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COMPARISON OF ATLAS TILECAL MODULE No. 8 HIGH-PRECISION METROLOGY MEASUREMENT RESULTS OBTAINED BY LASER (JINR) AND PHOTOGRAMMETRIC (CERN) METHODS

V. Batusov [a], *J. Budagov* [a], *J. C. Gayde* [b], *J. Khubua* [a], *C. Lasseur* [b], *M. Lyablin* [a], *L. Miralles Verge* [c], *M. Nessi* [b], *N. Rusakovich* [a], *A. Sissakian* [a], *N. Topiline* [a]

[a] Joint Institute for Nuclear Research, Dubna

[b] CERN, Geneva

[c] IFAE, Barcelona

The high-precision assembly of large experimental set-ups is of a principal necessity for the successful execution of the forthcoming LHC research programme in the TeV-beams. The creation of an adequate survey and control metrology method is an essential part of the detector construction scenario. This work contains the dimension measurement data for ATLAS hadron calorimeter MODULE No. 8 (6 m, 22 tons) which were obtained by laser and by photogrammetry methods. The comparative data analysis demonstrates the measurements agreement within ± 70 μm. It means, these two clearly independent methods can be combined and lead to the rise of a new-generation engineering culture: high-precision metrology when precision assembling of large scale massive objects.

Для успешного выполнения предстоящей исследовательской программы LHC на ТэВ-ном пучке необходима высокоточная сборка крупногабаритных экспериментальных установок. Создание адекватного метрологического метода обзора и контроля — важная часть подготовки сценария создания детекторов. Работа содержит данные обмера модуля №8 (6 м, 22 т) адронного тайл-калориметра установки ATLAS, полученные лазерным и фотограмметрическим методами. Сравнительный анализ данных показывает, что точность совпадения выполненных измерений составляет ± 70 мкм. Это означает, что рассматриваемые два независимых метода могут быть объединены для создания инженерной метрологии нового поколения — прецизионной сборки крупногабаритных, массивных объектов.

INTRODUCTION

The ATLAS hadron tile-calorimeter is composed [1] of one central barrel and two extended barrels (Fig. 1). Radially the tile-calorimeter extends from an inner 2.8 m to an outer 4.25 m radius. Azimuthally, the barrel and extended barrels are divided into 64 MODULES. Dubna began mass production of barrel modules in April 1999. To guarantee very high MODULES assembly precision, we proposed, developed and practically applied a new unique laser control system [2, 3]. The laser control system instrumentation and a brief description of the method see in Appendices 1 and 2.

In January 2000, the JINR and CERN groups measured the ATLAS tile-calorimeter MODULE No. 8 dimensions by the laser and photogrammetric methods at CERN.

The photogrammetric instrumentation and method are documented in Appendix 3.

During these measurements the MODULE was kept at the same position which allowed one to obtain the data for comparison of both methods. Clearly, these measurement methods are fully independent.

It must be also noted that the MODULE No. 8 was measured by standard surveying method using theodolites for industrial 3D metrology before the application of the photogrammetric method; the standard deviation (1σ) according to the DIN 18723 norm is given to 0.15 mgon (0.5°) for measurements of both horizontal and vertical angles. See the results on http://edms.cern.ch/document/309991/1

A small reference network was arranged around the MODULE in such a way that the theodolites sights were nearly parallel to the faces: therefore, the accuracy for the coordinate perpendicular to the face was given by the high-precision angle measurements.

The survey results for both the geometric methods and the comparisons have been documented in the reports noted in Appendix 4.

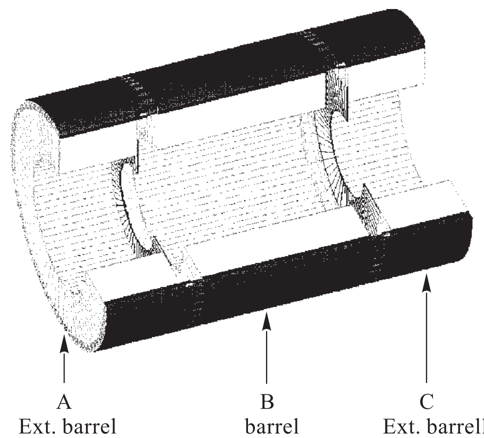

Fig. 1. The tile-calorimeter barrel and two extended barrels

In two sets of measurements (photo and laser) we had the following four measurement lines (common for both methods) on the MODULE surface [3] (see Fig. 2):

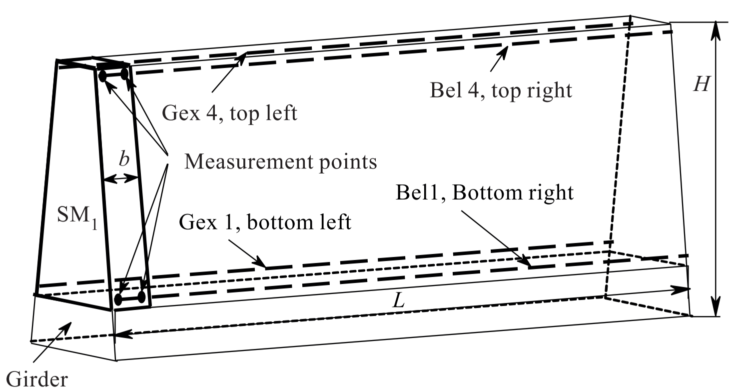

Fig. 2. Measurement lines on the MODULE surface

— Bottom-left line[1] of the laser method coincides with the bottom-left line Gex 1[2] of the photogrammetric method;

— Top-left line coincides with Gex 4;

— Bottom-right line[1] coincides with Bel 1[3];

— Top-right line coincides with Bel 4.

