Combined techniques for network measurements at accelerator facilities

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1. Introduction

At the previous International Workshops on Accelerator Alignment members of the **metronom** company presented the TASA system that was developed by **metronom** GmbH Germany as a new alignment method including hardware and software. First it was about the new concept, thereafter the implementation and first results of the survey and alignment of accelerator facilities at GSi using the TASA system were discussed.
metronom provides the measurement services for most of the surveying and alignment tasks at the Gesellschaft für Schwerionenforschung mbH (GSi), the heavy ion research center in Darmstadt, Germany.
TASA stands for Tacheometric Accelerator Surveying and Alignment. The system is based on the use of a high precision totalstation Leica TC2002K, atmosphere sensors, electronic inclinometers, mobile pillars, fixed welded consoles as fiducial points at various appropriate positions of magnets, the principles of the Taylor Hobson centering and a complete software package.
At GSi the TASA system is successfully in use since January of 1996.

Usually network measurements at GSi are carried out by employing the Leica tachymeter TC2002K etc. Due to time constraints and the fact that GSi possesses only one of these selected, high precision totalstations, it was suddenly necessary to think about employing a Laser tracker as the major instrument for a reference network measurement.
The idea was to compare the different instruments and to proof if it is possible at all to carry out a precise network measurement using a laser tracker.

In the end the SMX Tracker4500 combined with Leica NA3000 for network measurements at GSi, Darmstadt and at BESSY II, Berlin (both located in Germany) was applied. A few results are shown in the following chapters.

A new technology in 3D metrology came up. Some ideas of applying these new tools in the field of accelerator measurements are given.

Finally aspects of calibration and checking the performance of the employed high precision instrument are pointed out in this paper.

2. Network Measurements

2.1 GSi, Darmstadt

GSI (Gesellschaft für Schwerionenforschung mbH, Darmstadt) operates a heavy ion accelerator facility consisting of the linear accelerator UNILAC, the heavy ion synchrotron SIS (energy of 1-2 GeV per nucleon), the storage cooler ring ESR and approximately 30 experimental setups. Up to now about 85% of the entire machinery have been surveyed and aligned with the help of the TASA system.

2.1.1 Subject

The synchrotron with a circumference of 216 m consists of 12 sections with altogether 24 Dipols, about 48 Quadrupoles and Sextupoles and some special components (see figure 1). In order to determine the actual geometrical condition of the heavy ion synchrotron (SIS), that has been in operation since 1989 without any complete realignment, a reference network should be established and surveyed with the TASA method.

