Preliminary Results of the 'CT Audit' Project: First International Intercomparison of Computed Tomography Systems for Dimensional Metrology

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Abstract. *"CT Audit"* is the first international intercomparison on Computed Tomography (CT) systems for dimensional metrology. The project was coordinated by the University of Padova (Italy) and involved important Institutions and Companies in Europe, America and Asia. The interlaboratory comparison was based on the circulation of calibrated items that are sent to the Participants together with detailed measurement procedures.

First preliminary results are shown and discussed in this paper; a complete results' report is going to be distributed to the intercomparison's Participants at the end of June 2011.

Introduction

Nowadays x-ray computed tomography (CT) is mainly used in three different fields: medicine, material analysis science and dimensional metrology. Recently CT has been identified as a very promising technique in the metrology field due to important advantages respect to tactile and optical coordinate measuring machines (CMMs) and other measuring systems. The main advantages are [1]:

- Ability to measure as well the inner as the outer geometry of objects without disassembling or destroy it;
- Possibility to acquire a high point density in a relative short time;
- Non contact inspection.

On the other hand, several limitations are present, e.g. [1]:

- Complex and numerous influence quantities occur;
- Complete standards are not yet available;
- Measurements are typically not traceable since the uncertainty is difficult to evaluate.

Due to the previous CT disadvantages, CT systems are still not completely recognised as reference measuring instruments with well known metrological performances. An interlaboratory comparison may be an indispensable means to establish the effectiveness and comparability of measurement methods, and to validate uncertainty claims [2]. For this reason, the University of Padova organized the first international intercomparison of CT systems for dimensional metrology.

This project, called "*CT Audit*", involves important institutions and companies in Europe, America and Asia, including national metrology institutes, CT systems manufacturers, research institutes, and industrial users. [3]

A total of 15 CT systems took part to the intercomparison. The project leads to important and interesting results; some of them are going to be presented in this paper.

1. *CT Audit* project

1.1 Motivations

The main objectives and benefits of the *CT Audit* project are to deepen the knowledge on CT dimensional metrology and to spread information on available reference geometrical standards and procedures for metrological verification of CT systems.

The Participants gain many benefits from the *CT Audit* Project. First of all they receive calibrated geometrical standards and procedures for testing their CT Systems. They have the possibility to evaluate their measurement's results by comparing them to reference calibrated values and to results of other laboratories. Moreover they can validate their measurement and uncertainty evaluation methods. Finally, all Participants are now establishing an international network of laboratories using CT Systems for dimensional metrology; this network can be the basis for promoting further international initiatives in the field of industrial CT.

1.2 Participants and Circulation

The intercomparison involves 15 companies and laboratories form different Countries around the world, with a total of 15 CT systems. Names of participating organisations are listed in alphabetical order, for general information only, in Table 1. The confidentiality of results is ensured by associating an anonymous identification code to each Participant. Only the specific Participant and the Coordinator know the association with the identification code.

A website was built for distributing information and measurement procedures (www.gest.unipd.it/ct-audit). The time scheduling of the project can be divided in 5 phases, as schematically described in Figure 1, from September 2009 to June 2011. The circulation phase lasted one year, from March 2010 to March 2011. A final Workshop is going to take place in Padova (Italy) in October 2011, where all Participants will meet to discuss the results of the intercomparison.

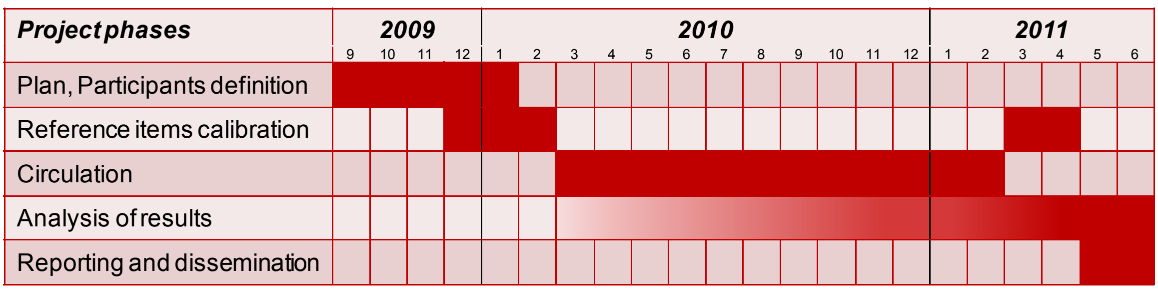

Figure 1: Time scheduling of the project's phases.

