DIGITAL PHOTOGRAMMETRY APPLIED TO LARGE PHYSICS DETECTORS
NCSX project – Visit PPPL, 8 and 9 October 2007
EDMS 873287

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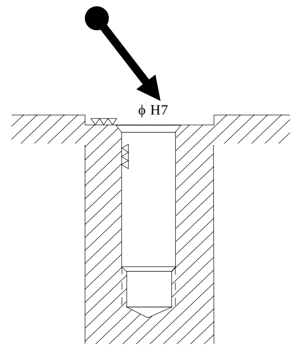
- **Basic Principles → Why digital photogrammetry ? …**
- **CERN basic and specific photogrammetric equipment**
- **Estimation and preparatory works**
- **Some examples plus significant examples**
- **Original approach … the real object**
- **Arising problems and a wishing list**
- **Specific tests and results**
- **Conclusion**

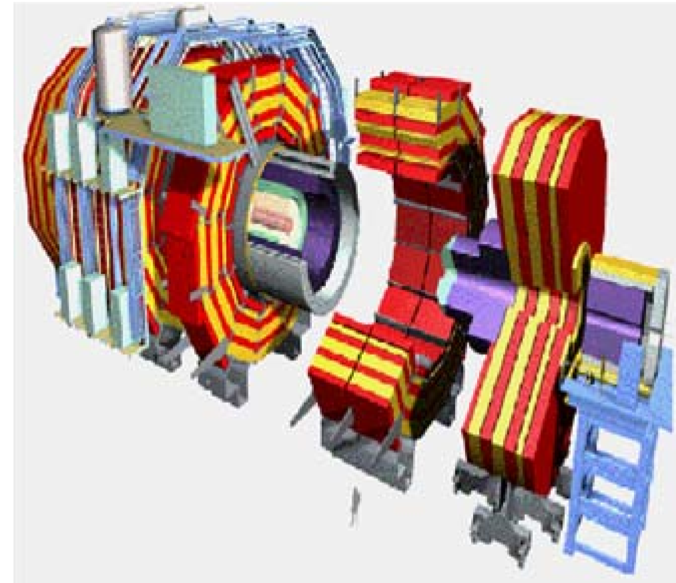
Basic Principles → Why digital photogrammetry ? …

A collider experiment is a composite element … CMS

→ Russian-doll configuration : reference → fiducial marks



What we see … What we want



To give the XYZ positions of the subsequent layers and also …

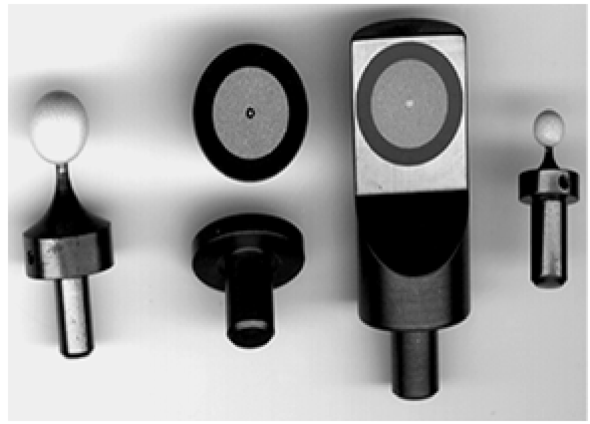
- verification of forms and dimensions, deformation tests (control FEA results),
- control after each assembly step, give ‘approximate’ values for on-line physics analysis,
- from < 30 microns up to better than 500 microns : large range of dimensions and volumes
- various assembly places and status : out-site , halls, caverns, mobile structures (in/out)

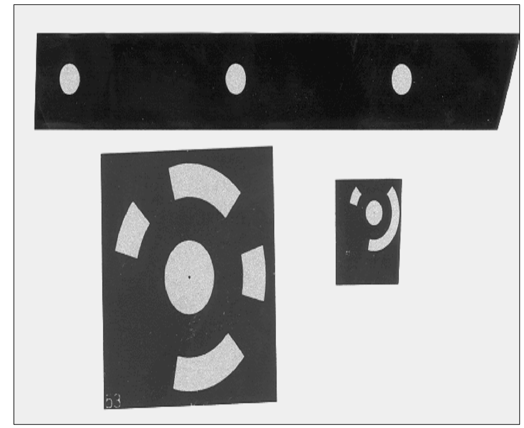
portability, versatility, accuracy, reliability, reduced time, reduced team ...

