LENGTH MEASUREMENT COMPARISONS BY INTERFEROMETRIC METHOD IN BRAZIL

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Abstract. *As a scientific and industrial activity, metrology is one of central practices to warrant the efficiency and productivity throughout many domains. To establish a traceability chain in dimensional measurements is necessary to rely upon the definition of its main SI dimensional unity (the "meter"). That definition is realized nowadays by stable wavelength light sources (following one of those internationally accepted), and its transfer to all scientific and industrial diversity of dimensional measurement systems is fullfilled through measurements and calibrations performed with the smaller possible uncertainties over specific material artifacts (gauge blocks, optical flats and parallels, reference surfaces, step gauges, etc) in optic devices called interferometers. Inmetro is the national metrology institute in charge of this traceability maintenance and its interferometry laboratory (Laint) perform such calibrations as widespread services to the brazilian metrologic community. This work intends to describe and compare some performances and results obtained from some actual working systems and its standard artifacts, employing normalized methods and good laboratorial practices (including some results obtained from our research instrumentation and systems). These comparisons could be taken as qualitative references to many measurement systems or as starting models for those laboratories whose aim is to validate their dimensional measurement systems.*

Keywords*: Metrology, dimensional measurements, interferometry, comparisons, traceability chain*

1. INTRODUCTION

Following good international laboratorial practices is one of the main goals that contribute to spread quality in production and industrial & scientific processes. Metrological systems are one of powerful tools to warrant the desired homogeneity between systems and to improve control of their results.

To check the metrological capabilities of laboratories we can rely mainly on skillful comparisons of its systems. These can be defined as bilateral, multilateral or "key-comparisons" (international). The last are considered as been the most important ones, having "official status", i.e., they are designed and plotted by the international organs responsible to stimulate compatibility between results obtained for similar measurements around the world. The higher instance for that is the BIPM, located in France, in the same region where the length unit "meter" was once defined. In the last decades some of its activities have been hierarchically de-centralized. Nowadays all countries must first take part in regional or local comparison rounds, but there have been exceptions where can be accepted countries from all continents, taking part in some big comparisons.

There are, at the other edge, many established methodologies to develop local comparisons that can validate the operation of similar systems inside a common area or even inside a laboratory.

The objective of this work is to present some comparison results obtained for a specialized sector of the measurement dimensional domain (more specifically, those related to length measurements by interferometric method), localized in Inmetro, the brazilian National Metrological Institute (NMI). And at the end we intend to offer some suggestions that could be used to any laboratory that need to validate the capabilities of their measurement systems.

For this we need first to expose some basic concepts and to describe some of the systems and equipments involved.

2. TRACEABILITY CHAIN IN LENGTH MEASUREMENTS

There can be a clear and well defined path to carry the realization of the unit "meter" from its definition in the SI to the practical applications in industrial and scientific communities.

According to the periodical publications of BIPM, as stated in Metrologia (2007), recommended radiations are defined that can be used as standard references in length measurements, and the way to implement the realization of unit pass through the production of such accurate defined wavelengths by stable sources. Nowadays only a specific kind of lasers constructed under certain conditions can be accepted as primary national standards according to that definition.

Inmetro owns one laser device that was designed to cover for these prerequisites. It is a He-Ne laser that has mounted inside its inner optical path a cell containing $^{127}I_2$, and its electronic stabilizing system let us select at will one of seven possible electronic transitions produced by this isotope in a defined standard temperature (15 °C) inside the stabilizing range as recommended by BIPM. This device took part at the first Key-Comparison in frequency measurements, scheduled to 2000. The main national interferometry laboratory (a.k.a. Laint, and located in Optical Metrology Division of Scientific and Industrial Metrology Directory of Inmetro) in Brazil was then the main seat for the beat-frequency measurements performed including all international portable stabilized lasers brought together there (they were compared pairwise with the brazilian sources and between one another) and the results were presented later by official indexed periodical (in Massone et al (2000)). That activity reassured the mutual international compatibility for this class of measurement standards for all countries that took part in that comparisons until now.

