], [13]) of measurements and calibrations using laser interferometry had demonstrated that relative expanded uncertainties (k = 2) < 0.1 % can be attained in calibrations of accelerometer standards at frequencies between 0.4 Hz and 5 kHz and of laser vibrometer standards between 0.4 Hz up to 20 kHz (measurand magnitude of sensitivity).

In simultaneous vibration measurements using different methods and techniques, no significant systematic deviation (bias) of the ISO laser interferometer methods (Method 1: Fringe-counting method, Method 2: Minimum-point method, Method 3: Sine-approximation method) from the SI unit could be found. This is valid within an uncertainty in the order of 0.01 % of the analysis of experimental results shown in Table 6 of Ref. [12].

Specific recommendations to suppress disturbing effects are given in [12] ,[15], [17].

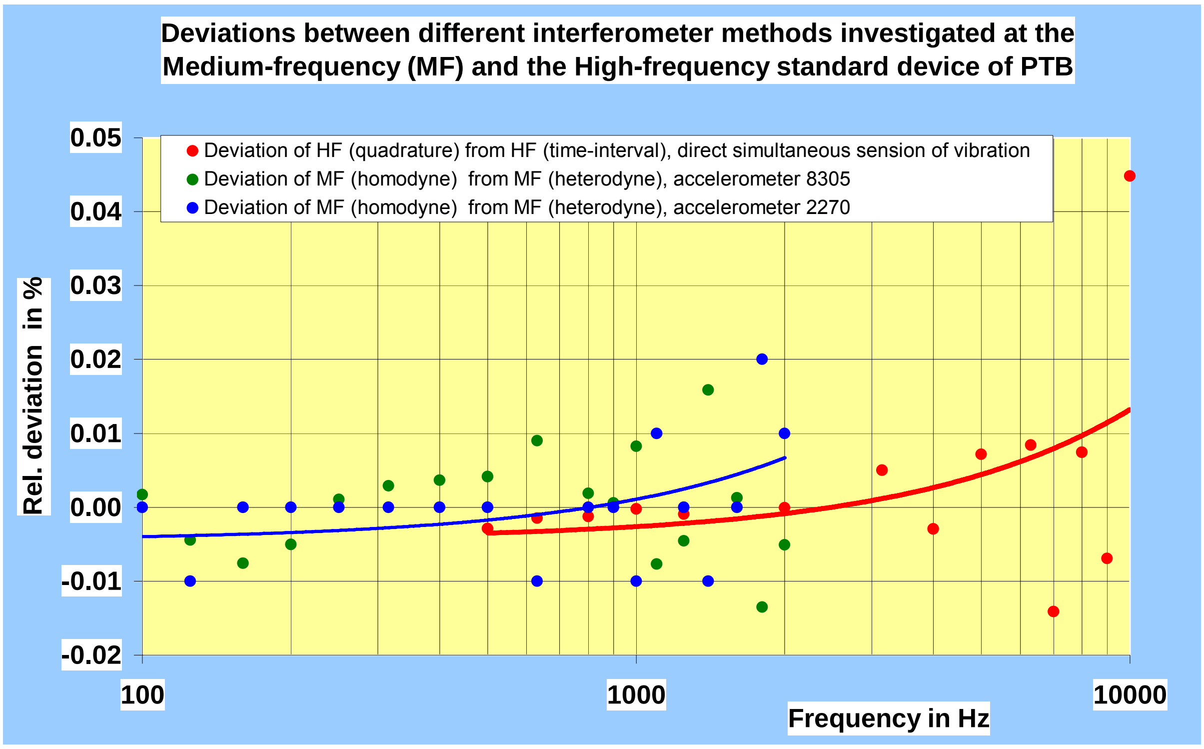

Figure 2: Deviations between measurement results of homodyne and heterodyne techniques in the frequency range 100 Hz to 10 kHz (Sine-approximation method). Investigation performed at PTB [12], [13]

4.4 Extended measurement ranges of standard methods

The ISO standards 16063-11 and 16063-15 specify for the interferometric measurement methods 1, 2 and 3 a specific frequency range, e.g. ISO 16063-11 the range from 1 Hz to 800 Hz for Method 1, 800 Hz to 10 kHz for Method 2 and 1 Hz to 10 kHz for Method 3. In fact, the applicability of the particular methods mainly depends on the displacement or velocity amplitudes measurable within given measurement uncertainties. These, however, not only depend on the measurement method itself but also on the frequency-dependent properties of the vibration exciters available. Using adequate vibration exciters to generate sufficient displacement or velocity amplitudes, the upper frequency limits of all three measurement methods can be expanded to higher than 100 kHz (see Fig. 3). Such wide measurement ranges are, however, applicable only to the calibration of laser vibrometers (ISO 16063-41) and not to the calibration of accelerometers (ISO 16063-11). For accelerometer calibrations in accordance with to ISO 16063-11:1999, the advanced state of techniques allowed the specified upper frequency of 10 kHz to be increased to 20 kHz. This is the upper frequency limit offered by NIST and by PTB in their CMCs (see Appendix C of the MRA, http://www.bipm.org, Key Comparison Database). Moreover, a calibration laboratory in Germany (DKD-KL 27801) was recently accredited for the calibration of accelerometers and laser vibrometers in the extended frequency range 0.2 Hz to 20 kHz. In the respective calibration certificates, compliance with ISO 16063-11:1999 may be stated, but a mark such as “extended to 20 kHz” should be made to indicate that the frequency limit stated in the ISO standard is exceeded. The alternative way to revise ISO 16063-11:1999 (to change the scope to the extended range up to 20 kHz) was discussed within the framework of a review of that ISO standard. It was decided to confirm the standard in view of the time-consuming ISO procedures for a revision of an international standard.