Comparison was made only along these lines.

In the photogrammetric method the measurement points were located (Fig. 2) on the submodule (SM) surface at a distance of $1/4 \times b$ from the submodule edge (b is the submodule width). The MODULE height $H = 1940$ mm and its length $L = 5600$ mm.

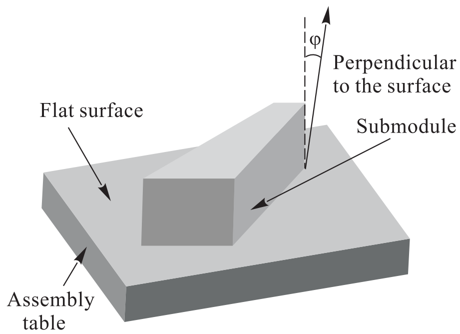

Fig. 3. Definition of submodule maximal twist angle φ

In the laser method the measurement points were located on the submodule edges. This location of the measurement points was motivated by the presence of the submodule twist angle φ (Fig. 3) and, consequently, only at such a positioning one can detect (observe) the parts, going farthest beyond the limits of the MODULE. We note that the top-lines data will expectedly demonstrate the largest discrepancies in comparison with the bottom-lines data as it is in the narrow part of the submodule where one observes the maximal twist angles φ reaching the value of 10^{-4} rad.

1. COORDINATE SYSTEMS (CS)

Requirements to the CS. When choosing CS, it seems natural to fix it to some element of the MODULE. It should be taken into account that the dimensions and shape (form) of such element (surface, edge) may differ from its shop-drawing dimensions (nonflat, not straight-lined, twisted, etc.).

As a result, systematic errors may arise and deteriorate final measurement precision.

In this sense it seems essential that the systematic error should be at worse comparable with the measurement precision. Otherwise the choice of the CS can give a distorted idea of the MODULES measured.

CS of JINR Laser Method. The choice of the CS is determined by the Dubna technology of the MODULE assembly [1]. The centre «0_L» of the CS is chosen in the middle of the bottom edge of the girder base surface from the side of submodule 1 (see Fig. 4).

• The Y_L axis goes along the line, which connects the point 0_L, and point «N», which is the middle (centre) of the bottom base of the girder at the side of submodule 19.

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[1]The left (right) side of the MODULE is the side on the left (right) of the observer looking from the SM_1 along the MODULE.

[2]Direction to the town Gex.

[3]Direction to the town Bellegarde.

• The Z_L axis goes along the line connecting the point 0_L and point «M» in the middle of the edge of the narrow part of the special submodule from the side of the endplate.

• The X_L axis is perpendicular to the Z_L and Y_L axes.

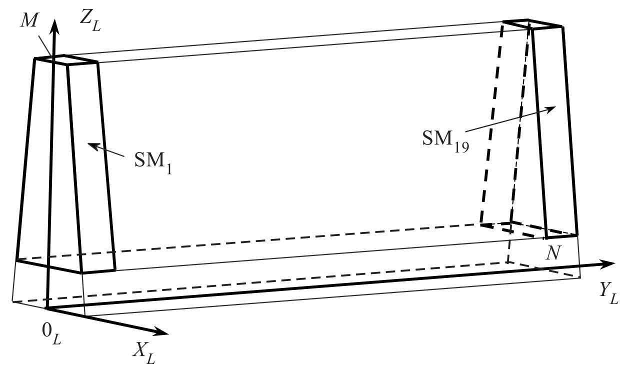


Fig. 4. Coordinate system of the laser method

CS of the CERN Photogrammetric Method and Measured Points. The four extreme corners of the girder were measured and set in the same horizontal plane within a max.–min. of 0.1 mm with using a precise optical level (precision of a direct measurement is 30 μ, then precision of a vertical difference between 2 corners is 42 μ).

The distances between the corners were measured within an accuracy of 0.1 mm using a precise electro-optical distancemeter associated with a metrological class theodolite as mentioned above. Then the coordinate system for the photogrammetry is referred to the plane of the girder, set horizontal, and to the four corners of the girder, altogether within 0.1 mm; so that margin value is referred to the procedure of setting the four extreme corners of the girder horizontal by using a precise optical level.

The coordinate centre «0_P» is the centroid of the four bottom corners of the girder (Fig. 5).

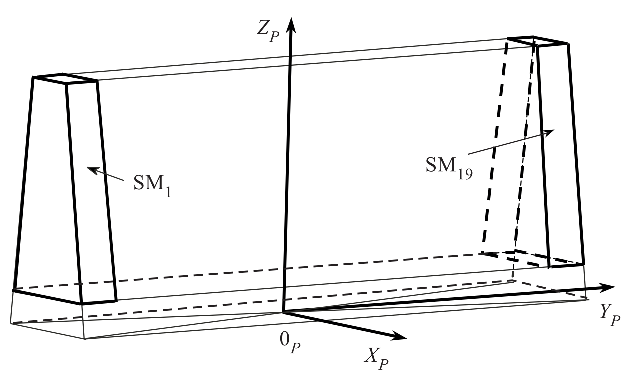


Fig. 5. Coordinate system of the photogrammetric method

• The Y_P axis is in the mean plane of the four corners and parallel to the girder longitudinal axis.