As such, our National Metrology Institute (Inmetro) has since then validated the top of its traceability chain for length unit. That chain must still be extended itself to material artifacts (mainly gauge blocks) that can be used as dimensional transfer standards to the industrial and scientific laboratories.

To achieve that goal we need devices called interferometers that are designed to perform length measurements of these material artifacts using optical wavelengths as length standards.

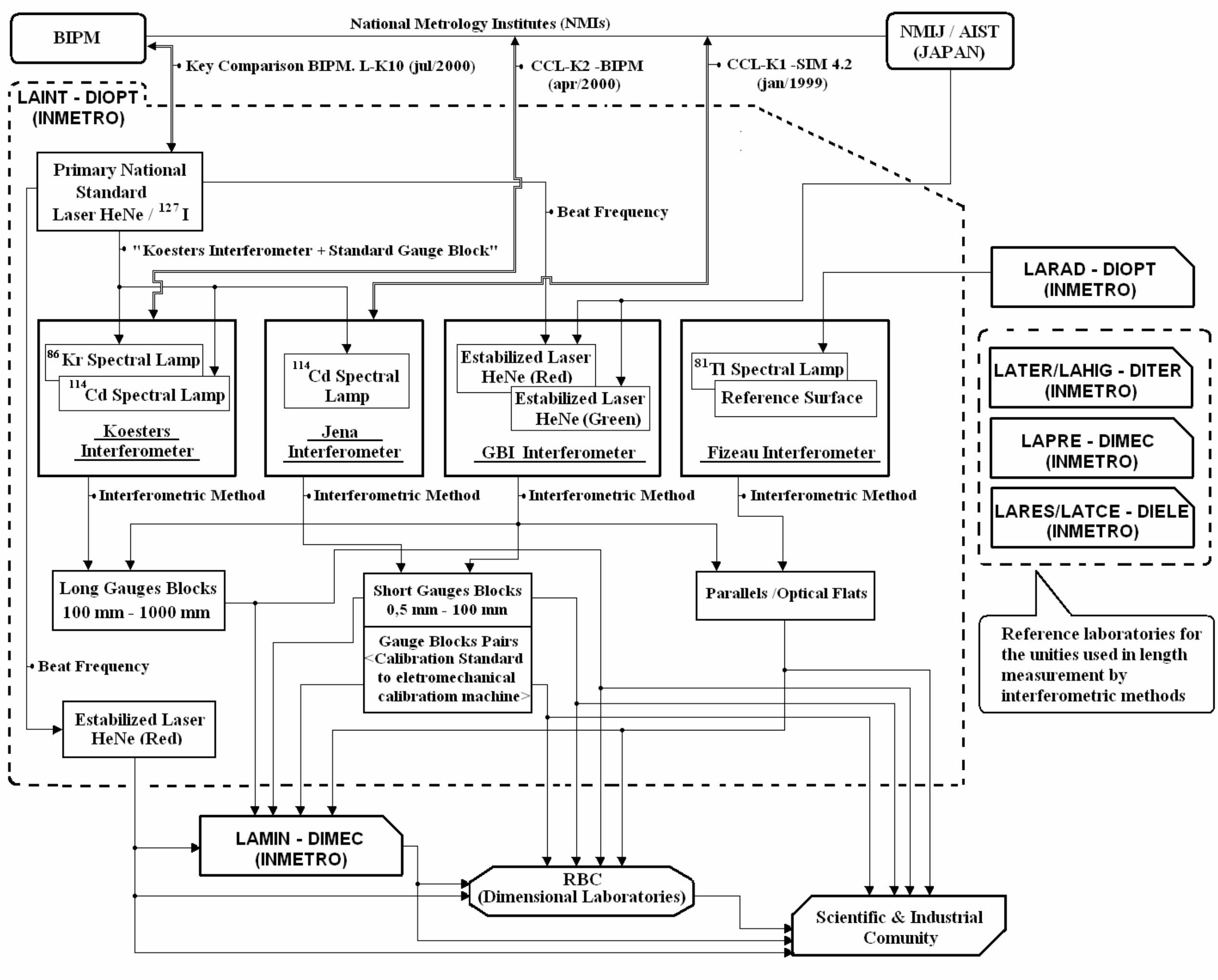

Figure 1 – Schema of traceability chain for all length calibrating systems of Laint