A similar situation may be encountered with ISO 16063-21:2003 (vibration calibration by comparison to a reference transducer) which specifies the frequency range from 0.4 Hz to 10 kHz. It turned that the method and procedures specified in that ISO standard are also applicable to lower and higher frequencies (e.g. 0.2 Hz and 20 kHz, respectively) if appropriate up-to-date techniques are used.

For the measurement of shock-shaped accelerations this is valid in a modified way: ISO 16063-13 specifies the instrumentation and procedure to be used for primary shock calibration of rectilinear accelerometers, using laser interferometry to sense the time-dependent displacement during the shock event. The scope of this ISO standard specifies that the method is applicable in a shock pulse duration range 0.05 ms to 10 ms and a dynamic range (acceleration peak value) 10^2 m/s² to 10^5 m/s^2 (pulse duration-dependent). However, peak values higher than 100 km/s² can be measured in conjunction with an appropriate high-acceleration shock exciter if the maximum velocity is measurable by the interferometer system. Thus, a standard method and procedure specified in ISO 16063-13 for shock calibrations up to 100 m/s² may be applied to higher acceleration peak values provided that the uncertainty requirements specified in this ISO standard are complied with.

For the new standard ISO 16063-41 (Calibration of laser vibrometers) under development, a more appropriate approach was applied to take any potential progress in calibration techniques and procedures into account: In the scope, the wording

"*This part of ISO 16063 specifies the instrumentation and procedures for performing primary and secondary calibrations of rectilinear laser vibrometers in the frequency range typically between 0.4 Hz and 50 kHz*"

has offered provisions for lower and higher frequencies. It was demonstrated by the NMI of Mexico (CENAM) – together with H.-J. von Martens - that the standard interferometer methods are applicable to frequencies beyond 50 kHz with adequately high accuracy (low uncertainty of measurement). Figure 3, and Figures B1, B2 and B3 in Appendix B show some experimental results obtained at the resonance frequencies 63.8 kHz, 100 kHz, 159.4 kHz and 347 kHz of special piezo-electric vibration exciters used for this purpose.

This approach may also demonstrate that the ISO standards developed for the calibration of vibration and shock transducers (including laser optical transducers and laser vibrometers) are based on up-to-date metrology, as ISO TC 108/SC 3 includes recognized metrologists from well-known NMIs representing altogether the five Regional Metrology Organizations (RMOs) APMP, COOMET, EURAMET, SADCMET and SIM.

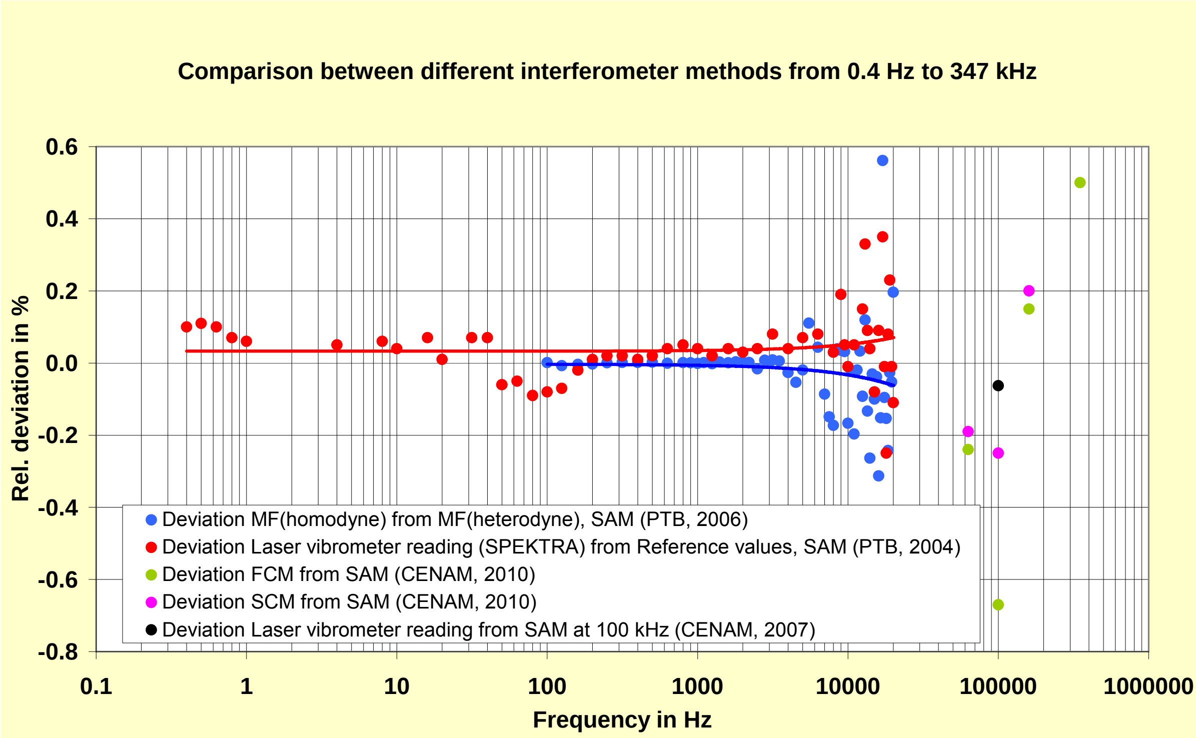

Figure 3: Deviations between measurement results of different interferometer methods in the frequency range from 0.4 Hz to 347 kHz. Measurement results taken from [12], [13], [14], [15], [16]. Abbreviations: FCM Fringe-counting method, SAM Sine-approximation method, SCM Signal coincidence method. For explanation of the SCM, see Appendix A.

4.5 The new standard ISO 16063-41 Calibration of laser vibrometers

A draft of an international standard under development is not available to the public. Because of the importance of ISO 16063-41, the project leader of this standardization project (author of this report) gives some significant information.