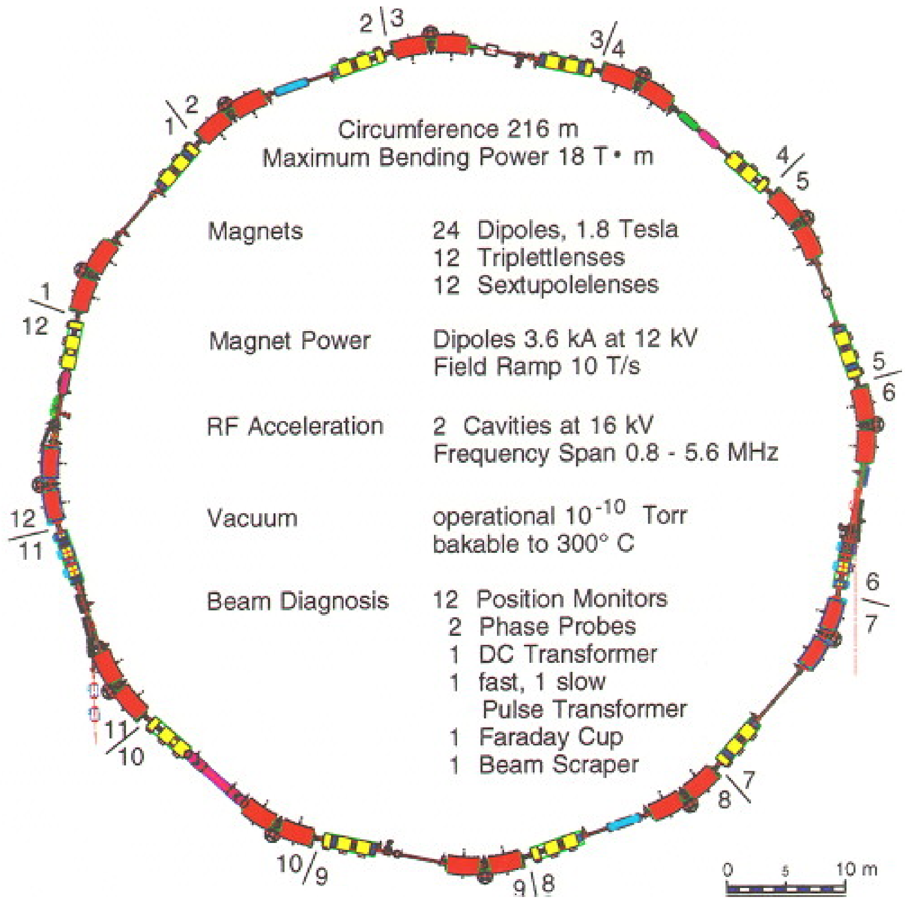

Figure 1 - Main features of the Heavy Ion Synchrotron (SIS), GSi Darmstadt

At the same time an alternative network should be measured with a laser tracker to verify the suitability of this instrument in the field of geodetic network measurements, concerning aspects of accuracy, time consumption etc.

2.1.2 TASA network

The TASA network for the SIS was defined by 11 mobile pillars, 12 instrument consoles fixed at the magnets and 2 consoles on the wall. Angle- and distance measurements were carried out employing the Leica TC2002K tachymeter that is used at GSI with its repeatedly checked standard deviation of 0.06 mm for distance measurements and a declared standard deviation of angle measurements of 0.15 mgon (0.5“) [1].
Furthermore the actual positions of all magnets of SIS were determined related to the reference network. Figure 2 shows a section of the TASA network to give an impression of the geometry. The large black points represent the reference points i.e. the instrument stations.

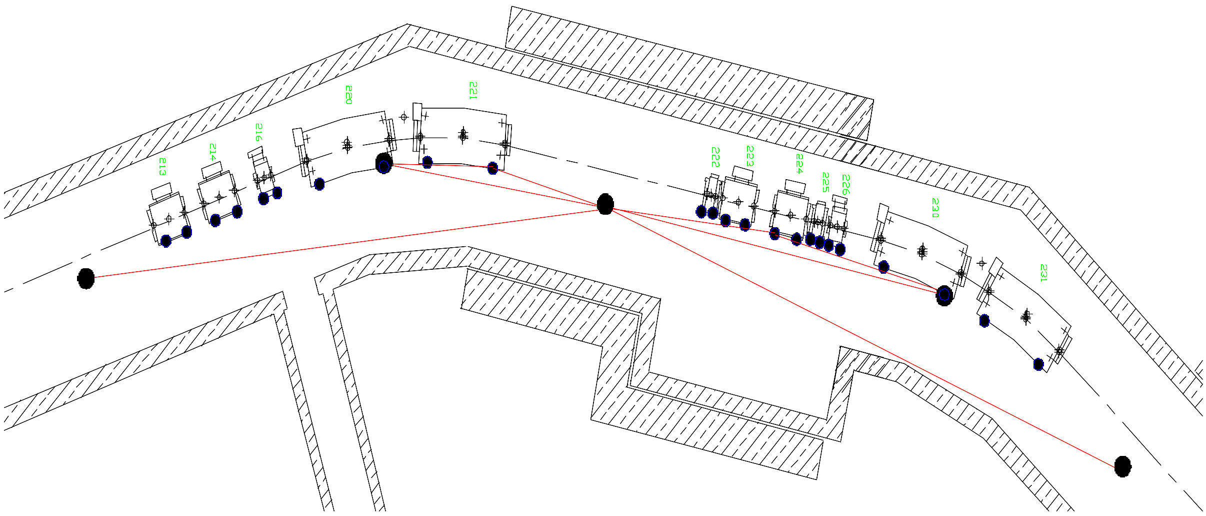

Figure 2 - Section of the TASA network at SIS

Measuring 25 reference points and 161 points at the magnets lead to 901 observations including leveling data to fix the elevation datum and to stabilize the network. Results of the least square adjustment process are coordinates of all points with a standard deviation of coordinates of typically 0.1 mm (x,y,z). More details are presented in [3].