Figure 1 above shows that all length measurement laboratories in Brazil (including the national reference laboratory for dimensional measurements – Lamin located in Inmetro – and the all accredited laboratories of RBC – the brazilian calibration network) are dependent of this traceability chain. The research system of Laint was the only not included in this schema because it is not used for services in a day-to-day basis (and because of that not included in Annex C of MRA), but it is chained to the same CCL-K2 Key-Comparison showed in second figure top vertical line and has its traceability of its length standard (a stabilized HeNe laser) directly traced to the Primary National Length Standard.

2.1. Interferometers and Length Standards

Historically speaking old wavelength standards as spectral lamps were considered as an useful and distinct class of wavelength sources. That sources could provide different wavelengths (compared with only one in the case of actual stabilized lasers as, for example, our primary length standard). The interferometers used until now in length calibration services by interferometric method in Brazil, mainly those that took part in the two above quoted key-comparisons in length measurements in 1999 and 2000, published, respectively, in Thalmann, R. (2002) and Lewis, A. (2003), still used such sources when the first proposal for international intercomparisons in length measurements was launched. To close the links for the traceability chain of Laint was necessary to compare first these local spectral sources with the National Primary Standard to validate their use as length standards, but not by using the beat-frequency techniques used to compare stabilized lasers (as these are only valid into a very short range of wavelengths) but using an experimental ensemble constituted of interferometer and well known gauge blocks, measuring the same artifact in differential way using both wavelength sources. Those procedures were realized in 1998. The Key-Comparisons previously mentioned were then employed as additional quality confirmation for the interferometric measurement systems as a whole.

Figure 2 shows some results concerning the Key-Comparison of four travelling long gauge blocks (CCL-K2 – occurred in 2000) that state the higher quality of the brazilian interferometric measurement system used in normal day-to-day calibrations (INMETRO values are showing in the center). The smaller difference spreads between Inmetro's values and the average values in length for each one of four blocks was consistently short. Since then it has been clear to us otherwise that the maintenance of a good traceability chain is only the starting point to operate a trustworthy measurement system for long times.