1.3 Calibrated Items

Four calibrated items, of different form, material and size were chosen in order to test several measurement characteristics using different CT systems.

The four items were sent within a dedicated suitcase (fig. 2) from one Participant to the next one in a sequential participation scheme [2].

Each Participant received from the project coordinator detailed measurement procedures, reporting sheets and Items' CAD models with nominal values.

Table 1: Participants' list in alphabetical order

	Participant	Country	Nr. CT systems
I	AIST – Human Technology Research Institute	Japan	1
II	BAM - Federal Institute for Materials Research and Testing	Germany	1
III	Elettra Sinc. S.C.p.A., Trieste	Italy	1
IV	Industrial Technology Center of Tochigi Prefecture	Japan	1
V	Katholieke Universiteit Leuven	Belgium	1
VI	Nikon Metrology, X-Tek Systems Ltd	UK	1
VII	NMIJ/AIST – National Metrology Institute of Japan	Japan	1
VIII	Novo Nordisk A/S, Device R&D	Denmark	1
IX	Novo Nordisk A/S, DMS Metrology & Calibration	Denmark	1
X	Pratt & Whitney, Austin	USA	1
XI	RayScan Technologies GmbH	Germany	1
XII	RWTH Aachen University - WZL	Germany	1
XIII	Universidad de Zaragoza	Spain	1
XIV	University of Erlangen-Nürnberg - QFM	Germany	1
XV	Werth Messtechnik GmbH	Germany	1
Total	***15 Participants***		***15 CT Systems***

Figure 2: *CT Audit* Suitcase

Items were protected in thin plastic sealed boxes for reducing the risk of damages, limiting contamination and avoiding measurements with other sensors. The sealed cylindrical boxes are made of polyethylene, with wall thickness of 0.8 mm circa. Participants were asked to measure the items without opening the sealed boxes. The four Items are shown in Fig.3 and 4.

Item 1, which is called *"CT Tetrahedron"*, consists of four calibrated ruby spheres on a carbon fiber frame. Item 2 is called *"Pan Flute Gauge"*; it is composed of five calibrated glass tubes of different lengths. Both items 1 and 2 were developed by University of Padova, Italy.

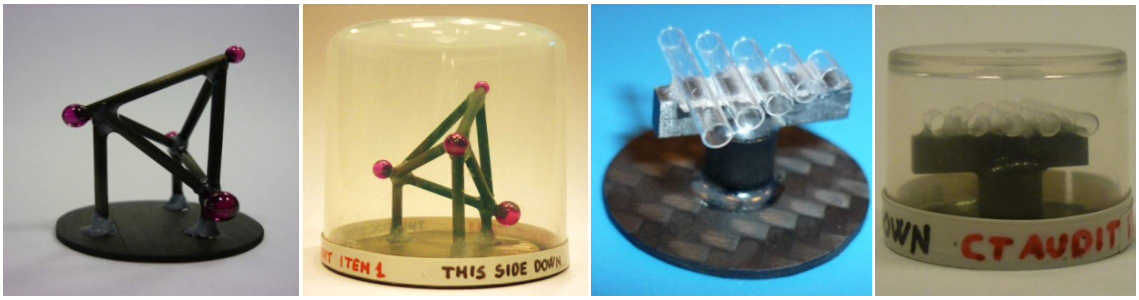

Figure 3: Item 1 (first two pictures from the left side), Item 2 (two pictures on the right)

Item 3 is the *"Calotte Cube"*, which consists of 75 spherical calottes on three sides of a titanium hollow cube. This item is provided by Physikalisch-Technische Bundesanstalt, Germany.

Finally, item 4 is the *"QFM Cylinder"*, consisting of a titanium cylinder and a ball plate with five sapphire balls. This item is provided by QFM − University Erlangen-Nuremberg, Germany.

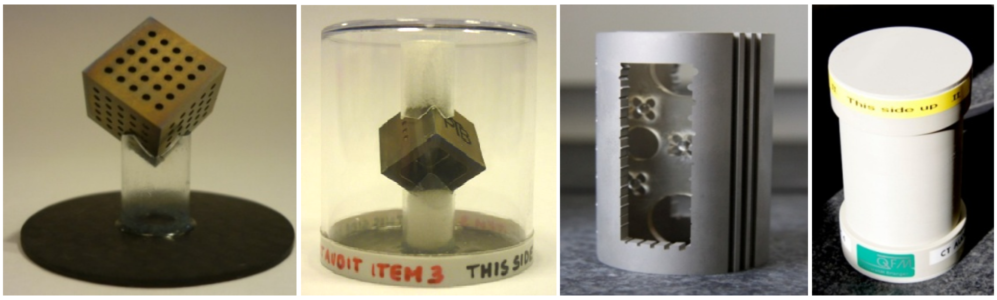

Figure 4: Item 3 (first two pictures from the left side), Item 4 (two pictures on the right)

The four Items have been calibrated using tactile CMMs. They were calibrated before and after the circulation period, in order to verify and document their stability.