2.1.3 Laser tracker network

The laser tracker network was defined by 24 instrument stations and 276 net points including points at the magnets and more than 100 tracker nests placed on the floor and the walls. The 3D coordinate determinations were carried out using the SMX Tracker4500.

A section of the laser tracker network at GSI is shown in figure 3. The red points represent the tracker stations, the yellow and green ones identify the tracker nests on the floor and walls while the magnet points are shown in blue colour.

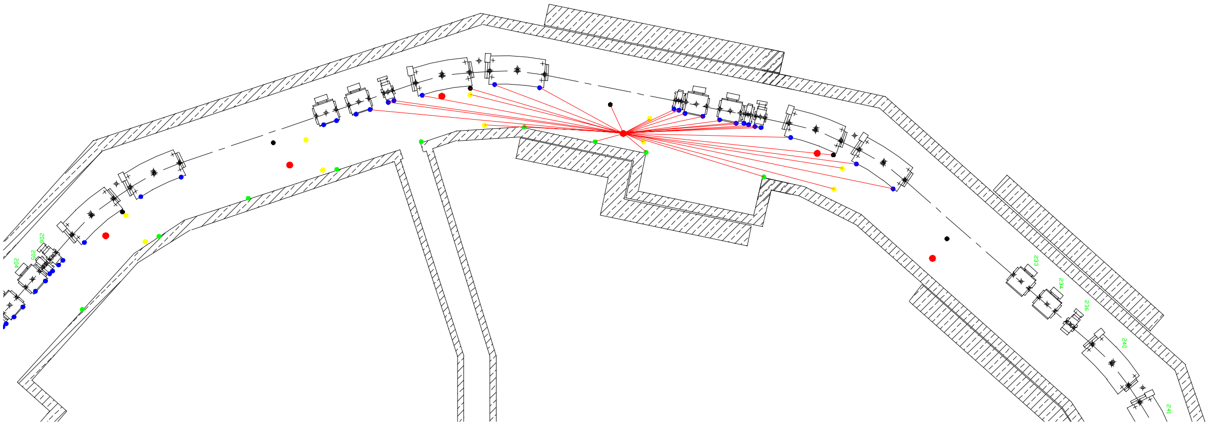

Figure 3 - Section of the Laser tracker network at SIS

Including height differences about 3110 observations had to be adjusted. This number is about 3 to 4 times higher than the number of tachymeter measurements.
The resulting standard deviation of coordinates are in a range of 0.01 mm (x / y axis) respectively 0.06 mm (z axis).