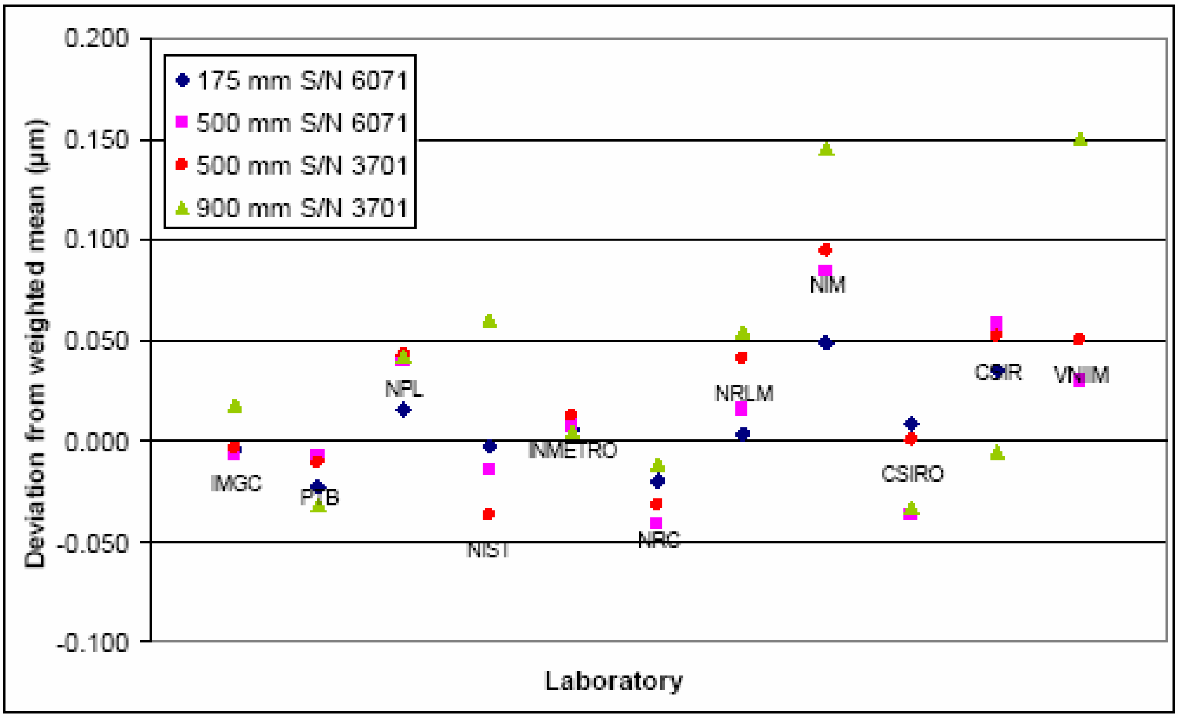

Figure 2 – Deviation from weighted mean of length deviations for 4 long gauge blocks, measured in 11 different National Metrology Institutes around the globe, for the first international Key-Comparison (CCL-K2)

We can identify more explicitly the different interferometric systems in use at Laint, unequivocally, as below:

2.1.1. Long Gauge Block Koesters-Zeiss Interferometer (INT-1)

It's a simultaneously very sophisticated and simply reliable optic system, surrounded by a group of old-fashion designed devices. Its main wavelength source still at work is a ^{86}Kr spectral lamp (offering four or more useful wavelengths – one was specially suggested by BIPM before the appearance of good stabilized lasers), and its working temperature is the triple-point of Nitrogen to increase its wavelength definition of their spectral emission. The open nature of this system presents also the possibility of inclusion of other spectral sources (more spectral lamps and/or stabilized lasers) as length standards, working simultaneously. But was operating in the original design that it was used in the Key-comparison quoted in Fig. 2.

2.1.2. Short Gauge Block Interferometers

Other two interferometric measuring systems working in Laint took part in the SIM-K1 Key-Comparison of short gauge blocks (CCL-K1 of 1999-2000). The first one was the system used in calibration services operating for almost three decades and the second one was through ten years equipped with best disposable instrumentation in the laboratory. There were developed special techniques that reduced the measurement uncertainty to ten times less than the previous system. Additionally there was purchased after that a third automated interferometric system.

Below we now discriminate between these three similar systems operating in Laint:

2.1.2.1. “Vertical” Jena-Zeiss Interferometer (INT-2)

As said before, it is the present “workhorse” for length calibrations of short gauge blocks in Laint. Its wavelength source is a ^{114}Cd spectral lamp (offering four practical wavelengths), specially designed to replace the electrodeless lamps (made of the same isotope) recommended by BIPM. Rugged and reliable, this system has only few of their accessories and measurement systems accessed in automated form, but there have been updates in parts of it from time to time. One of improvements developed for this system was to design and implement a new service in gauge block pairs calibration, following the EAL-G21 standard (august, 1996) named “Calibration of Gauge Block Comparators”, whose results were presented by Belaïdi et al (2000) and França et al (2000).