⇨ DIGITAL PHOTOGRAMMETRY since 1998 !

CERN basic photogrammetric equipment …

- DCS 660 / D2X … ‘non metric camera’
- 18 mm, 20 mm, 24 mm lenses
- Format: 24 mm * 36 mm
- Rollei DPAWin, 3DSTUDIO, option FiBun





retro-reflective targets centered in reference hole

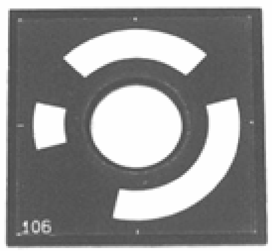
strips and coded labels (paper or on magnetic supports): 12, 14 et 20 bits

f/16, f/22 … under-exposed photos … large depth of field

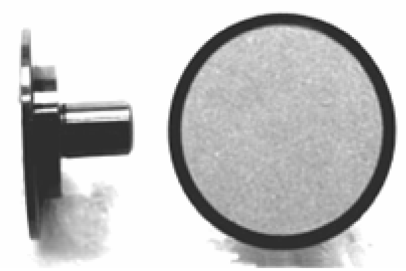
… 7 pixels in diameter illuminated, various dot diameters

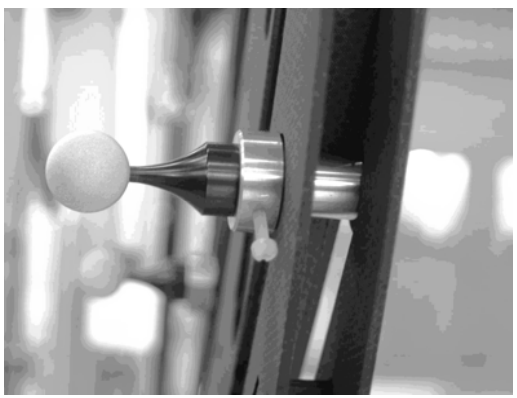
… also ‘paper target’: un-and coded

… and specific equipment



large code-extended ring on magnetic foil around a 40 mm retro-button for long distances





15 mm / 25 mm retro-sphere … wide view angle

<u>Environmental constraints …</u>

- **long recording distances, cramped zones**
- **connections between numerous faces**
- **deformation under loading**

synchronized up to 5 cameras …

- **nearly on-line → relative motion / deformation**
- **BUT precision limited by stability and no auto calibration of camera**

Some important 'using' and 'users' configurations

IMAGE RECORDING DISTANCE → object dimensions … and form

TARGET DIAMETER → image recording distance + object + target diameter

DEPTH OF FIELD → recording distance, environment, aperture

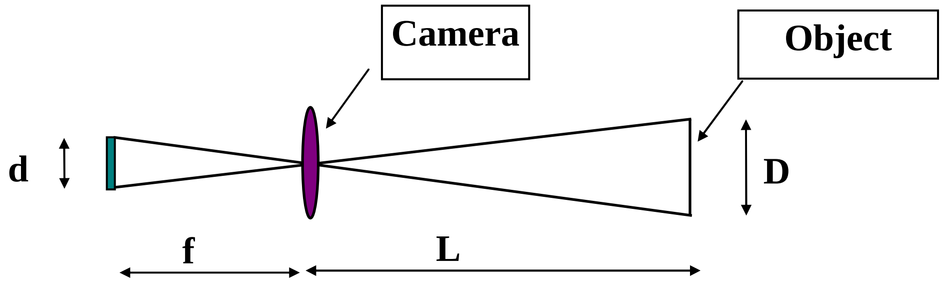
UNCERTAINTY OF COORDINATES ('plane' and depth) → recording distance, uncertainty images coordinates, configuration,