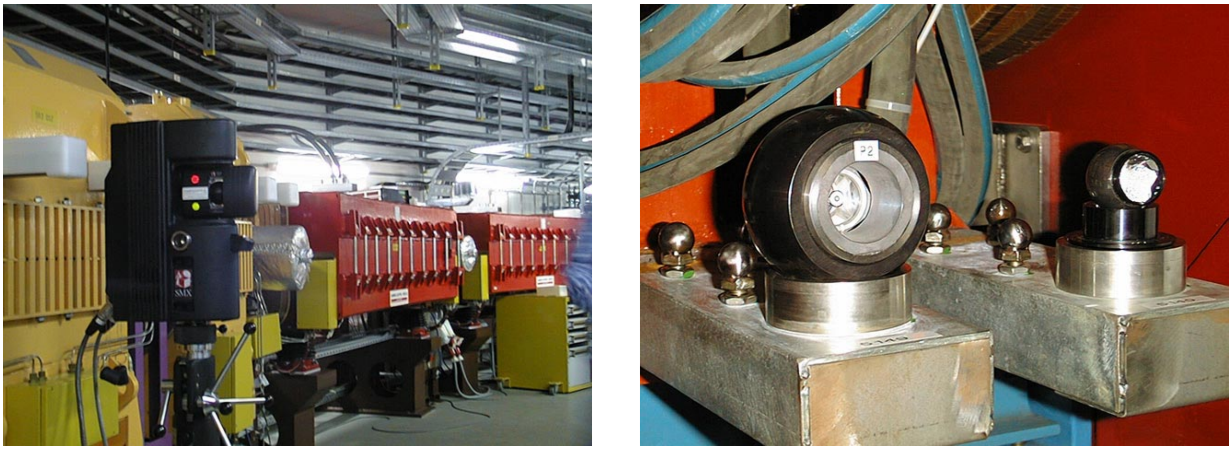

Figure 4 - Network measurement at SIS, GSi Darmstadt

2.1.4 Conclusion

As a result of the comparison of both methods we recognize that time consumption was about the same, however measurements done by laser tracker reduces man power. The accuracy of coordinates as a result of the laser tracker network adjustment is much better than the results of the TASA measurements. This improvement requires special measurement strategies. Furthermore the large number of observations requires qualified adjustment software.
An advantage of the laser tracker network is the free stationing that enables an optimal stand concerning line of sights or similar, but as opposed to the tachymeter network there are no

observations between the stations itself. Reliability increases if more observations are collected than needed. In order to achieve a net structure at all and to stiffen the laser tracker network, about 100 more points were needed compared to the TASA network..
More details are presented in [3].

2.2 BESSY II, Berlin

BESSY II (Berliner Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung mbH abbreviated BESSY) is a high brilliance synchrotron radiation source located in Berlin-Adlershof, Germany. BESSY II started operation in 1998 consisting of the synchrotron, the storage ring (energy of 1.7 GeV) and about 70 experimental stations.

2.2.1 Subject

In October 1998 we were requested to carry out a control network in the storage ring tunnel of BESSY II. The actual condition of the ring should be analyzed.
The storage ring with its circumference of 240 m is divided into 16 sections with 10 to 12 magnets each (see figure 5). A period of only one week was given to accomplish the entire measurements. At BESSY II the principles of the Taylor Hobson centering are used.

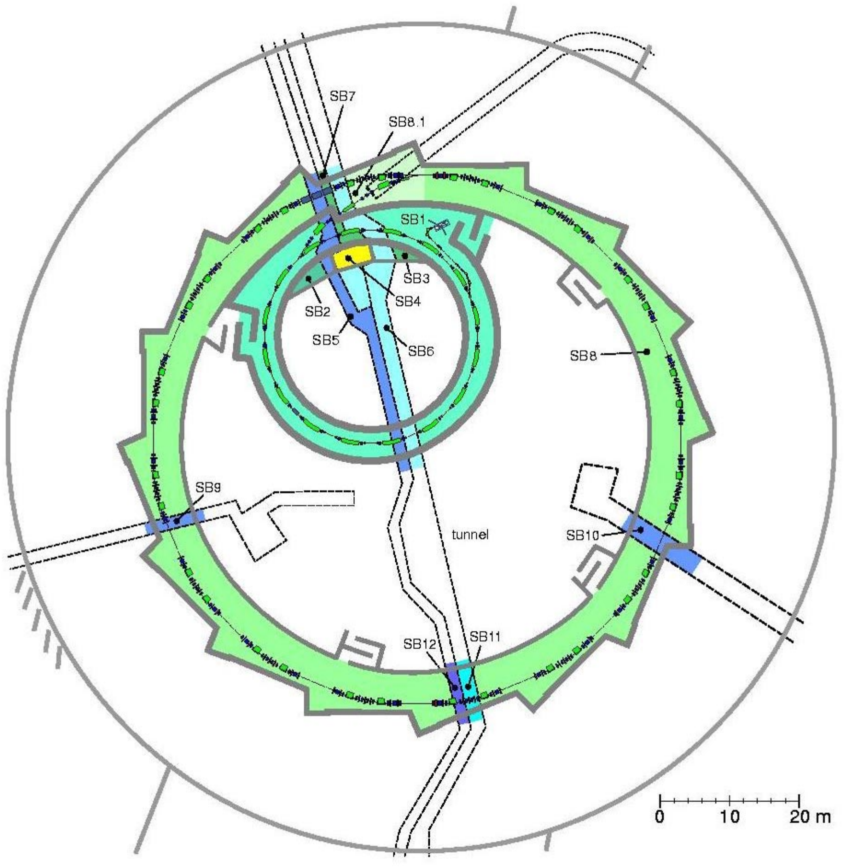

Figure 5 - Storage Ring of BESSY II

2.2.2 Laser tracker network

Although we had never seen the tunnel at BESSY II before, we decided to employ the SMX Tracker4500 because of our experiences obtained at the heavy ion synchrotron of GSI.
Paying attention to measuring strategies like doing two-face measurements, leveling the instrument on every station, placing connection points within the entire measurement volume and so on, we attempted to meet the requirement of less than 0.1 mm for the absolute error ellipses. Within 6 days we collected 3198 observations including height differences determined by precise leveling. 374 points (magnets, pillars and tracker nests) were measured in all, partly from up to 4 different stations.