2. Preliminary Results

2.1 Item 1

15 CT Systems measured the "CT Tetrahedron". The Participants were asked to measure diameters and form errors of the four spheres, and the distances between the spheres.

As an example, the results of diameters measurements are summarized in Figure 5. The results show that the values obtained by the Participants for measurements of diameters and distances between spheres are closer to the actual calibrated values than those of form errors (taking into account the stated uncertainties). In particular, the comparison of diameters measurements with form error measurements is summarized in Figure 6 in terms of the "E_n value", which describes the difference between the calibration results and the measured ones compared to the stated uncertainties [2]. It is defined as:

$$E_n = \frac{Value(partcipant) - Value(calibration)}{\sqrt{U(participant)^2 + U(calibration)^2}}$$

If $|E_n|<1$ there is good agreement between calibration and measured data [2].

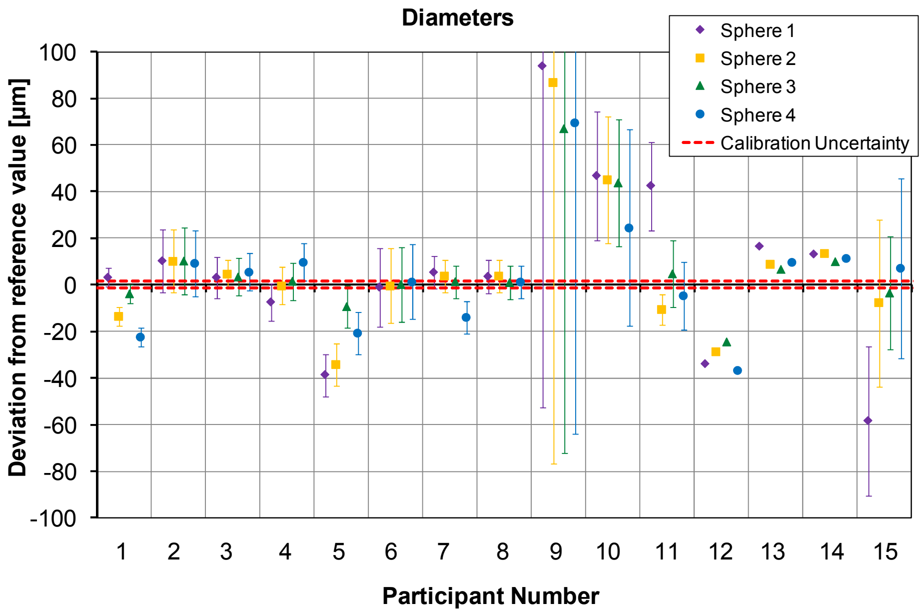

Figure 5: Summary of results obtained by the CT Audit Participants: Item 1, Diameters measurements. Vertical error bars represent expanded uncertainties specified by the Participants.