• The Z_P axis is perpendicular to the mean plane of the four corners.

• The X_P axis is in the mean plane of the four corners at the origin and perpendicular to the Y_P axis.

The plane $X_P 0_P Y_P$ is horizontal within 0.1 mm, i. e., 0.02 mrad as a longitudinal tilt angle and 0.2 mrad as a transversal tilt angle; the Z_P axis is vertical within the same accuracy along the two angular components.

Despite the accuracy of the photogrammetric process, within 50 μ spatially at 1σ, and in order to include the uncertainty on the definition of the CS, all the results documented in the reports were given within 100 μ accuracy.

In fact the four corners, measured by standard precise level and metrological class theodolite, were also measured by photogrammetry so that the coordinates given by that method were directly expressed in the CS as described above.

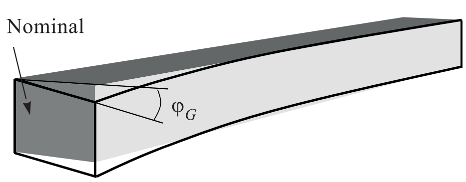
Each submodule was equipped with 16 coded retroreflective targets (3×3 cm), 8 on each side and arranged by two at four levels quoted respectively at 0.35, 0.88, 1.44, and 1.77 m from the reference mean plane of the four corners measured and set horizontal as described above. That regular arrangement permitted one to calculate the thickness of the module at each level, to give the median plane at each level, i. e., the misalignment with respect to the reference axis of the girder and then the spatial banana shape of the entire MODULE. Finally there were 152 points measured on each side for the definition of the MODULE envelope and its geometrical parameters, all referred to the girder as defined above.

In addition to these parameters, the best fit plane was calculated for each side as well as the differences for each point to the mean plane so that the max. and min. values were identified easily. The wedge angle was calculated for the entire MODULE and could be extracted for each submodule.

Comments on the CS of the CERN photogrammetric method. 1. The girder may have the following (compared with the drawing) distortions measured at JINR by the Dubna survey group:

• The girder may have the «twist» angle φ_G (Fig. 6); we measured this angle by the minilevel: $\varphi_G = 10^{-4}$ rad.

• The girder may have a banana shape (Fig. 7).



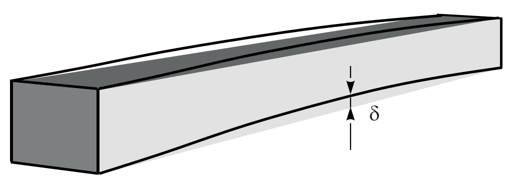


Fig. 6. «Twist» of the girder

Fig. 7. Sagging («banana») of the girder

Sagging may reach a value of $\delta = 0.6$ mm. As the girder bottom surface is not flat, the possible final effect is that the CS can be not orthogonal. It seems to us that this is practically impossible to take this effect into account as one cannot determine the shape of the bottom girder base (down plane) for the already assembled MODULE.

2. The lines of the long side edges of the bottom girder base are not straight-lined and sagging may reach $\delta_{\max} = 0.6$ mm (Fig. 8).

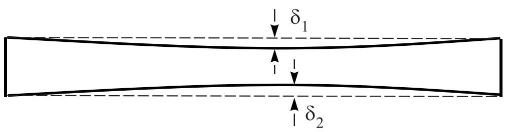


Fig. 8. Sagging of side edges of the girder bottom base

The difference $\delta_1 \neq \delta_2$ may lead to the asymmetric location of the coordinate centre 0_P.

3. As was already said, the girder arrived from Romania with some residual «twist» along the longitudinal axis and this twist may reach $\varphi_G = \pm 2 \cdot 10^{-4}$ rad (our data for girder 12). One can measure the twist before the MODULE is assembled, or before submodules are positioned. After the MODULE is fully assembled, the twist amplitude will change in an uncontrolled manner. If, however, one assumes that this change is insignificant, one can conclude that the vertical axis of the girder is oriented to the angle $\varphi_K = \pm 2 \cdot 10^{-4}$ rad relative to the vertical axis of the submodule (see Fig. 9). This effect (twisting of the girder) will finally influence the photogrammetric data: the measured «distance» (distance from the ideal MODULE surface to the nearest points of the real MODULE) will be larger on the one side of the MODULE and smaller on the other. In other words, the pseudo-worsening of the photogrammetric measurement data will take place.

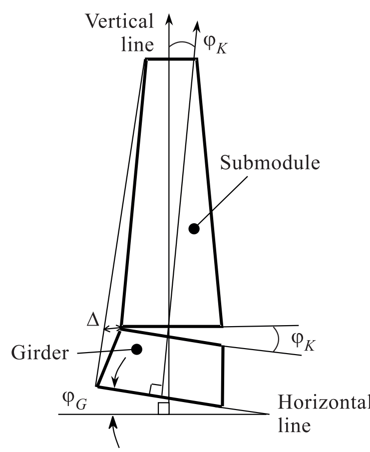


Fig. 9. Relative position of the submodule and of the «twisted» girder

It must be noted at that stage that one advantage of the photogrammetric method is to give a full complete geometrical envelope of the MODULE referred to a proper reference attached to the object itself, namely, the girder which is the real backbone of the assembly of the MODULES. See the section on the measured points.