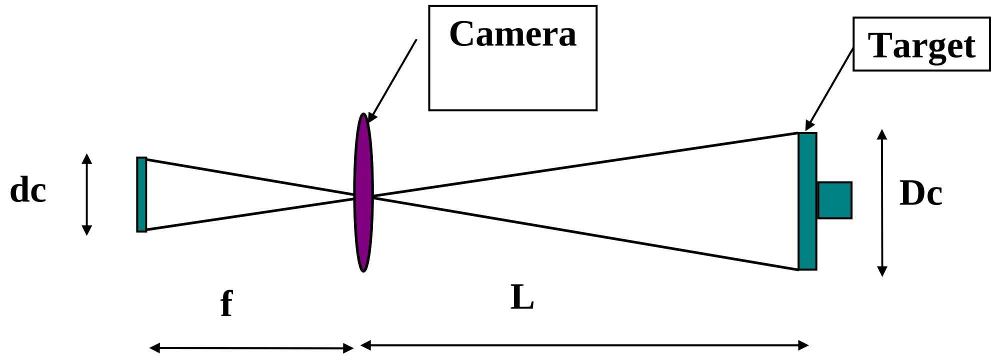
OFFSET MEASURED CENTER AND REAL CENTER → 'intersection' angles, targets diameters

d (d') : width/height CCD sensor,
f = focal lenght, L : recording distance,
D (D') = WIDTH/HEIGHT OBJECT
→ D (D') = d (d') / f * L

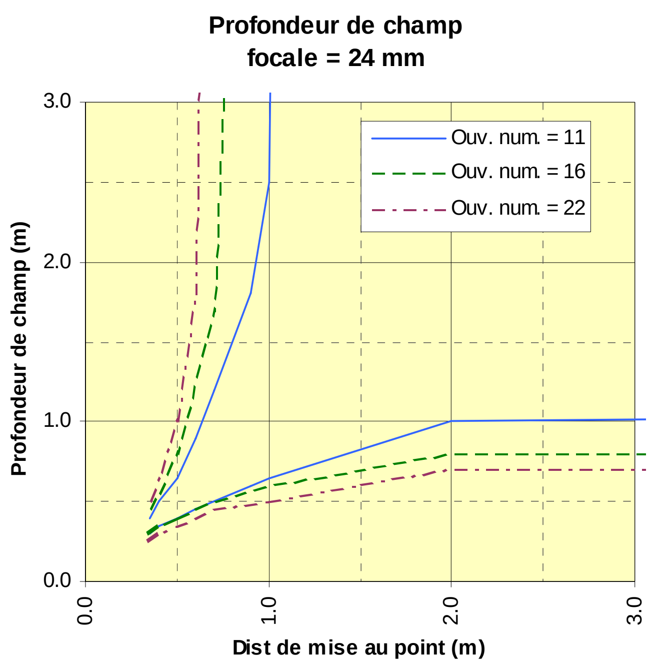
dc : target diameter on the sensor

Dc : real target diameter
→ $dc = (D \times f / L) \times 9.10^6$ (pixel width)





Depth of field : 1 m to infinite …



Coordinates uncertainty

Sig obj = object coordinates uncertainty (1 sigma)
Sig img = image coordinates uncertainty (1 sigma) -
f = focale lenght
L = recording distance
q = configuration factor w.r.to the number of photos (literature, experience …)

→ q = 2 for :

- **Good intersection angles in the three planes !!**
- **Good overlapping in both directions (1/3)**
- **Good distribution and 'full' format**
- **Object always in the image !!!**

→ Sig obj = q × L × Sig img / f

Standard Sigma image = around 0.3 µm namely 1/30 pixel.