ISO 16063-41 specifies the instrumentation and procedures for performing primary and secondary calibrations of rectilinear laser vibrometers in the frequency range typically between 0.4 Hz and 50 kHz. It describes the calibration of laser vibrometer standards designated for the calibration of either laser vibrometers or mechanical vibration transducers, as well as the calibration of laser vibrometers by a laser vibrometer standard or by comparison to a reference transducer calibrated by laser interferometry.

Tables 2 and 3 demonstrate an even more inclusive approach applied to ISO 16063-41, compared with ISO 16063-11, to provide a variety of applicable techniques and procedures. A specific problem of the new ISO standard 16063-41 (current stage: approved DIS) is that Laser vibrometers are available for vibration frequencies up to the MHz and even GHz regions. To date, vibration exciters for such high frequencies have not been provided. To give a recommendation on how traceability to the SI unit may be established also for such high frequencies (MHz range), the German Member Body made, within the framework of the voting procedure on the DIS, the proposal to insert a new NOTE such as:

“Calibration of such laser vibrometers can be limited to calibration of their signal processing sub-systems utilising appropriate synthetic Doppler signals under the following preconditions:

- *Synthetic Doppler signals as an equivalent substitute for the output of the photodetector can be generated with defined accuracy requirements.*
- *The optical subsystem of the laser vibrometer to be calibrated has been proven to comply with defined accuracy requirements."*

More detailed specifications of this approach are not subject of ISO 16063-41 but it is proposed to give reference to a paper from the NMI of Japan (NMIJ) which describes a method, technique and procedure for demodulator calibration using an RF signal generator and shows experimental results [18]. The author of this report (H.-J. von Martens) expects that the discussion of the comments and proposals on DIS 16063-41 during the forthcoming ISO TC 108/ SC 3/ WG 6 meeting (London, September 2010) will lead, among other things, to a decision which addresses the above problem and proposal. The outcome of the discussion of the comments and proposals on DIS 16063-41 at the ISO TC 108/ SC 3 meeting in London in September 2010 will be reported in the presentation to be given during the 7th CCAUV meeting at the BIPM (item 13.3 of draft agenda).

Table 2: Comparison of ISO 16063-11 (Calibration of accelerometers) and ISO 16063-41 (Calibration of laser vibrometers) demonstrating the need for a new ISO standard for the calibration of laser vibrometers, and a more inclusive approach

Property	ISO 16063-11	ISO 16063-41
Frequency range	0.4 Hz to 10 kHz	0.4 Hz to 50 kHz (provisions for higher frequencies)
Vibration generator	Electrodynamic	• Electrodynamic • Piezoelectric (→high frequency)
Measurement method	Interferometry	• Interferometry • Comparison
Interferometer technique	Homodyne	• Homodyne • Heterodyne (→high frequency)
Terms and test methods	Specified in some detail	Defined in a separated clause, specified in great detail
Applicability of commercial laser vibrometer standards	Not included	Detailed specification
Calculation of measurement uncertainty	Uncertainty components in calibration	• Uncertainty components in calibration • Example of uncertainty calculation

Table 3 : Applicability of calibration methods of ISO 16063-41 influencing the uncertainty of measurement

Marking of method	Characterization of method (optical transducer/signal treatment)
Method 1	Homodyne interferometer (single output signal/ fringe counting)
Method 2	Homodyne interferometer (single output signal/ spectral analysis)
Method 3 (homodyne)	Homodyne interferometer (two output signals in quadrature / sine approximation)
Method 3 (heterodyne)	Heterodyne interferometer (output with frequency offset / sine approximation)
Method 4	Comparison to a reference transducer calibrated by Method 1, 2 or 3 in the arrangement used for laser vibrometer calibration

5 Summary and conclusions

ISO TC 108 was established in 1964 to develop documentary standards for mechanical vibration and shock, including transducer calibration. The calibration standards 5347 series and the 16063 series comprise over 20 standards. The ISO TC 108/SC 3 includes recognized metrologists (a number of whom are CCAUV members) from national metrology institutes (NMIs) along with a wide range of manufacturers and users. The ISO 5347 and 16063 series are under continuous development to provide a documentary standard base needed to ensure world-wide uniformity of vibration and shock measurements and calibrations and their traceability to the international system of units (SI). In particular, ISO standards have specified various methods and techniques for vibration and shock measurements and calibrations, applicable to perform international comparisons of national measurement standards organized under the auspices of the BIPM (CCAUV).

The realization and dissemination of the SI units of motion quantities (vibration and shock) have been based on laser interferometer methods specified in international documentary standards. New and upgraded ISO standards were reviewed with respect to their suitability for ensuring traceable vibration measurements and calibrations in an extended frequency range of 0.4 Hz to higher than 100 kHz. Using adequate vibration exciters to generate sufficient displacement or velocity amplitudes, the upper frequency limits of the laser interferometer methods specified in ISO 16063-11 for frequencies $\leq$ 10 kHz can be expanded to higher than 100 kHz, as demonstrated in Fig.3.

Using the ISO methods specified, hierarchies of measurement standards (traceability chains) have been established and are operated by NMIs as well as accredited and non-accredited calibration laboratories in compliance with the upgraded and new ISO standards.

For key comparisons at the CIPM and RMO levels and supplementary comparisons in the field of vibration and shock measurements (quantity of acceleration), the methods specified in the relevant ISO standards are used - preferably primary vibration calibration by laser interferometry as specified in ISO 16063-11 and secondary calibration by comparison to a reference transducer as specified in ISO 16063-21. Both standards specify a maximum frequency of 10 kHz but proved to be applicable at least up to 20 kHz, using advanced techniques. The new standard ISO 16063-41 for the calibration of laser vibrometers (stage: Draft International Standard DIS approved) will extend the frequency range of the primary calibration standard methods and techniques to higher than 100 kHz. This includes the calibration of laser vibrometer standards commercially available and used in numerous NMIs and increasingly also in accredited calibration laboratories for primary calibrations of accelerometers or optical transducers (laser vibrometers as ordinary measuring instruments included).