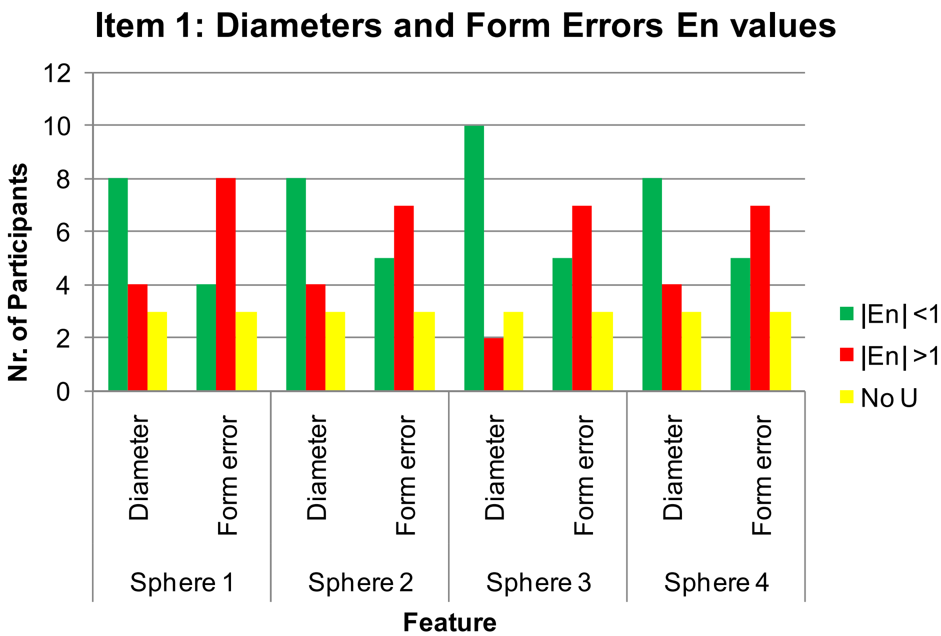

Figure 6: Item 1, E_n-values for Diameters and Form errors measurements obtained by the Participants.

2.2 Item 2

15 CT Systems measured the "Pan Flute Gauge". The Participants were asked to measure Inner and Outer Tubes' Diameters and Tubes' lengths.

The majority of the Participants measured with E_n value smaller than 1. Moreover, a very interesting result trend has been observed: the deviations of inner and outer diameters from the calibrated values have a systematic "mirror distribution" as shown in Figure 7. The cause of this systematic trend will be discussed with all the Participants.

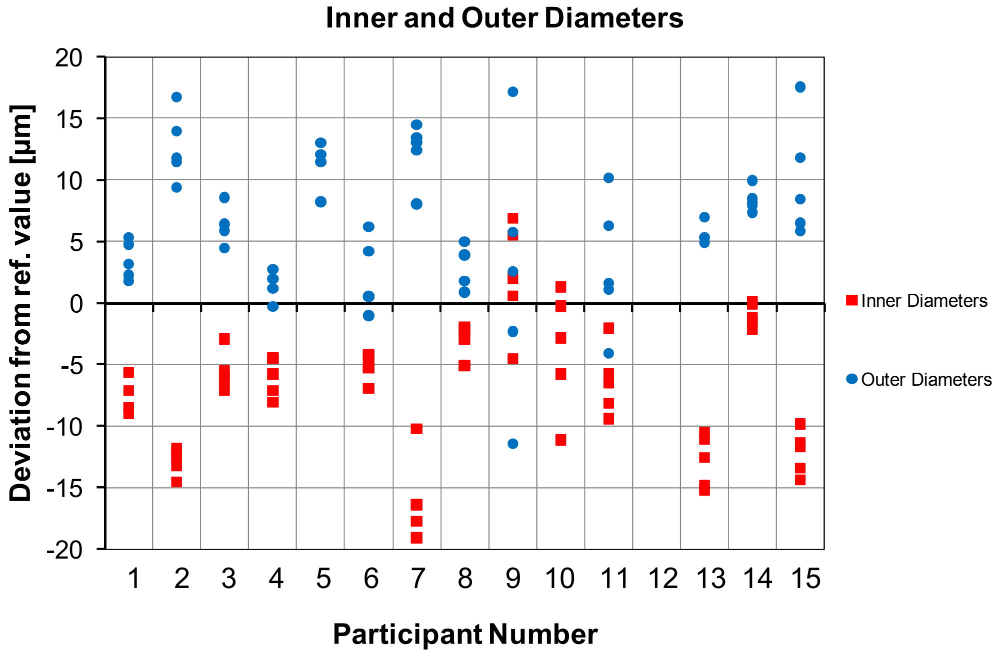

Figure 7: Item 2, results from Inner and Outer Diameters measurements.

In order to correct the lengths' measurements results of Item 2, the calibration values of the tubes diameters were distributed to all Participants at the end of the *CT Audit* round robin in March 2011. The values were obtained from CMM calibration. In particular, the Participants could use the calibrated internal and external diameters values to correct their systematic errors, including errors due to threshold determination and scaling factor. Each Participant was free to decide which correction procedure to apply and was asked to send the new lengths' results to the project coordinator. This second part was facultative, and only 6 Participants corrected their values; most of them obtained significant improvement from this correction of systematic errors. Results of Participant Nr. 10 has been reported as an example in Figure 8.