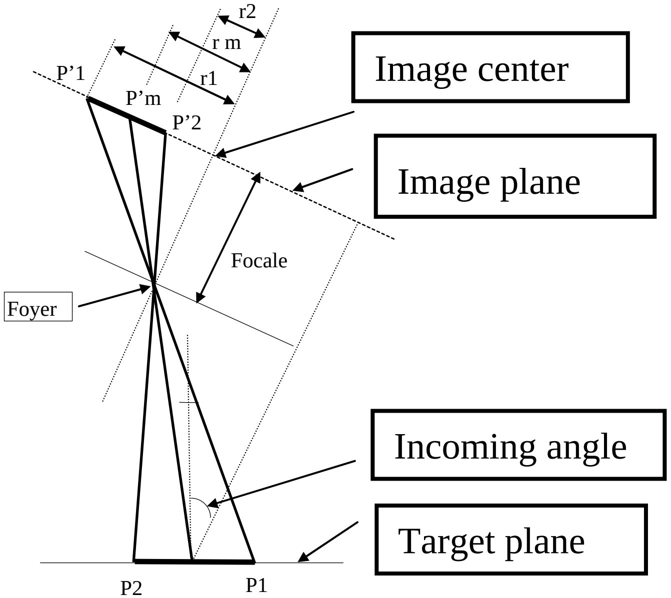
- IF bad conditions : hided targets requiring several close stations, poor lights

→ 0.45 µm (1/20 pixel)

-VERY good conditions : not too many points/stations) BUT well distributed in 3D, good lights and contrasts (some tests before for settings)

→ 0.20µm (1/40 pixel)

When the targets are oversized and the image plane rarely parallel to the object surface, (principalement si les cibles utilisées sont surdimensionnées), there is an offset that may be larger then the uncertainty, the circular target being projected as an ellipse



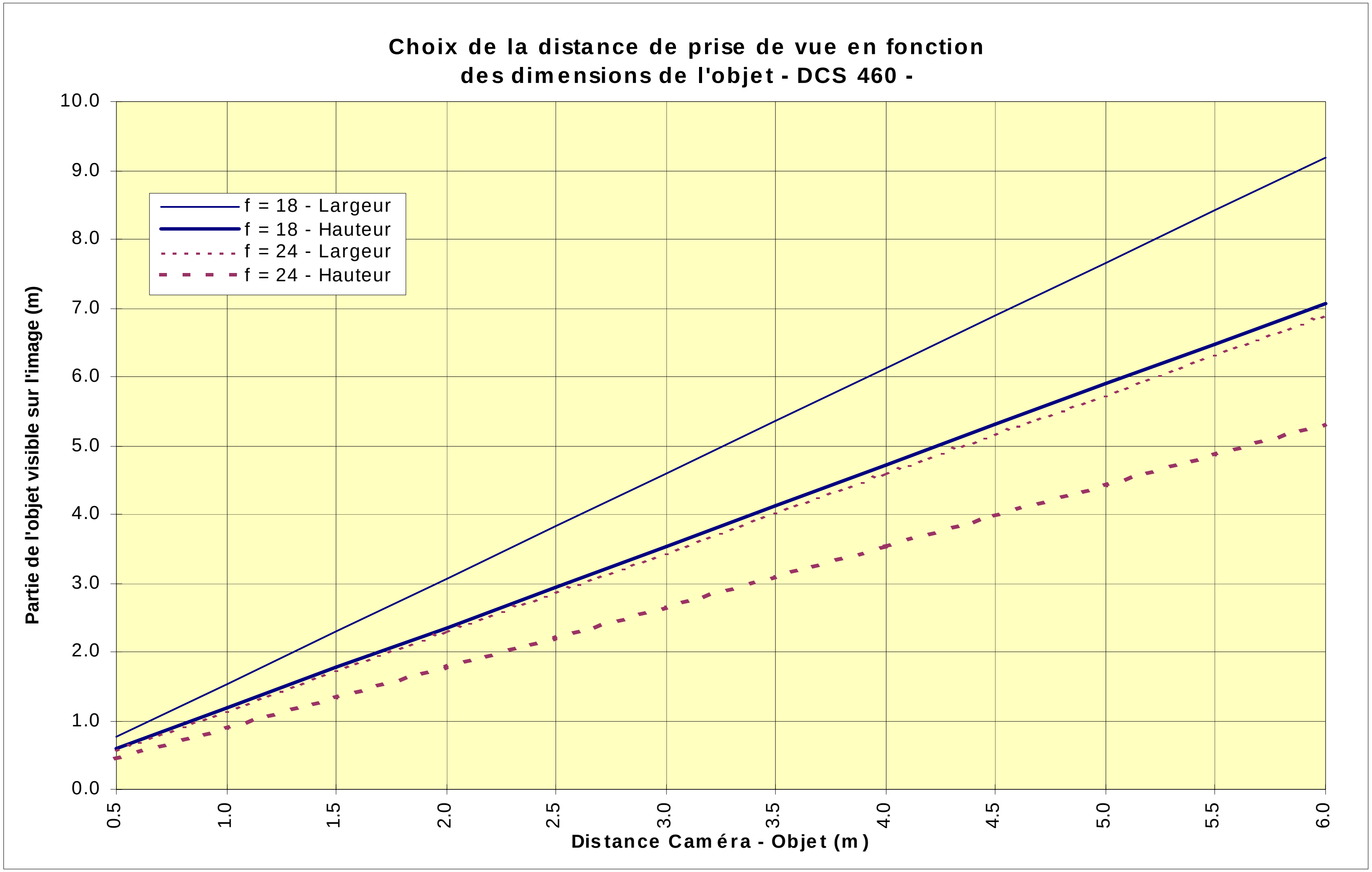
ε = offset between measured target and real center
r1 = image radius P'1
r2 = image radius P'2
rm = image radius P'm (real target center)
α= incoming angle w.r.to the perpendicular line
→ ε = rm - (r1- r2) / 2