2.1.2.2. “Horizontal” Zeiss Research Interferometer (INT-3)

This research interferometer was the focal point for a lot of studies over all systematic effects that can arise in similar types of equipment for a decade long in, presented for example, in Titov et al (1998, 2000, 2001, 2003) and Malinovski et al. (1998, 1999, 2000). This interferometer was specially equipped with a stabilized laser as wavelength source that was previously compared to the National Length Standard by the beat-frequency calibration system for HeNe lasers, and with a sophisticated software based on pattern recognition of interferometric fringes captured by a digital camera (comprising a automated system developed locally). Its only disadvantage is the fact that to achieve the higher quality length measurements it relies on long-term procedures, what became to be a little bit non-practical for using it as a regular service machine. But it is, nonetheless, a finely crafted equipment for verification and validation of other systems.

The results presented in CCL-K1 Key-comparison show that the claimed reduced length uncertainties for this research system fits fairly close to the averaged values of the blocks measured in this intercomparison, therefore validating a claiming that it is one of the best system nowadays operating in the world for short gauge block length measurements.

2.1.2.3. Automated Mitutoyo GBI – Gauge Block Interferometer (INT-4)

Due to operational reasons the laboratory has acquired recently a fully automated and versatile commercial system for interferometric dimensional measurements. It uses two stabilized lasers as spectral sources and, using a motorized external automation system, it can be put to measure in a sequence twelve artifacts (gauge blocks; optical flats; step gauges) in a single row. This system can process the images obtained through a digital camera and combined with acquisition of ambient variables measured in automated and fast way provides the length deviation result through employing its commercial software containig all necessary equipment parameters just embedded in it.

2.1.3. Flatness Interferometers

There is still an interferometer designed to flatness calibrations: A Fizeau interferometer (INT-5) that uses two distinct standards: A ^{81}Tl spectral lamp (wavelength of 535 nm, checked by a double-grating monochromator) as spectral wavelength source; and a circular flatness reference surface, with analysis diameter of 75 mm, checked by “three-flat method”, to compare surfaces of artifacts to obtain their flatness deviation.

The GBI interferometer above mentioned (INT-4) has embedded also the capability to flatness calibration, but only covering a smaller circular diameter of 50 mm.

3. INTERFEROMETRIC METHOD

Following our focus on dealing only with higher quality length measurements we must first explain some details concerning interferometric methods, and whenever possible making references to mechanical methods in dimensional measurements.

3.1. Optical Path

The standard definition of standard mechanical length, in this case taking a gauge block as length standard, is stated as an one-dimensional distance ranging from one of its extremes or faces to the other (center-to-center). Its measure is performed by using the optical reflection of a light beam over two flat and reflective surfaces, comparing the reflection path of gauge block upper face with the reflection path coming from a plate with good surface quality (with low flatness deviation) tightly wrung to the lower gauge block face and therefore in molecular contact with it. The difference between both optical paths corresponds to the block length in that dimension. If the measuring procedure is realized in air, its refraction index must be obtained directly (using refractometers, for example) or indirectly by acquiring its values of pressure, temperature and humidity in its surroundings because their change modify length estimations.

3.2. Interference Fringes

For the case of generic Michelson interferometers the interference fringes are produced by combination of two beams coming from a reference mirror and from the artifact to be measured (in this case the "compound" block-base). The relative phase between the fringe pattern corresponding to the central fringes (over the block surface) and these fringes corresponding to both lateral sides (over the base surface) provides the information about the traversed optical path for each chosen wavelength.

3.3. Correction Factors

There are some effects to be taken in account as corrections applied to interferometric measurements, as stated below, that can affect directly the final results.

3.3.1. Phase Shift

Caused by the physical phenomena in which the real optical reflection plane on both the surfaces (function of its roughness and light penetration depth) of gauge block and plate is different of the maximal mechanical contact height for both surfaces. It depends on surface finishing quality and material properties of gauge blocks and wringing plates and it is added as a length contribution due to differential values between both surfaces. This factor represents the difference between "optical" and "mechanical" measuring length. If this correction is added to the length deviation of the gauge block obtained by interferometric method, the final result is the mechanical length deviation for its nominal value, and that is the value presented in the calibration certificate.