Comments on the CS of the JINR laser method. According to «item 3» (see above) the systematic error will appear in determination of the coordinates of the bottom-line along the X axis. The magnitude of this error (for maximal observed $\theta = \pm 2 \cdot 10^{-4}$ rad of the girder twist) will be $\Delta = 60$ μm, which is compatible with the measurement precision. Note that following the MODULE assembling technology, the girder is to be positioned on the base unit in such a way that its «twist» must be symmetric about horizontal line (Fig. 9).

2. DATA PRESENTATION

The results of both methods are presented in the form of the table (see Appendix 5) of deviation of the measured points from the surface of the nominal MODULE (Fig. 10).

— Top size «A» is the size that coincides with the width of the narrow part of the master plates in the indicated place.

— The «1–2–3–4» contour coincides with the contour of the master plates.

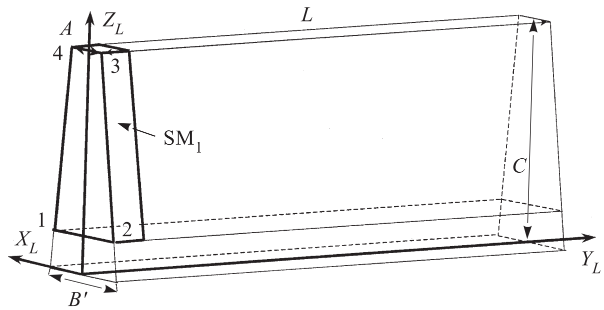


Fig. 10. Position of the nominal MODULE in the laser method coordinate system

For the laser method the dimensions of the nominal MODULE are:
$A = 223.31$ mm, top (narrow) base;
$B = 408.80$ mm, bottom (wide) base;
$C = 1942$ mm, height;
$L = 5600$ mm, length;
$B' = 414.16$ mm, theoretical dimension derivable as a result of master plates imaginary extension on the 1942 mm height.

The nominal MODULE must be positioned in such a way that positive maximal deviations of both sides of MODULE became equal (sort of «symmetrization» of the positive deviations).

3. RESULTS OF COMPARISON

Transformation of the Laser Data to the Photogrammetric Data. Figure 11 presents nontransformed (primary) data for both methods (see item 1 of the comments on the CS of the photogrammetric method). Recall that the twist angle $\varphi = \pm 2 \cdot 10^{-4}$ was determined for the girder of MODULE No. 10.

We find it rather logical to assume that the MODULE No. 8 twist is also $\varphi \approx \pm 10^{-4}$.

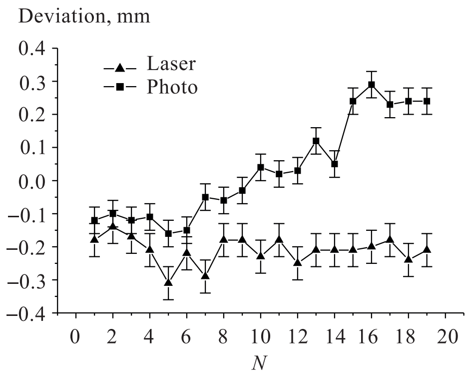
If so, one may expect that (attention!) MODULE No. 8 in the laser measurements will be turned as a whole by an angle of $\approx 10^{-4}$ rad as compared with the photogrammetric method.

This assumption is confirmed by the measurement data disposition (Fig. 11). Indeed, if one turns the laser set of measurements by an angle $\theta_0 = 0.8 \cdot 10^{-4}$ along the Y axis, the laser data set practically coincides with the photogrammetric series.

One more disagreement between the data of both methods is clearly visible (see Appendix 5). The envelope top overall size chosen in the photogrammetric method (the A value in Fig. 10) is 0.3 mm narrower than in the laser method (see Appendix 5).

Direct caliper measurements of the outer dimensions of the master plates on the narrow part (these are the dimensions which determine the envelope top overall dimension) indicate that the master plates were manufactured about 0.3–0.4 mm smaller than the nominal size. It is in favor of the overall dimension chosen in the laser method (see item 3).

To reach the most complete data coincidence we turned the laser data by an angle $\theta_0 = 0.8 \cdot 10^{-4}$ rad with respect to Z axis and also made the overall dimension noncontradicting in



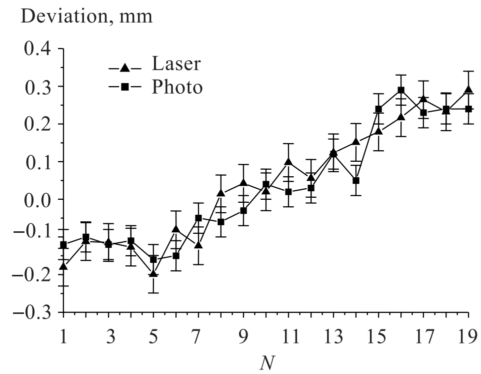


Fig. 11. Line Bel 1 measurement data by the photogrammetric and laser bottom-right methods with no correction applied for MODULE No. 8

Fig. 12. The same as in Fig. 11 but after correction (turn by $0.8 \cdot 10^{-4}$ rad)

both methods (Fig. 12). The value obtained for θ_0 agrees with the above estimate correction angle $\approx 10^{-4}$ rad.