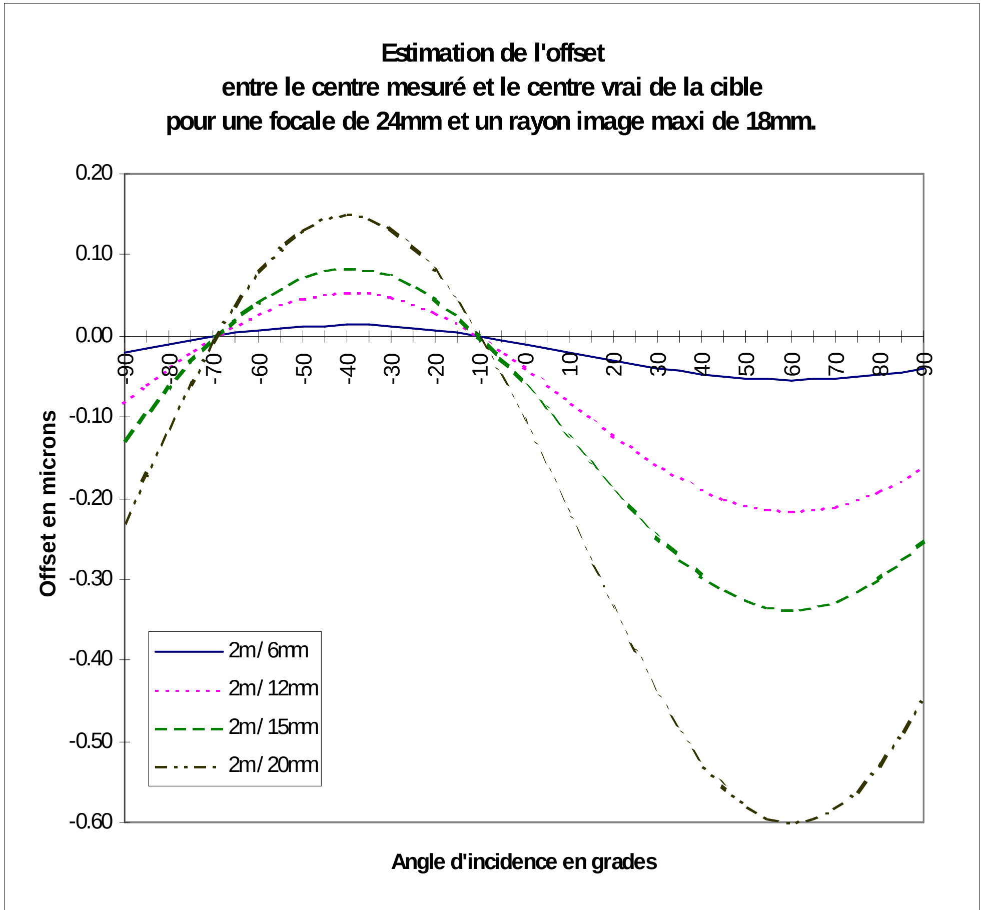
Example : f = 18mm, L recording distance = 2m, ***d cible =20mm***