3.3.2. Geometrical Cosine Error

That factor depends on some dimensional characteristics of interferometer optical components and is directly proportional to the block length itself. It is due to Abbé deviation and other optic effects associated with the partial sphericity of the wave plane after passing through the ocular piece.

3.3.3. Gauge Block Temperature

As the length of any object must be defined mainly in a reference temperature any deviation of that parameter causes a dilatation or shortening of the block itself, that is function of the expansion coefficient for the gauge block material. Therefore this modification must be first taken in account before presenting the length deviation to the client in reference temperature (20 °C).

3.4. Non-correcting Effects

3.4.1. Wringing

A very relevant effect in performing good interferometric measurements is the surface wringing between gauge block and plate. If the surfaces are not flat enough, or if any dirty is caught between them, wringing is not possible. Some deformations sometimes are possible to occur when is used excessive force or heating to wring the surfaces. Because of that must be given to the ensemble after wringing some hours to "rest" to relieve the mechanical/thermal tensions and stress. These are among the most unpredictable effects occurring in this kind of measurement.

3.4.2. Wavefront Errors

These geometrical effects are due to tiny irregularities in the wave propagation plan along the optical paths inside interferometers caused by non-ideal curvatures and flatnesses produced by optical components. Those can deform the interferometric fringes and therefore modify the length estimation. It can be measured and either added directly in the uncertainty budget or be computationally compensated in digital imaging systems (like those methods applied in the measures performed by INT-3 and INT-4).

4. INTRA-COMPARISON RESULTS

4.1. Length Measurements

For inner mutual validation, one technique to compare different interferometers is to measure the same kind of standards in short intervals. In that case, for maximal compatibility, specific gauge blocks were chosen that could fit easily in more than one system. The only length size that can be measured in all gauge blocks interferometers is 100 mm. Smaller blocks can be not measured by INT-1, only by INT-2, INT-3 and INT-4.

The chosen blocks (the most frequently measured gauge-blocks of Laint) for this checking were defined as:

A) 100 mm nominal length value; material: steel/grade: K; Frank 3693; α = 12,0 x 10^{-6} K^{-1} (measured at INT-3); wrung on rectangular steel plate (Cary).

B) 23,5 mm nominal length value; material: steel/grade: K; Mitutoyo 930681; α = 10,8 x 10^{-6} K^{-1} (company value); wrung in rounded quartz plate (Bernhard Halle).

	Horizontal Zeiss INT-3 (automated –research)	**Jena-Zeiss INT-2 (actual services)**	**Koesters-Zeiss INT-1 (actual services)**	**GBI-Mitutoyo INT-4 (full automation - future services)**
Lm(A) =>	-165 nm (10/10/2005)	-158 nm (22/12/2006)	-175 nm (11-12-15/12/2006) – ^{114}Cd – 3 meas.	-177 nm (05/12/2006) – 3 meas.
	-143 nm (22/02/2002)	-190 nm (02/12/2006) – 6 meas.	-141 nm (07/12/2000) – ^{114}Cd – 2 meas.	
		-189 nm (28/04 -04/05/2005)	-127 nm (28-29/07 – 29/12/1998) – 11 meas.	
		-127 nm (13/12/2000) – 9 meas.	-79 nm (08/08/1992-19-26/01-01/02/1993) – 4 meas.	
Lm(B) =>	Not available	-86 nm (06-12-19-20-21-22/12/2005) – 6 meas. -110 nm (13/08/2004) – 20 meas.	Not available	-109 nm (07/06/2006)

Table 1 – Result comparison between different interferometers measuring same gauge blocks

It can be seen by measurement values of both our systems with best uncertainty (the automated-research system and long gauge-block Koesters interferometer – INT-3 and INT-1, respectively) we could extract an estimated drift of aprox. 6-7 nm/year for the 100 mm block (A). The values (in nanometers) of length deviations Lm correspond to a mean average, whenever a number of measures is indicated in Tab. 1. If we consider the drift we can consider that the 2006 value of INT-3 for Lm(A) is aprox. 172 nm