2.2.3 Results

A least square adjustment was calculated with the help of PANDA, a software that is usually used for geodetic 3D network calculation based on observations of theodolites or tachymeters. At that time there was no other commercial software available that took into consideration the insufficient vertical axis tiltmeter integrated in the SMX Tracker4500.
The resulting standard deviation of coordinates (1σ) were in a range of 0.02 mm (x / y axis) respectively 0.06 mm (z axis). The large axis of the received absolute error ellipses amounts to 0.03 mm (x/y) respectively 3 times larger in z, i.e. in vertical direction. Error ellipses are shown in figure 6.

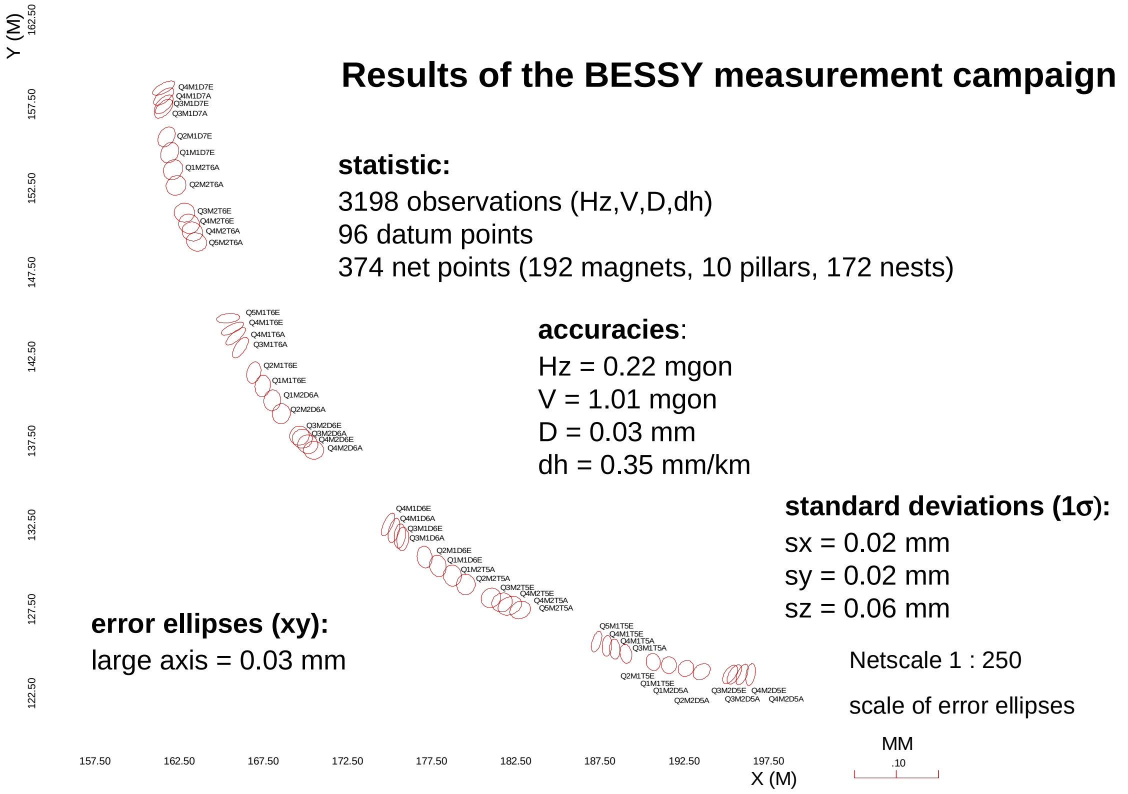

Figure 6 - Results of the BESSY measurement campaign

As a conclusion it is important to mention that it is possible on principle to carry out network measurements applying laser tracker. In order to strengthen the vertical component it is inevitable to do a precise leveling. A bundle adjustment that is now introduced into the new version of the SMX analyzing software helps to evaluate and interpret laser tracker network measurements more appropriate.