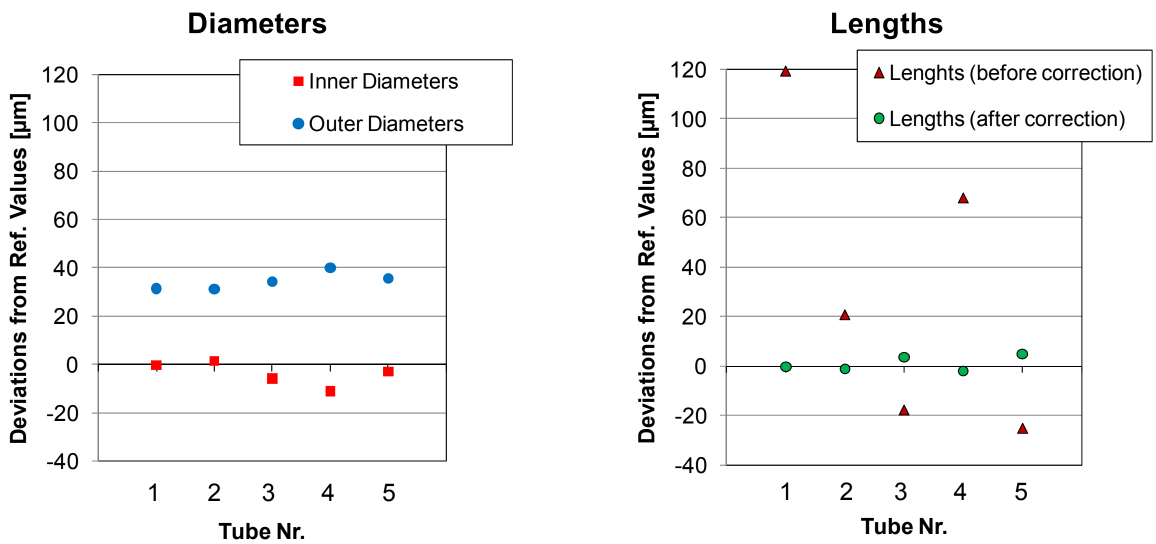

Figure 8: Item 2, results of Participant Nr. 10.

2.3 Item 3

12 CT Systems measured “Calotte Cube”. The Participants were asked to measure x, y and z coordinates of calottes centers respect to given reference coordinate system, diameters and form errors of the calottes, and also some selected distances between calottes.

Looking at Figure 9 it is seen that the E_n values are better ($|E_n|$ <1) for distances measurements than for diameters evaluations, and E_n of diameters are better than those of form errors. Distances between calottes, in fact, are less subject to the influence of specific errors, due to their bi-directionality. Form errors measurements, instead, are affected by the influence of scatter and noise of data. Indeed, measurement results show that there is an overestimation of the form error value by all Participants.

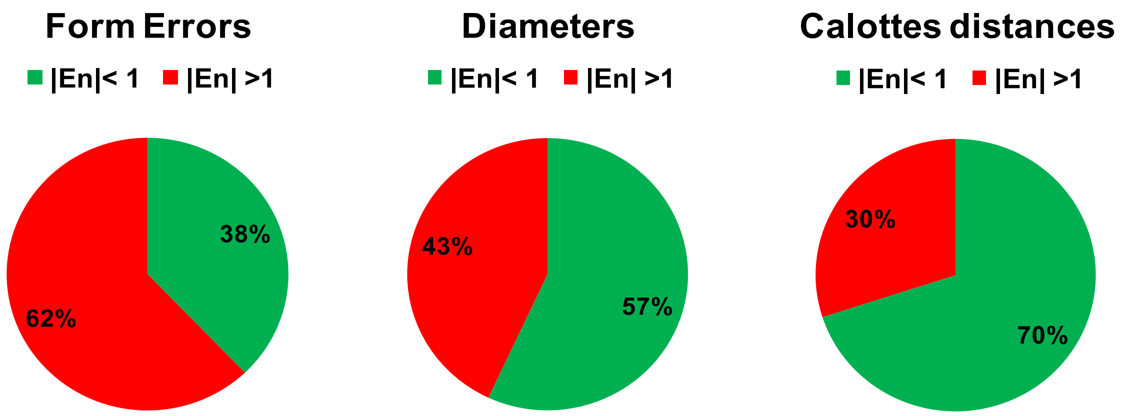

Figure 9: Item 3, E_n-values for Form errors, Diameters and Calottes Distances measurements, in percentage.

2.4 Item 4

8 CT Systems measured “QFM Cylinder”. The Participants were asked to measure Inner and Outer Cylinder diameters, Calottes diameters, Spheres distances of the ball plate, Diameter of the smallest cylindrical structure and the distance of the micro cylinder axis from the bottom face of titanium cylinder.