4.2. Flatness Measurements

As this verification depends only on smaller variations in height along the surfaces there is no need to calibrate accurately its spectral sources as in the other interferometers, but for the reference surfaces higher are the constraints. If a more generic interferometer type (Michelson or Twyman-Green) is used to calibrate flatness instead of simpler Fizeau interferometers there must be taken in account other effects as wavefront errors from the optic compound consisting of a reference mirror (the real “reference surface” in this case) and all other optic elements that could modify the optical path between the two surfaces to be compared.

4.2.1. Fizeau Interferometer (INT-5)

In 2005 has been proceeded the last verification of its main reference surface through the established “three-flat method”, described in Damião et al (2003), that consists in comparing pairwise three different reference surfaces. As we only had two reference surfaces as themselves accessories of interferometer we had to complete the procedure with a well known quartz optical flat (total diameter – 100 mm).

The result of the flatness deviation for the three chosen reference surfaces (within a maximum diameter of 75 mm) is posted below:

Reference Surface 1 (main) => -6 nm
Reference Surface 2 (reserve) => 14 nm
Quartz Optical Flat => 11 nm

As seen above the small flatness deviation obtained for the working surface (number 1) characterizes it as a good reference standard, because it is much smaller than the associated total system uncertainty (normally more than 30 nm), but nevertheless it was included in its uncertainty budget.

4.2.2. Jena Interferometer (INT-2)

In 2005, using a high sensitivity digital camera (due to the low brilliance obtained in emission of the reference spectral lamp) with software specifically developed in Laint to minimize the observational errors, and the previously measured reference surface of INT-5, was accurately estimated the maximal wavefront error of INT-2 as been around 3 nm (valid for its measuring area only). The result was included as an additional factor in the updated uncertainty budget for calibration of small gauge blocks.

4.2.3. GBI Interferometer (INT-4)

In 2006 after the first tests performed in installation of equipment we measured a set of four small optical parallel flats (due to intrinsic limitations in diameter) previously measured in Fizeau interferometer (INT-5) and the results of both systems are compared in the table below:

Parallel Flats (Zeiss)	Flatness deviations (μm) – INT-4	Flatness deviations (μm) – INT-5	Delta (INT-4 – INT-5)
24,370	0,027	0,015	0,012
24,250	0,025	0,023	0,002
24,120	0,026	0,018	0,008
24,000	0,029	0,020	0,009

Table 2 – Flatness measurement comparison between two different interferometric systems (INT-4 and INT-5)

4.3.1. Mathematical Treatment

4.3.1.1. Uncertainty Budget

For comparing different systems one possible first step is to define their particular measurement uncertainties, as presented in the table below.

Interferometer	**U (nm) – Expanded Uncertainties – for 95% coverage factor**
INT-1 (long GB int.)	$[(32)^2 + (0,14)^2L^2]^{1/2}$ (35 nm – 100 mm)
INT-2 (short GB int.)	$[(28)^2 + (0,50)^2L^2]^{1/2}$ (57 nm – 100 mm; 30 nm – 23,5 mm)
INT-3 (research GB int.)	$[(3)^2 + (0,04)^2L^2]^{1/2}$ (4 nm – 100 mm)
INT-4 (automated GB int.)	$[(17)^2 + (0,35)^2L^2]^{1/2}$ (39 nm – 100 mm; 19 nm – 23,5 mm)
INT-5 (Fizeau int.)	30 nm (optical cylindrical flats, diameters until 75 mm)

Table 3 – Measurement Uncertainties (where “GB int.” means “gauge-block interferometer”, “U” means the expanded uncertainties in nanometers and “L” is the length of each gauge-block in mm)

Table 3 shows the expanded uncertainties (for a well-known 95% coverage factor) for each interferometric system as defined before. The two first systems (INT-1 and INT-2) and the last one (INT-5) have defined as uncertainties the same values as declared in CMC (Calibration Measurement Capabilities) of MRA´s Annex C, corresponding to brazilian best measurement capabilities for the respective services. The research interferometer (INT-3) has the same uncertainty value as declared in the last short-gauge block SIM intercomparison in Thalmann et al (1999). The system uncertainty of INT-4 is defined as the same written in its manual and is the same as defined by Narumi et al (1998).