In Figs. 11, 12 the data analysis shows good agreement for the shapes of the curves, too. Appendix 6 represents a very full data set and shows that after «turning» correction (see above) laser and photogrammetric results are in agreement with the precision quoted on the hystogram. The σ value of the distribution of $D_L - D_P$ differences (or «distances»), measured by the laser and photogrammetric methods is: $\sigma_b = 65$ μm for bottom lines; $\sigma_t = 90$ μm for top lines.

As was mentioned in the introduction, the σ_t value for the top lines always turns out to be larger than σ_b.

All the above results confirm the quoted measurement precision. The coincidence of the shapes of the distributions of the results obtained by both methods is enough to state that both methods are close in precisions.

CONCLUSION

Measurements performed by both methods indicate that MODULE No. 8 is within tolerance (0.6 mm from the nominal size).

Impressive coincidence of both laser and photo fully independent methods has been achieved by applying two corrections:

— turning of the laser method data by an angle $\theta_0 = 0.8 \cdot 10^{-4}$ rad with respect to the Z axis;

— correction of the nominal MODULE width in the nominal MODULE top part (see item 3, size «A») chosen in the photo method; this correction is based on direct measurements of size «A».

So the results of measuring the «MODULE geometry» by both methods coincide with an accuracy of about $(\sigma_b + \sigma_t)/2 \approx 80$ μm.

All the above-said allows one to conclude that, as we understand:

It seems very important to use both methods (they are independent) for fulfilling such a complex technical task as the precision assembly of the barrel hadron calorimeter and a much more difficult task like final assembly of all ATLAS systems in the near future.

The joining of the JINR and CERN groups' efforts might lead to the rise of engineering culture of a new generation: high-precision metrology when precision assembling of large-scale massive objects.

Acknowledgements. The CERN team would like to express their gratitude to the JINR team for having initiated that study and incorporated the photogrammetry concepts and results.

Some other persons from the CERN team participated in the regular measurements of the tile MODULES: Katia Nummiaro, Dirk Mergelkuhl, Jean-Frédéric Fuchs, for the photogrammetric parts — measurements, analysis and report; Jean Noel Joux and André Froton, for the geometrical preparatory works.

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2. *Alikov B. A. et al.* Metrological Inspection of MODULES of Hardon Calorimeter for ATLAS Detector. Tile Cal. Inter. Nat. Note No. 79. 1997.
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Appendix 1
LASER MEASUREMENT SYSTEM (LMS)

Parts of the measurement equipment we use, are precision instruments industrially produced: CALIPERS (± 20 μm precision) and MINILEVEL ($\pm 10^{-5}$ rad/m precision).

The special laser measurement system (Fig. 13), we have designed and constructed, has a potential of precision of ± 50 μm when operated over a distance of typically 6 m in length. The gaining factor has been in the combination of this precision to an operation and manipulation simplicity for this device.

The LMS has been designed and constructed for the control of the surface geometry. The LMS (Fig. 14) consists of a laser and photo-detector (PhD) built up by four independent parts; both the laser and the PhD are fixed on special and high-precision adjustment units.

The LMS measurement principle was proposed by the authors for an earlier [2] application. Its principle is based on the measurements of the distance $H(i)$ between the surface under control (LL') and the axis of the laser beam directed in a quasi-parallel way to that surface (Fig. 14). By positioning the PhD detector at different positions $A(i)$, the associated values of $H(i)$ are determined by adjusting (using a system of a microscrews) the centre of the photo-detector relative to the laser beam. The full surface geometry is determined by a series of such measurements (Fig. 15).

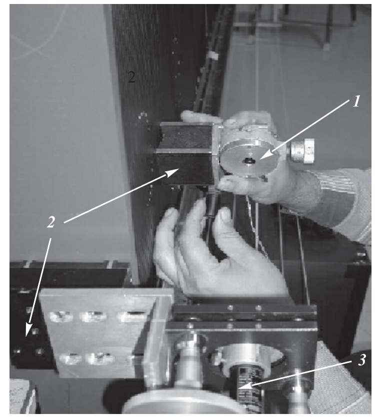


Fig. 13. Measurement system: *1* — quadrant photodiod; *2* — magnetic bases; *3* — laser

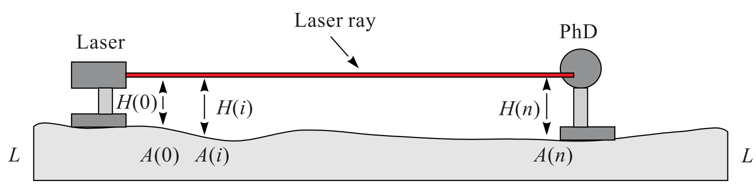


Fig. 14. LMS measuring principle

The measurement precision is limited by the precision of the adjustment system and by the air convective fluxes, which can be noticeably improved by positioning the laser beam inside a special telescopic dielectric tube.

Multiple measurements done with our LMS have shown that the standard deviation value for individual $H(n)$ measurements on a 6 m long calibrated base is 30 μm. By adding to this the intrinsic precision, the precision of the positioning of the LMS system on the surface to be measured (specific submodules surface), the resulting measurement precision for the entire area $(1.9 \times 5.6$ m) of the MODULE side surface is within ± 50 μm.