The calibration and measurement capabilities (CMCs) offered in Appendix C of the Mutual Recognition Arrangement MRA (see. http://www.bipm.org, Key Comparison Database) for the branch vibration are based on the up-to-date ISO standard methods.

For uncertainty evaluations of measurements to be performed in accordance with the GUM [10], within the framework of key comparisons, of CMC specifications and of calibrations for accredited calibration laboratories and other clients, the ISO standards of the series 16063 have provided an adaptation of the GUM to the calibration of vibration and shock transducers as stated in ISO standard for basic concepts, ISO 16063-1:1998 Annex A [1], and lists of the main principal components of the uncertainty budgets for the specific calibration methods and procedures specified in the respective ISO standards (e.g. ISO 16063-11, Annex A [2], ISO 16063-21, Annexes A and D [3], ISO 16063-41, Annexes A and C [9]).

Acknowledgement

The applicability of the interferometric vibration measurement standard methods up to high frequencies was investigated and demonstrated at the NMI of Mexico - Centro Nacional de Metrologia (CENAM) - with the collaboration of the author of this report. H.-J. von Martens is grateful to the General Director of CENAM, Dr. Hector Nava, to the Director of the Area of Physics Metrology, Dr. Salvador Echeverria Villagómez and to the Head of Division of Vibrations and Acoustics, Dr. Guillermo Silva Pineda, for providing the support of his visit to CENAM and for valuable discussions on vibration metrology. He thanks particularly Dr. Guillermo Silva Pineda and his scientific and technical staff of the vibration laboratories for the common experiments which essentially contributed to the metrological foundation of the first ISO standard for the calibration of laser vibrometers, ISO 16063-41, and to its implementation up to frequencies higher than 100 kHz. Selected results of the investigations are reported in Appendices A and B of this report, and in References [12], [14], [15], [16].

References

[1] International Standard ISO 16063-1, Methods for the calibration of vibration and shock transducers – Part 1: Basic concepts, *Int. Org. for Standardization* (*ISO*), Geneva (1998), reviewed and confirmed in 2009

[2] International Standard ISO 16063-11, Methods for the calibration of vibration and shock transducers – Part 11: Primary vibration calibration by laser interferometry, *Int. Org. for Standardization* (*ISO*), Geneva (1999), reviewed and confirmed in 2009

[3] ISO 16063-12, Methods for the calibration of vibration and shock transducers –
a. Part 12: Primary vibration calibration by the reciprocity method, *Int. Org. for Standardization*
b. (*ISO*), Geneva (2002), reviewed and confirmed in 2007 with a technical corrigendum Cor. 1:2008

[4] International Standard ISO 16063-13, Methods for the calibration of vibration and shock transducers – Part 13: Primary shock calibration using laser interferometry, Int*. Org. for Standardization* (*ISO*), Geneva (2001), reviewed and confirmed in 2006

[5] International Standard ISO 16063-15, Methods for the calibration of vibration and shock transducers – Part 15 Primary angular vibration calibration by laser interferometry*, Int. Org. for Standardization* (*ISO*), Geneva (2006), reviewed and confirmed in 2009

[6] International Standard ISO 16063-21, Methods for the calibration of vibration and shock transducers – Part 21: Vibration calibration by comparison to a reference transducer, *Int. Org. for Standardization* (*ISO*), Geneva (2003), reviewed and confirmed in 2008 with a technical corrigendum Cor.1:2009

[7] ISO 16063-22, Methods for the calibration of vibration and shock transducers
Part 22: Shock calibration by comparison to a reference transducer. *Int. Org. for Standardization* (*ISO*), Geneva (2005), reviewed and confirmed in 2008

[8] ISO 16063-31:2009 Methods for the calibration of vibration and shock transducers – Part 31 Testing of transverse vibration sensitivity, *Int. Org. for Standardization* (*ISO*), Geneva (2009)

[9] Draft International Standard ISO/DIS16063-41 Methods for the calibration of vibration and shock transducers – Part 41 Calibration of laser vibrometers , approved 2009

[10] Guide to the expression of uncertainty in measurement, corrected edition, *Int. Org. for Standardization* (*ISO),* Geneva (1995)

[11] von Martens, H.-J., Evaluation of uncertainty in measurements - problems and tools, *Optics and Lasers in Engineering*, **38**, 185-206 (2002).

[12] von Martens, H.-J., Metrology of vibration measurements by laser techniques. Invited lecture to the 8th International Conference on Vibration Measurements by Laser Techniques, *Proc. SPIE* Vol. **7098**, pp. 709802-1 – 709802-24 (2008)

[13] von Martens, H.-J., Bruns, Th., Täubner, A., Wabinski, W., Göbel, U., Recent progress in accurate vibration measurements by laser techniques, *Proc. SPIE*, **6345**, 01-1 - 01-23 (2006)

[14] Silva Pineda, G., von Martens, H.-J., Rojas Ramirez, S., Ruis Rueda, A., Muñiz, L. , Calibration of laser vibrometers at frequencies up to 100 kHz and higher, *Proc. SPIE* Vol. **7098**, pp. 70981K-70981K-10 (2008)

[15] von Martens, H.-J., Standardization of Laser Methods and Techniques for Vibration Measurements and Calibrations, Invited lecture to the 9th International Conference on Vibration Measurements by Laser and Noncontact Techniques, Ancona Italy 22-25 June 2010, *Conference Proceedings of American Institute of Physics* (*AIP*) Vol. **1253**, 423-445 (2010)