“QFM Cylinder” revealed to be the most challenging item to measure, indeed only 8 Participants measured it and the deviations from the calibrated values were higher compared to the other items. Since Item 4 is a relatively big item, some Participants decided to scan the object in three different ways, with their own magnifications and voxel sizes:

- The whole item,
- Only the top calottes,
- Only the top calottes.

In Figure 11, the results provided by Participant 4 are reported, in order to show the improvement obtained in terms of deviations concerning the Top Calottes Diameters. Top calottes have been measured twice, first scanning them with the whole sample and then with the top calottes in the centre plane of the image with a different magnification and voxel size. From Figure 10 it is possible to deduce that the second measurements are generally closer to the calibrated values.

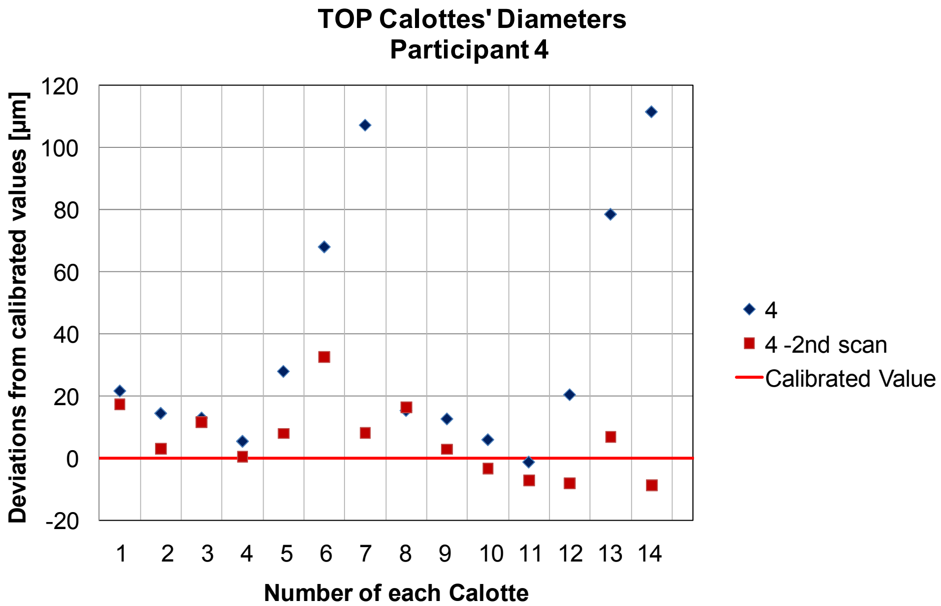

Figure 10: Item 4, Top calottes' diameters measured by Participant 4.

3. Conclusion and Further Developments

This paper presented preliminary results obtained from the first international interlaboratory comparison of CT systems for dimensional metrology. The comparison involved metrological verification of 15 CT systems in Europe, Asia and America. They were tested in the period March 2010 to March 2011.

For the comparison, a set of 4 different items was selected. The audit items were chosen in order to test several metrological characteristics of the CT systems. All the audit items were verified for dimensional stability with CMM calibrations before and after the circulation. Detailed measurement procedures were sent together with the calibrated objects to each Participant.

At the end of the comparison, a report is going to be produced where the results of the single Participants are analyzed and compared with the reference CMM calibrations. The most accurate results were achieved in the measurements of distances between spheres, especially referring to Item 1. Higher deviations were found in the measurements of form errors. The correct evaluation of measurement uncertainty has been confirmed to be a very difficult task in CT metrology, due principally to the numerous influence quantities in CT measurements.

An important outcome of the *CT Audit* project is the establishment of an international network of laboratories using CT dimensional measuring systems. This network is an important basis for further international collaborations in the field of metrological verification and uncertainty evaluation of CT systems. A meeting for discussing the results of the *CT Audit* project is going to take place in Padova (Italy) in October 2011.

References

[1] Kruth J.P., Bartscher M., Carmignato S., Schmitt R., De Chiffre L., Weckenmann A., (2011). Computed Tomography for Dimensional Metrology. Keynote paper. CIRP Annals, vol. 61/2 (in press).
[2] ISO/IEC 17043:2010, Conformity assessment – General requirements for proficiency testing
[3] Carmignato S., Pierobon A., Savio E., 2011, First international intercomparison of computed tomography systems for dimensional metrology, Proc. of 11th Euspen int. conf.; Como, Italy, 2011.
[4] CT Audit website: www.gest.unipd.it/ct-audit .