Fig. 15. LMS during assembly and quality control

Appendix 2
DUBNA LASER MEASUREMENT SYSTEM MAIN COMPONENTS

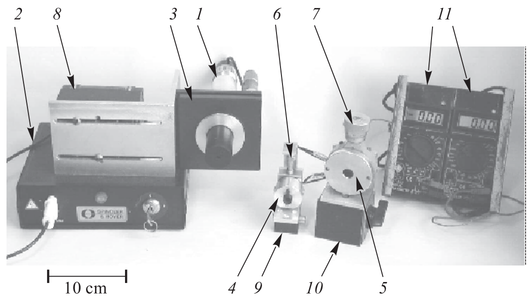


Fig. 16. Dubna Laser Measurement System main components: *1* — laser; *2* — power module; *3* — adjustment module; *4, 5* — quadrant photodiode devices (*4* — type I; *5* — type II); *6, 7* — positioning module (*6* — type I; *7* — type II); *8, 9, 10* — magnetic base (*8* — type I; *9* — type II; *10* — type III); *11* — multimeters

Appendix 3
GEOMETRICAL AND PHOTOGRAMMETRIC OPERATIONS FOR THE MODULE No. 8

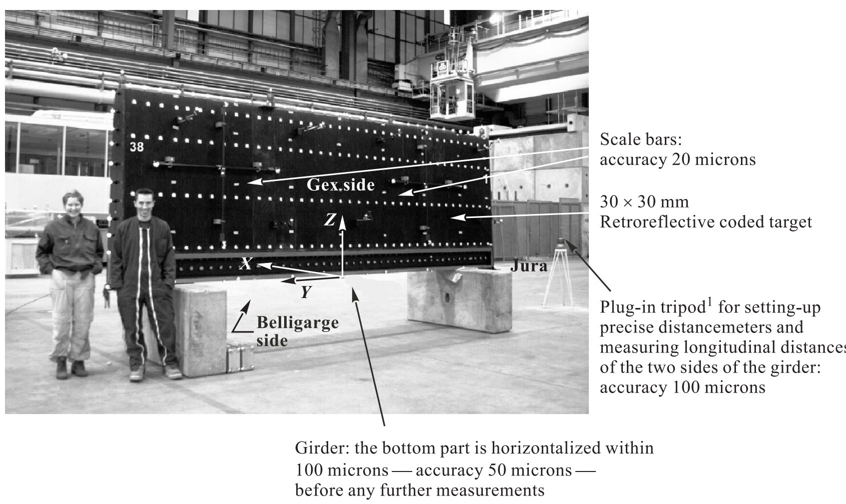
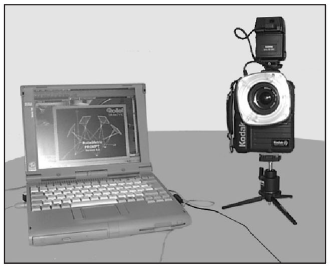


Fig. 17

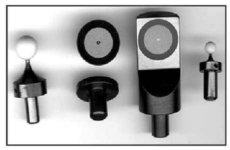
The MODULE No. 8 was measured at CERN in January 2000, first by theodolite (see the results on http://edms.cern.ch/document/309991/1) then by photogrammetry (see the results and the comparisons on http://edms.cern.ch/document/309987/1).[1]

[1]This tripod was also used for the first measurement by theodolite: specific targets were hold in the gap between two successive plates so that the target was referred to the average external surface of four successive plates apart the gap.

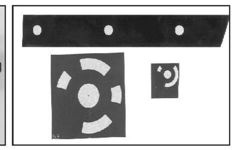
CERN MAIN PHOTOGRAMMETRIC EQUIPMENT



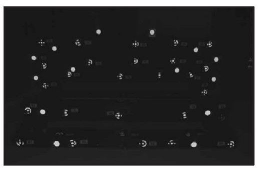
— DCS 460 — sensor CCD ⇒ 6 millions pixels/pixels = 9 m
— 18, 20, 24 mm lenses
— Rollei DPA/CDW software package



Usual retro-reflective targes



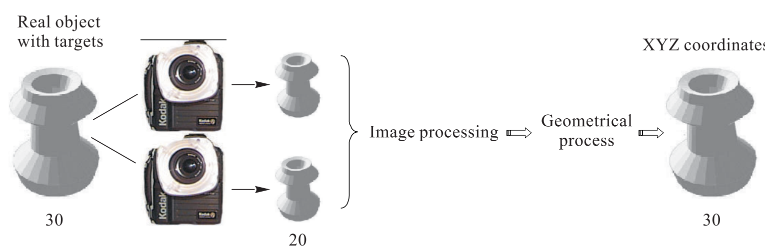
Strips and coded labels



f/16, f/22 ⇒ under-exposed photos
⇒ necessity of reflective targets and annular flash
⇒ good contrast
⇒ image processing precision = 1/30 pixel = 0.3–0.4 m

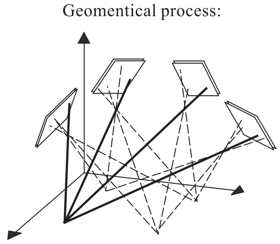
Fig. 18

Appendix 4
WHAT IS DIGITAL PHOTOGRAMMETRY?
...3-D COORDINATE MEASURING TECHNIQUE



At least two images from two different locations. One cannot measure the object itself... but its image.