Figure 7 - Network measurement at BESSY II, Berlin

3. New Technologies

After 10 years of development a new 3D measurement technology emerged, designed for applications in industrial environments. Just as years before when the first laser tracker appeared on the market - initially to be a tool for aerospace or automotive industry - it deserves to think about possibilities to operate this measurement system within the accelerator area.

The new three-dimensional measuring instrument is called MetricVision 100B Coherent Laser Radar abbreviated MV-100B or simply CLR. Its innovative aspect is the eliminated need of any kind of cooperative target such as photogrammetry dots, laser tracker spherically mounted reflectors or retroreflectors while providing non-contact, auto-locating and precise measurements of surfaces and points or scan features.

The CLR consists of a distance measuring device based on an infrared laser and a turning and tilting mirror with encoders for angle measurements. An integrated color video camera helps targeting measurement areas. A red visible Laser is used for beam positioning.

Figure 8 - Coherent Laser Radar

3.1 Characteristics

The MetricVision 100B Coherent Laser Radar is a portable coordinate measuring machine which is said to have features that set it apart from conventional metrology technologies:

Precise
with range accuracy to within 2.5 ppm

Robust
allowing measurements of over 60 meters with a tiny 700 microwatt laser

Non-contact
does not require cooperative targets, nevertheless photogrammetry dots, laser tracker SMR´s or various steel balls are useable

Fast
making 1000 measurements per second

Versatile
insensitive to surface reflectivity (from 5% to 100% in infrared frequency)

Flexible
FM Laser radar can measure through mirrors, eliminating line-of-sight constraints

Eye-Safe
Class I Laser Radar

3.2 Visions

Up to now there are no experiences in applying the CLR at any accelerator facility. The presented features open a wide range for speculations how to employ the instrument within this specific area of metrology.
One of the most import aspect might be the possibility to carry out measurements with or without any target. The system does not rely upon expensive optical / mechanical targets. It is thinkable to equip the fiducial points of magnets with steel balls instead of rather more expensive SMR´s while measuring with a laser tracker. Resulting from the aspect of reducing the costs it might be possible to fit out different components with several steel balls and to align them at the same time, also due to the CLRs ability to measure in an automated unattended data acquisition mode. The capability of using all available targets within only one set-up should also be taken into account. Any objects that would pose targeting problems e.g. due to its size are ideal candidates for precise measurement with the CLR. Targets like affordable steel balls could be fixed on components or experiment installations and remain there not only during one session but the complete length of time measurements are ever required.

These few aspects can only be suggestive of the various possibilities one might have concerning the requirements of accelerator alignment. We are looking forward to implement this powerful new tool within the field of accelerator surveying and alignment, to find out if it meets the requirements, and to present the first results at the next International Workshop on accelerator alignment.

4. Performance Check

When we talk about high precision measurement systems we certainly should not forget aspects of proving and calibration to achieve the specified accuracy. Mostly errors are eliminated by certain measurement strategies, visiting a calibration field and/or using different internal check routines.

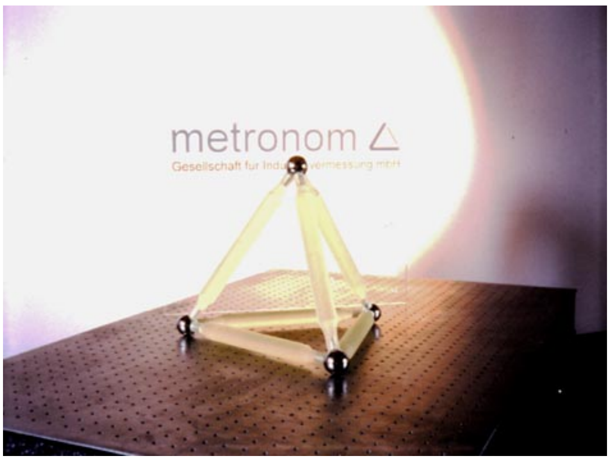

Figure 9 - **Tetronom**: 3D-check and calibration artifact

According to our experiences the customer is very often no metrology expert so that these proving methods does not satisfy him because of the insufficient transparency. There is a need for a check method that is possible to carry out very fast, easy but effective, on-site and independent of the instrumentation.