All particular budget contributions (like uncertainties due to wavelength radiations, block temperature, ambient conditions, wringing, fringe observation, etc) taken in account for length measurements by each system were omitted for clarity in this work.

4.3.1.2. Normalized Error

This mathematic tool can be used to check pairwise the mutual compatibility between two systems. The formula is defined as below:

$$NE = (X_1 – X_2) / (U_1^2 + U_2^2)^{1/2} \qquad (1)$$

Where:
X_1 and X_2 are the expected mensurand value obtained by each system
U_1 and U_2 are the expanded uncertainties for each system
In second column of Tab. 4 below is seen the normalized error (NE) obtained for each system pair of these “Intra-comparisons” (by using the selected underscored values of Lm in Tab. 1):

Interferometer “Intra-Comparisons”	**NE**
INT-1 X INT-2 (100 mm GB)	0,254 (0,224)
INT-1 X INT-3 (100 mm GB)	0,284
INT-1 X INT-4 (100 mm GB)	0,038
INT-2 X INT-3 (100 mm GB)	0,122 (0,438)
INT-2 X INT-4 (100 mm GB)	0,275 (0,188)
INT-2 X INT-4 (23,5 mm GB)	0,333
INT-3 X INT-4 (100 mm GB)	0,306
INT-4 X INT-5 (set of 4 flats)	0,395 -- worst case

Table 4 – Normalized Error (NE) for each measurements ensemble performed upon the same artifact (gauge-block or parallel flat) for two interferometers at short time intervals.

Between brackets are the optional values taking in account the value corresponding to the mean of 6 measured values in 2006 for INT-2, instead of the first indicated one. The last worst “Delta” case corresponds to only one parallel flat (24,370), and to flatness deviation expanded uncertainty of 5 nm for GBI system (INT-4) – derived from its length measurement budget – and 30 nm for Fizeau system (INT-5).

Following the results above, we can see that all are far below the accepted boundary (NE < 1), what reassures the validity of all measurement methods/systems for all the interferometric length-dimensional measurements performed in Brazil in its reference laboratory. By using the “drifted” value (ranging from 2005 to 2006) for INT-3 measures of Lm(A) we can achieve comparable values for NE in second, fourth an seventh row that were 0,085, 0,245(0,315) and 0,127, respectively.

Nonetheless, it can be seen that each equipment may present different ways to check its operation, depending on construction features and dimensional limitations.

5. CONCLUSIONS

All measurements were performed at intervals less than 6 months for each interferometer pair (an exception was those including the INT-3 measurements that present the best and continuous uncertainty control of all systems as showed by its “drifted” values), what rules out any aging or drifting effects that could affect the gauge-blocks themselves or the systems as a whole. And even considering variations due to the annual calibrations of many of their sub-systems we can compare successfully different systems if we cling to some single rules (comparison of same artifacts, maintenance of traceability chain for their reference standards and periodic checks and verifications).

As such when using similar systems it is easier to compare results, and even considering the structural differences between types, procedures and technology employed by all systems in that analysis, the robustness of the results shows that it can apply itself at many cases, wherever the system characteristics dealt in the comparison are well defined, including their limitations of operation and uncertainty budgets.

A suggestion can be stated by furthermore include more elaborate techniques as Circle Technique Analysis, or Monte Carlo Simulation techniques to check further correlations between individual uncertainty factors (for example, distinct plate wringing for gauge block interferometric measurements, influences of temperature measurements and its systematic effects, ambient conditions, etc.).

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