Geomentical process:



1. Multi-image orientation
Resection = process that enables one to know
the camera position and aiming angles
Triangulation = intersecting lines in space,
computes the location of a point in all three dimensios

⇒ Approximate positions and approximate coordinates
= 3 translations + 3 rotations

Fig. 19

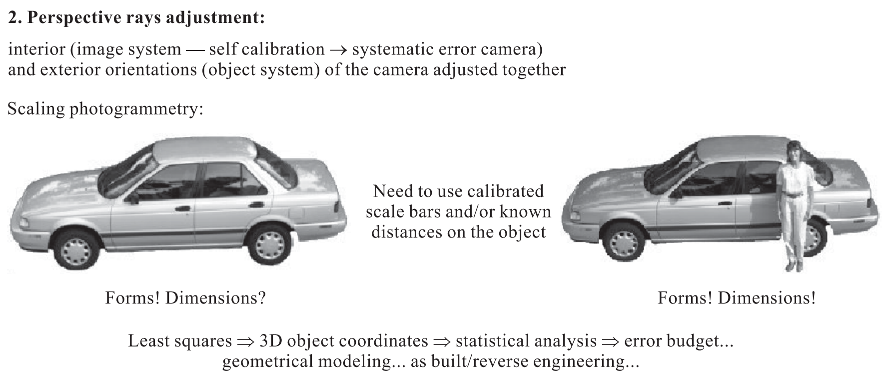


Fig. 20

Appendix 5
DEVIATION OF THE MEASURED POINTS FROM THE SURFACE OF THE NOMINAL MODULE

The results of the LASER (Bot R, Top R, Top L, Bot L) and photogrammetry (Bel 1, Bel 4, Gex 4, Gex 1) methods are presented in the form of the table of deviation of

Table 1

No. of submodule	Right side				Left side			
	Distance for bottom line		Distance for top line		Distance for top line		Distance for bottom line	
	Bel 1	Bot R	Bel 4	Top R	Gex 4	Top L	Gex 1	Bot L
1	−0.12	−0.18	0.04	−0.28	0.22	−0.23	0.30	−0.18
2	−0.10	−0.14	0.11	−0.14	0.13	−0.35	0.23	−0.21
3	−0.12	−0.17	0.17	0.06	−0.10	−0.44	0.28	−0.22
4	−0.11	−0.21	0.14	−0.13	−0.02	−0.33	0.19	−0.17
5	−0.16	−0.31	0.08	−0.34	0.00	−0.22	0.18	−0.12
6	−0.15	−0.22	0.19	−0.22	−0.11	−0.24	0.10	−0.19
7	−0.05	−0.29	0.21	−0.08	0.21	−0.44	0.06	−0.28
8	−0.06	−0.18	0.14	−0.11	−0.10	−0.12	−0.07	−0.25
9	−0.03	−0.18	0.22	−0.16	0.12	−0.22	0.04	−0.19
10	0.04	−0.23	0.29	−0.06	−0.27	−0.26	−0.04	−0.18
11	0.02	−0.18	0.07	−0.32	−0.16	−0.28	−0.14	−0.29
12	0.03	−0.25	0.12	−0.41	0.06	−0.05	−0.04	−0.21
13	0.12	−0.21	0.08	−0.40	0.00	−0.01	−0.11	−0.25
14	0.05	−0.21	−0.06	−0.54	0.06	0.18	−0.04	−0.19
15	0.24	−0.21	−0.05	−0.49	0.18	0.14	−0.03	−0.20
16	0.29	−0.20	−0.16	−0.70	0.33	0.26	−0.06	−0.24
17	0.23	−0.18	−0.09	−0.58	0.38	0.52	−0.06	−0.17
18	0.24	−0.24	−0.25	−0.86	0.33	0.35	−0.14	−0.22
19	0.24	−0.21	−0.29	−0.96	0.38	0.48	−0.16	−0.21

the measured points from the surface of the nominal MODULE for each submodule. The left (right) side of the MODULE is the side on the left (right) of the observer looking from the SM1 along the MODULE

Appendix 6
RESULTS OF COMPARISON

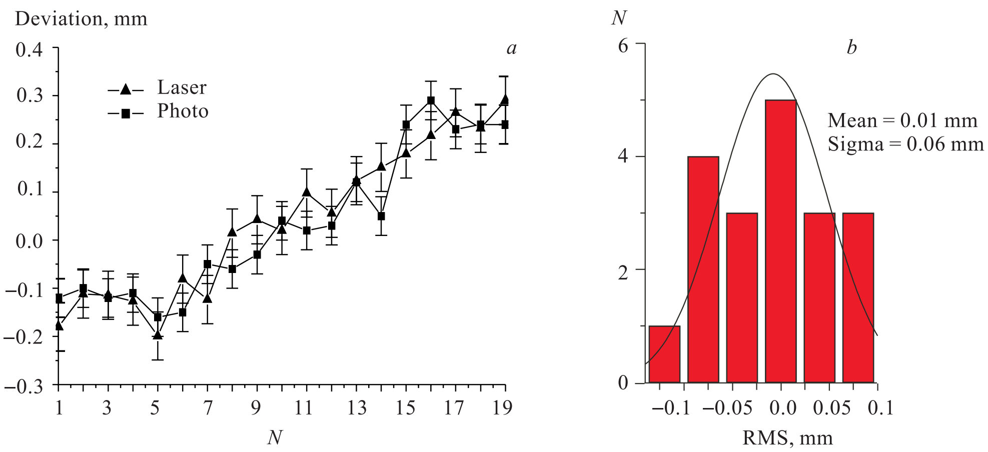


Fig. 21. Line Bel 1 measurements data by the photogrammetric and laser bottom-right methods after correction (turn by $0.8 \cdot 10^{-4}$ rad)