[16] von Martens, H.-J., Silva Pineda, G., Ruis Rueda, A., Vasquez Ovando, R., Comparison of 3 independent interferometer methods at high frequencies, *unpublished report*, Centro Nacional de Metrologia (CENAM) Mexico (Feb. 2010)

[17] von Martens, H.-J., Metrology and traceability of vibration and shock measurements, Chapter 53, 633-646, *Handbook of noise and vibration control*, Edt. by M.J. Crocker, John Wiley & Sons., Inc. Hoboken, New Jersey (2007)

[18] Oota, A., Usuda, T., Ishigami, T., Nozato, H., Hino, Y., Effect of demodulator unit on laser vibrometer calibration, *Proc. SPIE* Vol. **7098**, pp. 70981J1-70981J7 (2008)

[19] von Martens, H.-J., Interferometric counting methods for measuring displacements in the range 10^{-9} to 1 m, *Metrologia*, **24**, 163-170 (1987)

Appendix A

The Signal coincidence method (SCM) – a specialization of the Fringe-counting method, explicitly included in the new standard ISO 16063-41

The Signal coincidence method (SCM) after H.-J. von Martens [19] has been used as a check method in accelerometer calibrations at frequencies from 1 kHz to 10 kHz because its typical relative measurement uncertainty of 0.5 % to 1 % (at a coverage factor $k = 2$) did not allow high-precision measurements. Recent investigations performed at CENAM/Mexico [14], [16] have demonstrated that the uncertainty between 0.5 % and 1 % can be retained up to high frequencies (see Fig. 3 of this report, results at 63.8 kHz, 100 kHz and 159.4 kHz). Moreover, using digital data acquisition and processing of the interferometer signal and a formula established by H.-J. von Martens for elimination of systematic deviations from the ideal "coincidence" state, an expanded uncertainty even smaller than 0.5 % can be attained up to high frequencies in the 100 kHz range [15].

This recent achievement was taken into account by inclusion of an explanation of the SCM in an advanced stage of the development of ISO 16063-41, i.e. the Draft International Standard [9]. The respective wording is as follows (*clause 3.2.1*):

"Method 1: Fringe-counting method
vibration measurement method using a homodyne interferometer with a single output (see NOTE 2) in conjunction with instrumentation for fringe-counting of the interferometer signal. Considering that the displacement corresponding to the distance between two fringes (intensity maxima or intensity minima) is given by half the wavelength of the principal lines in the emission spectrum of neon of the He-Ne laser, the displacement amplitude can be calculated from the number of fringes counted during a given number (e.g., 1 000) of vibration periods. For details, see Clause 8 and, for further information, ISO 16063- 11:1999, Clause B.1.

NOTE 1 …

NOTE 2…

NOTE 3 The electronic fringe counting can be substituted by the signal coincidence method [1] [23] [24] which indicates a displacement amplitude of one-fourth wavelength, $\lambda/4$, of the laser light (158,2 nm for a red helium-neon laser). In the general case, the interferometer signal shows relative maxima and minima, respectively, at the times when the vibration displacement approaches its positive and negative peak values. In the discrete case (158,2 nm), the relative signal maxima and minima approach the same signal level from negative and positive direction, respectively ("coincidence"). By observing the interferometer signal as a function of time on an oscilloscope and adjusting the vibration amplitude to the level where a bright sharp line appears, the discrete amplitude (158,2 nm) is identified. The bright line varies with time as the initial phase of the interferometer signal varies due to low-frequency motion."

(References [1], [23], [24] in ISO DIS16063-41 are Refs. [19], [14], [12] in this report.)

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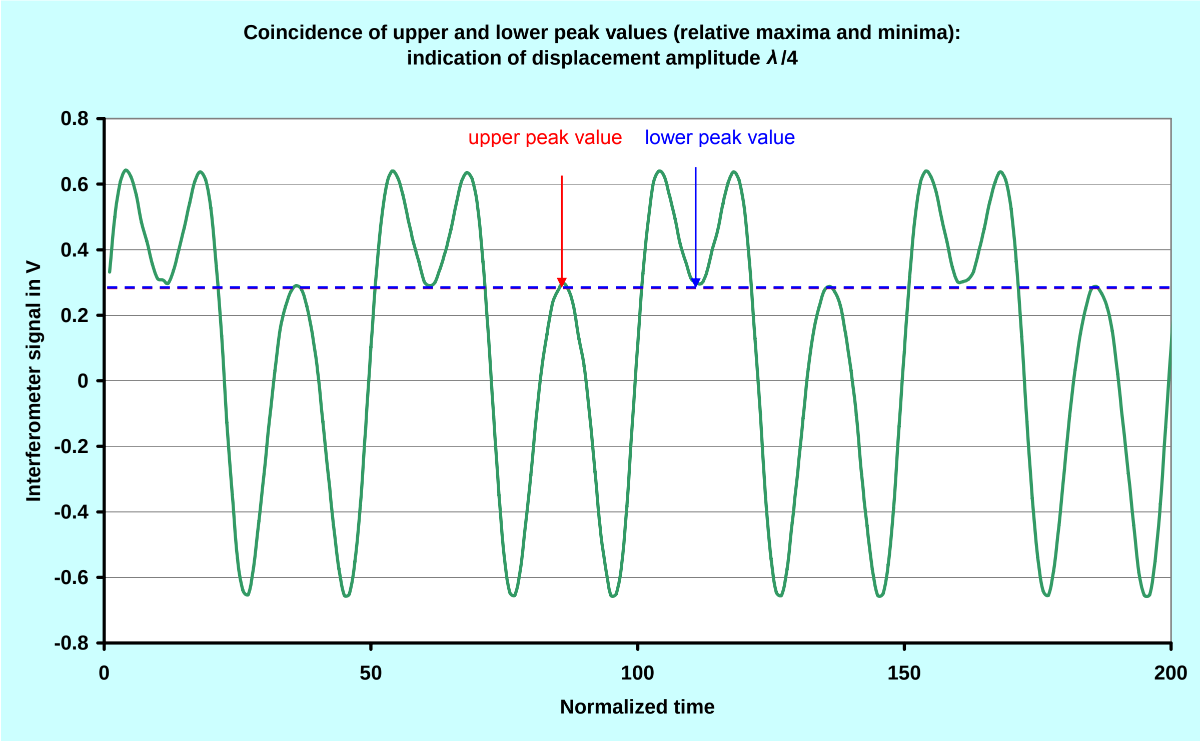