Our approach to check the performance of different kinds of high precision measuring systems and to increase the acceptance of the results is a new patented 3D-check and calibration artifact called **Tetronom**. This **Tetronom** is in the first instance formed as a tetrahedron consisting out of 6 calibrated bars and 4 (1.5 inch diametric) balls or targets kept together by magnetic power. Because of the form of a tetrahedron there are no internal constraints.

4.1 Features

The **Tetronom** is the tool to validate easily and very fast if the equipment is within specification concerning 3D operations. Measuring 4 targets - that may be photogrammetry targets, spherically mounted reflectors, theodolite spheres, ... see figure 10 - leads to 6 lengths, 12 angles and a volume. The results are compared to the certified nominal values.

The advantages of the **Tetronom** are based on its genuine 3D structure, the variety of targets, bar materials and lengths that shows the compatibility to different measuring systems as photogrammetry and theodolite systems, laser tracker, articulating arms, ... It is easy to build up and down. Its compact size and little weight enables a good portability.

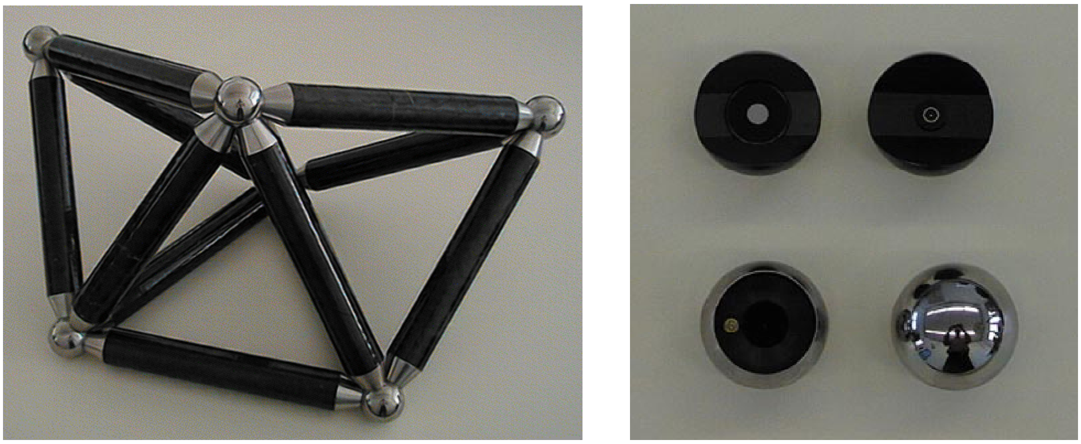

Figure 10 - **Tetronom**: Variety of targets and shape

4.2 Technical Characteristics

As shown before the use of different kinds of targets are useable. The bars are available in different materials and different lengths. ZERODUR, a kind of glass, and carbon fiber, that have a remarkable small thermal extension, as well as other materials are available.

Material	Thermal expansion	Bar lengths	Weight	Certified (PTB) Accuracy
		[mm]	[kg]	[µm]
ZERODUR	$< 0.1 \times 10^{-6}$ °K^{-1}	400	5.1	2
ZERODUR	$< 0.1 \times 10^{-6}$ °K^{-1}	900	10.4	3
CFK / V2A	$< 0.2 \times 10^{-6}$ °K^{-1}	400	3.1	4
CFK / V2A	$< 0.2 \times 10^{-6}$ °K^{-1}	900	4.2	5
CFK / V2A	$< 0.2 \times 10^{-6}$ °K^{-1}	2000	6.2	7
Steel	11.5×10^{-6} °K^{-1}	900	6.2	10
Aluminum	23.0×10^{-6} °K^{-1}	900	5.0	20

Table 1 – Technical characteristics

No comparable testing body has been established yet. The **Tetronom** is a product of **metronom** and will be introduced into market at the beginning of year 2000.

5. References

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[4] MetricVision Homepage *http://www.metricvision.com*

[5] MetricVision 100B Product Guide

[6] J. Blondeau, S. Obenauer, ***Tetronom:*** *A new testing body for large measurement volumes*, CMSC 1999, Seattle, USA