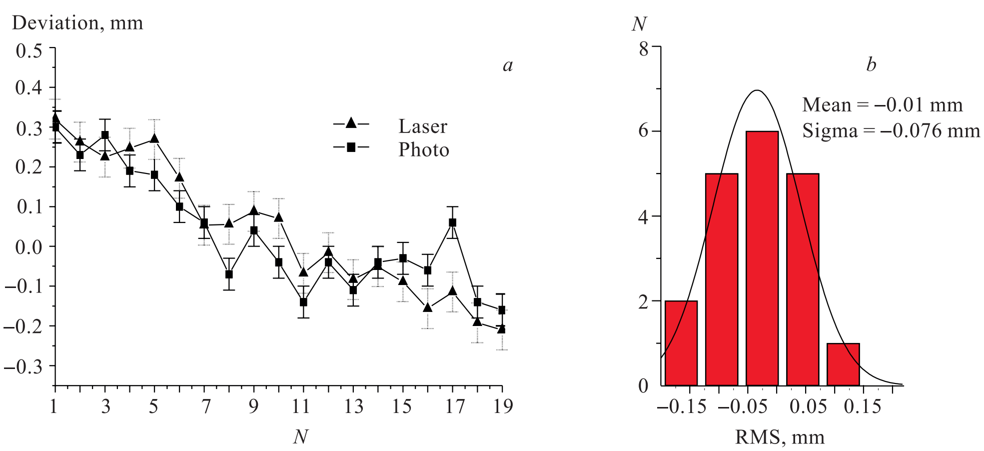


Fig. 22. Line Gex 1 measurements data by the photogrammetric and laser bottom-left methods after correction (turn by $0.8 \cdot 10^{-4}$ rad)

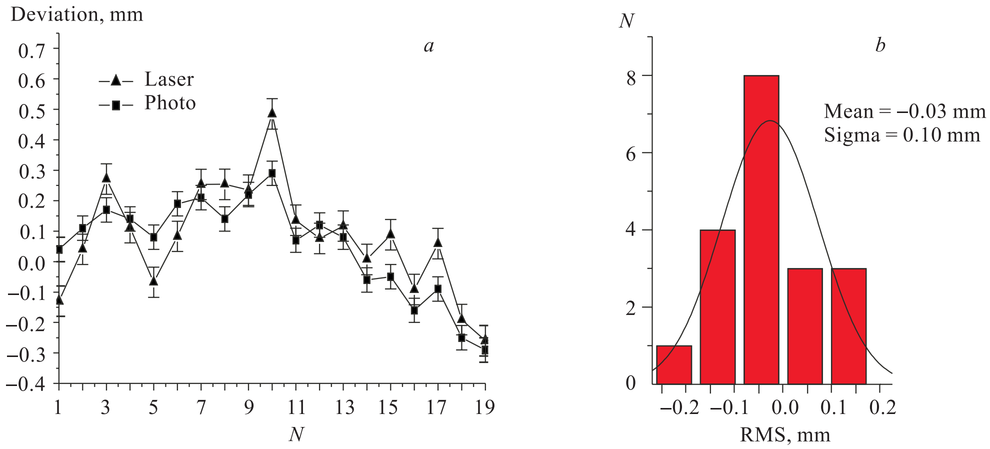


Fig. 23. Line Bel 4 measurements data by the photogrammetric and laser top-right methods after correction (turn by $0.8 \cdot 10^{-4}$ rad)

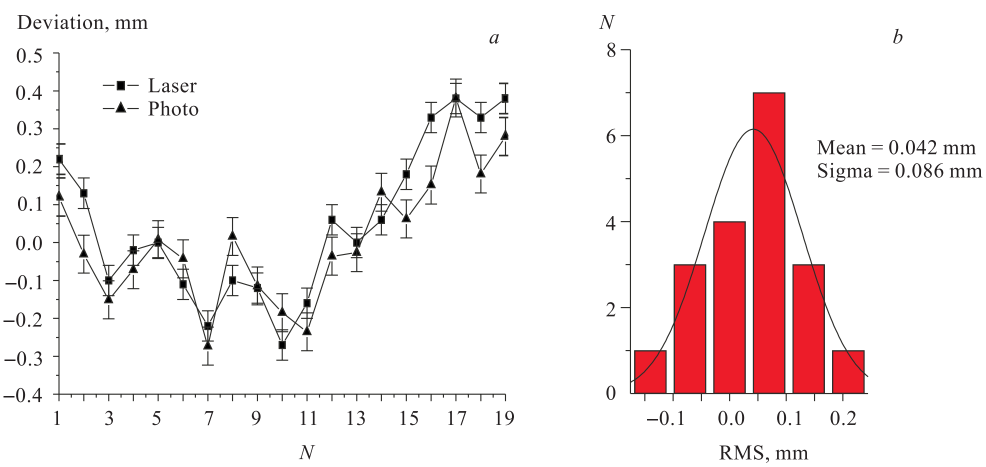


Fig. 24. Line Gex 4 measurements data by the photogrammetric and laser top-left methods after correction (turn by $0.8 \cdot 10^{-4}$ rad)