Figure A1: Demonstration of the SCM as a special case of the FCM: indication 2 fringes per vibration period, corresponding to $\lambda/4$ = 158.2 nm. The diagram shows the output signal of the laser interferometer system over four vibration periods, as shown by an oscilloscope.

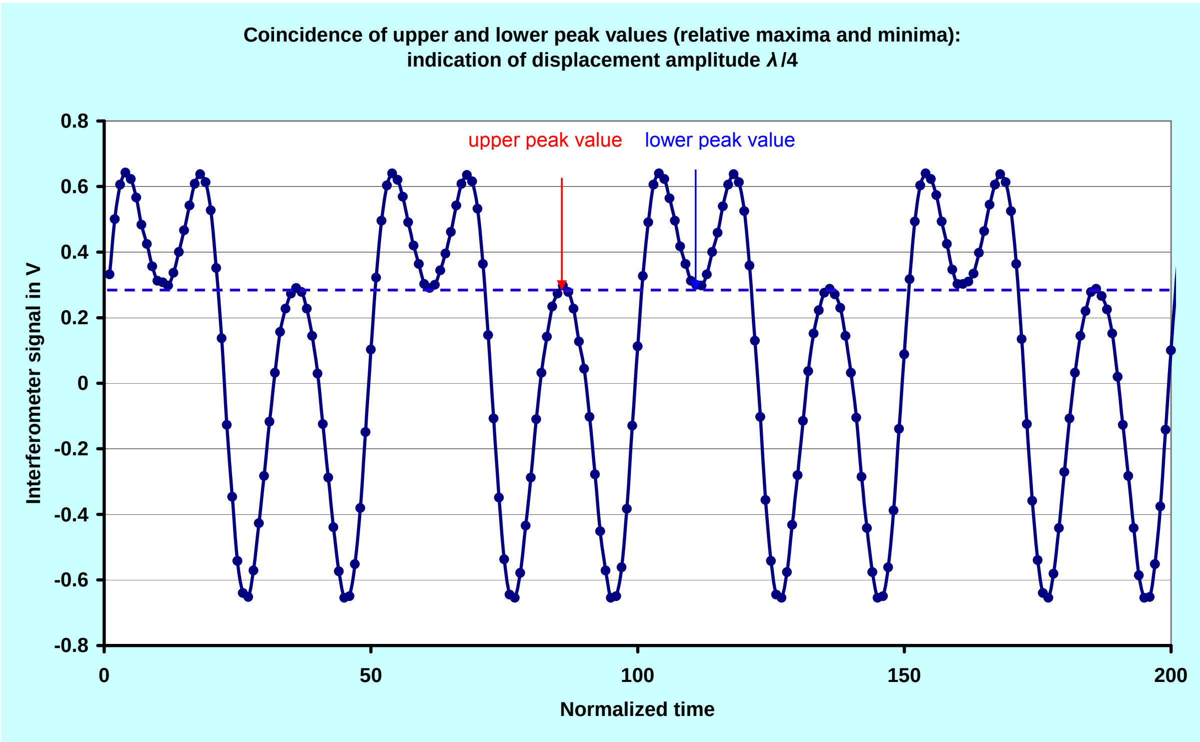

Figure A2: Output signal of the laser interferometer system at a displacement amplitude of $\lambda/4$ = 158.2 nm (ideal coincidence) sampled by an analogue-to-digital converter and approximated by a smoothing average

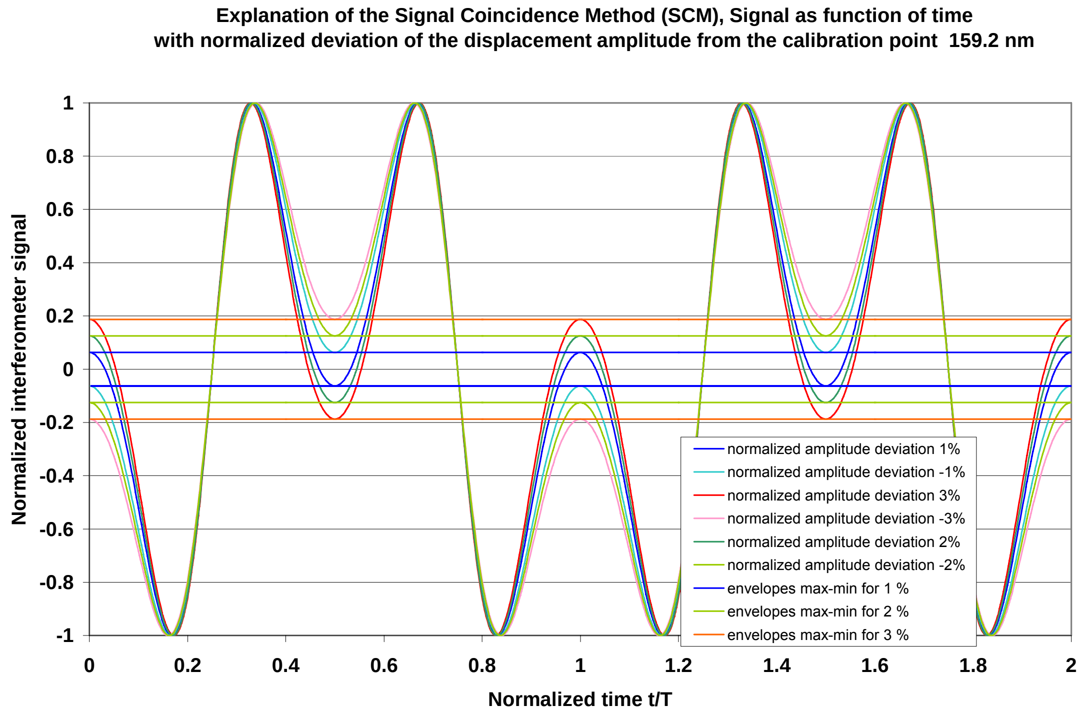

Figure A3: Refined version of SCM - indication 2 fringes per vibration period, corresponding to $\lambda/4$ = 158.2 nm, and calculation a systematic deviation for correction [15]. The diagram demonstrates the influence of specified normalized deviations from the nominal coincidence amplitude on the signal shape.

Appendix B

Examples of simultaneous measurements of vibrations at high frequencies using the Fringe-counting method (FCM), the Sine-approximation method (SAM) and the Signal coincidence method (SCM)

Investigations performed or initiated by the author (see [14], [19] for example) to explore the applicability of the different interferometric methods and techniques (homodyne and heterodyne as well) to wider frequency ranges than that specified in the respective ISO standards [2], [9] have been continued. The vibration measurements performed up to 100 kHz in November 2007 at CENAM with collaboration of H.-J. von Martens [14] were continued up to 347 kHz (acceleration amplitudes up to 360 km/s²) in January 2010 [16]. It turned out that the differences between the measurement results of simultaneously applied measurement methods - in particular the Fringe-counting method (FCM), the Sine-approximation method (SAM) and the Signal coincidence method (SCM) - were in the order of 0.5 % (smaller than 1 % in all cases). Some results of the analysis of the measurements reported in [16] are given in Figures 3, B1, B2 and B3 of this report, and in [15].

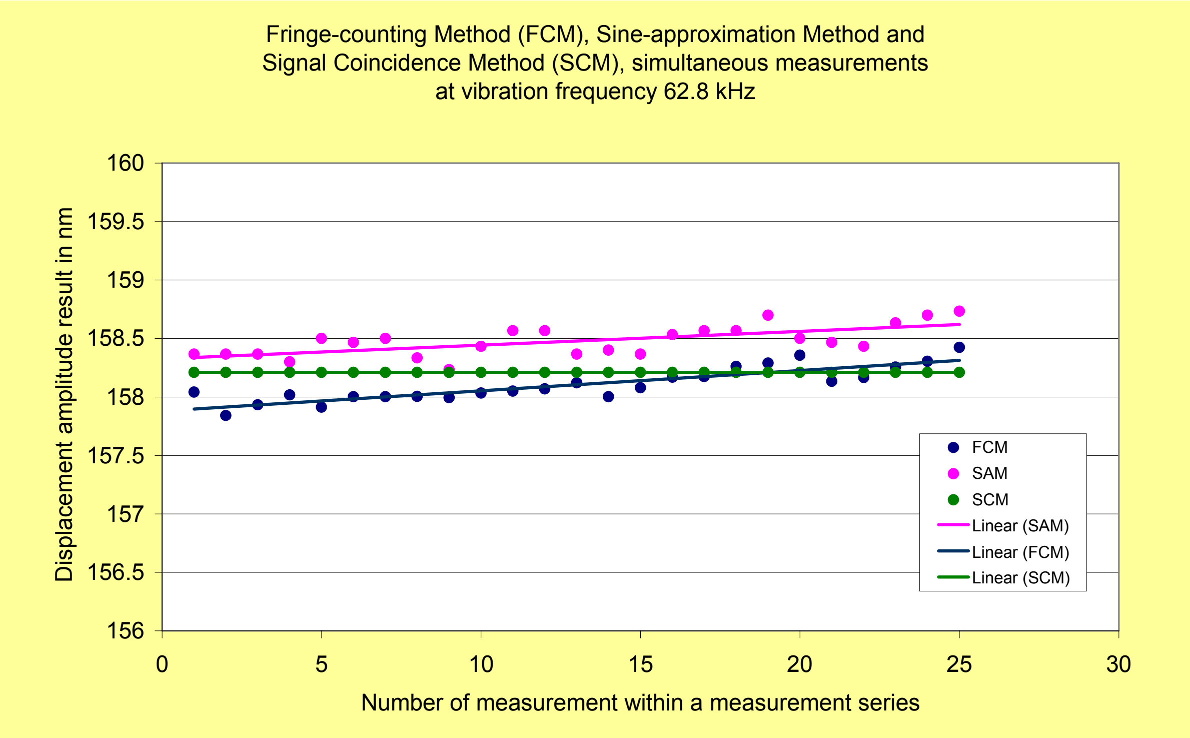

Figure B1: Simultaneous measurement of a displacement amplitude close to $\lambda/4$ (158.2 nm) at 62.8 kHz by the laser interferometer methods FCM, SAM and SCM. Measurement results taken from [16].

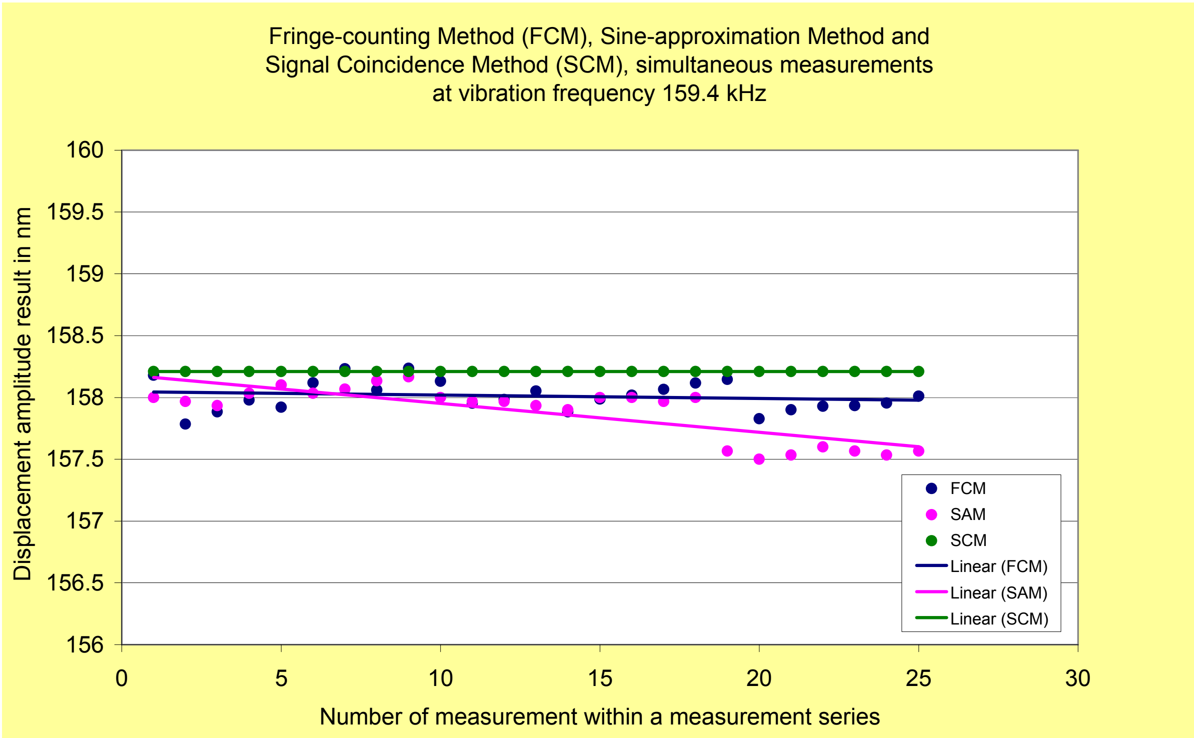

Figure B2: Simultaneous measurement of a displacement amplitude close to $\lambda/4$ (158.2 nm) at 159.4 kHz by the laser interferometer methods FCM, SAM and SCM. Measurement results taken from [16].

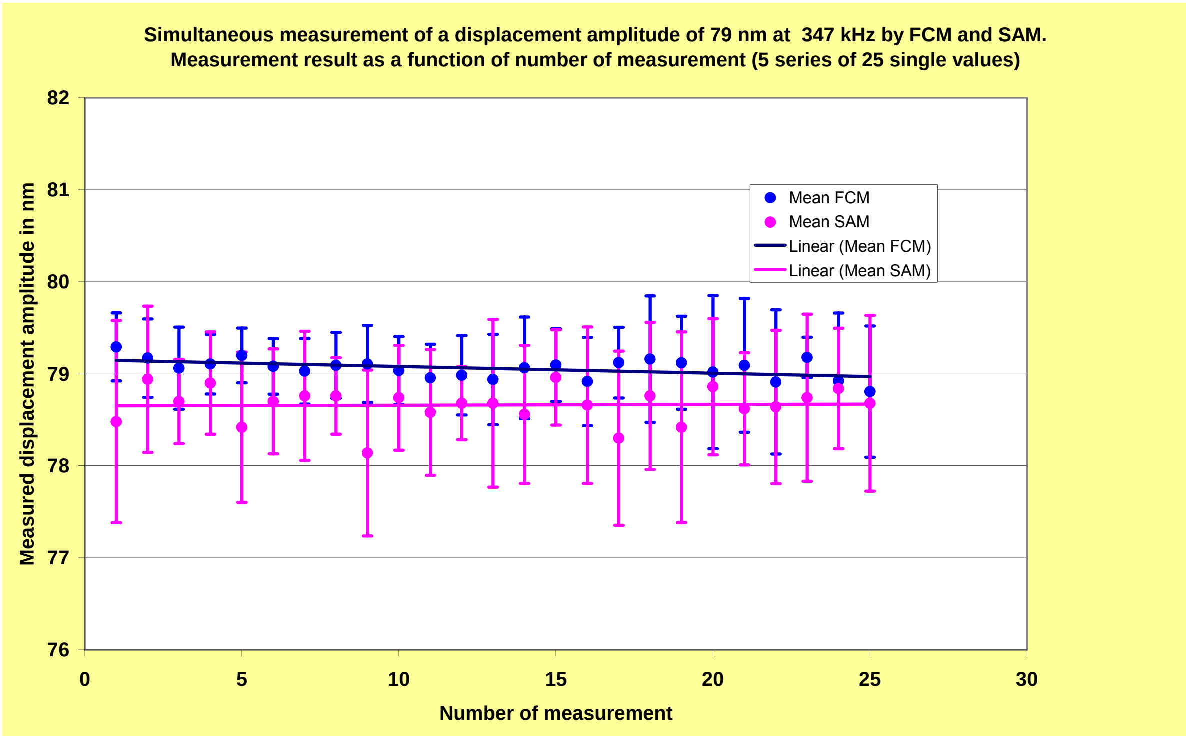

Figure B3: Simultaneous measurement of a displacement amplitude close to $\lambda/8$ (79.1 nm) at 347 kHz by the laser interferometer methods FCM and SAM. The interval around the mean values marks the standard deviation (5 values). Measurement results taken from [16].