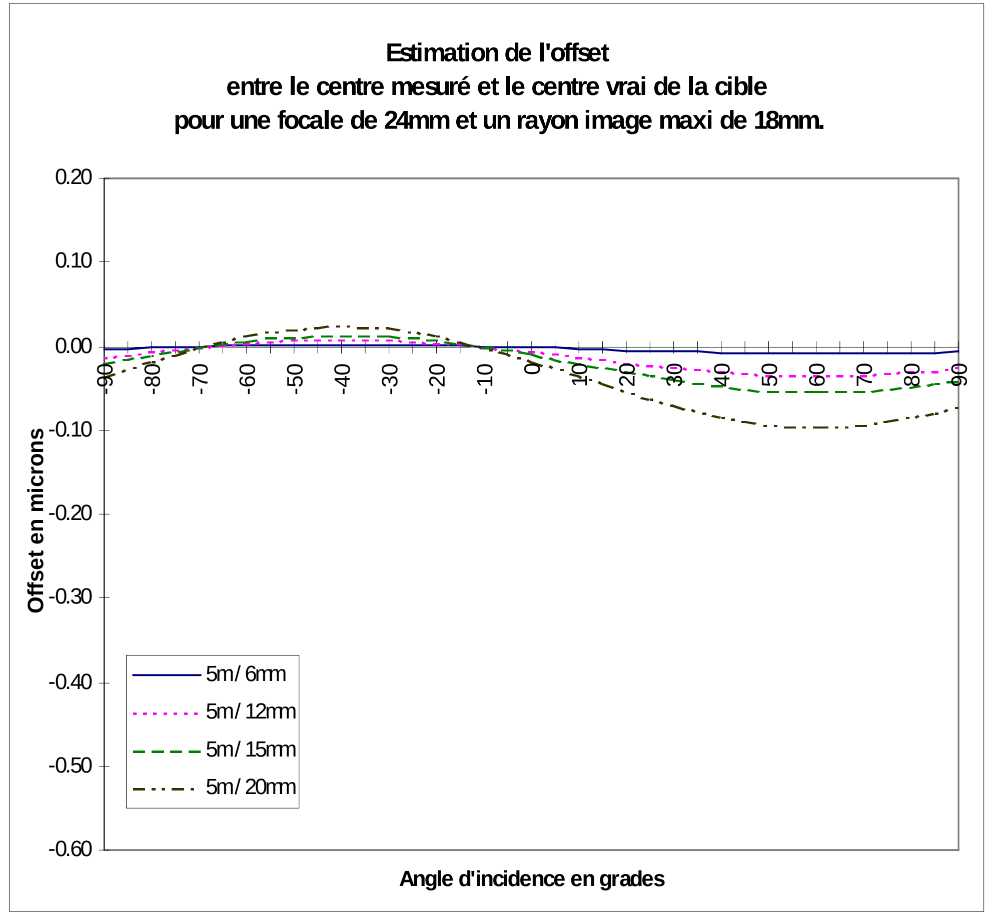
→ *Offset = 0.55 µm for incoming angle of 60 grades*

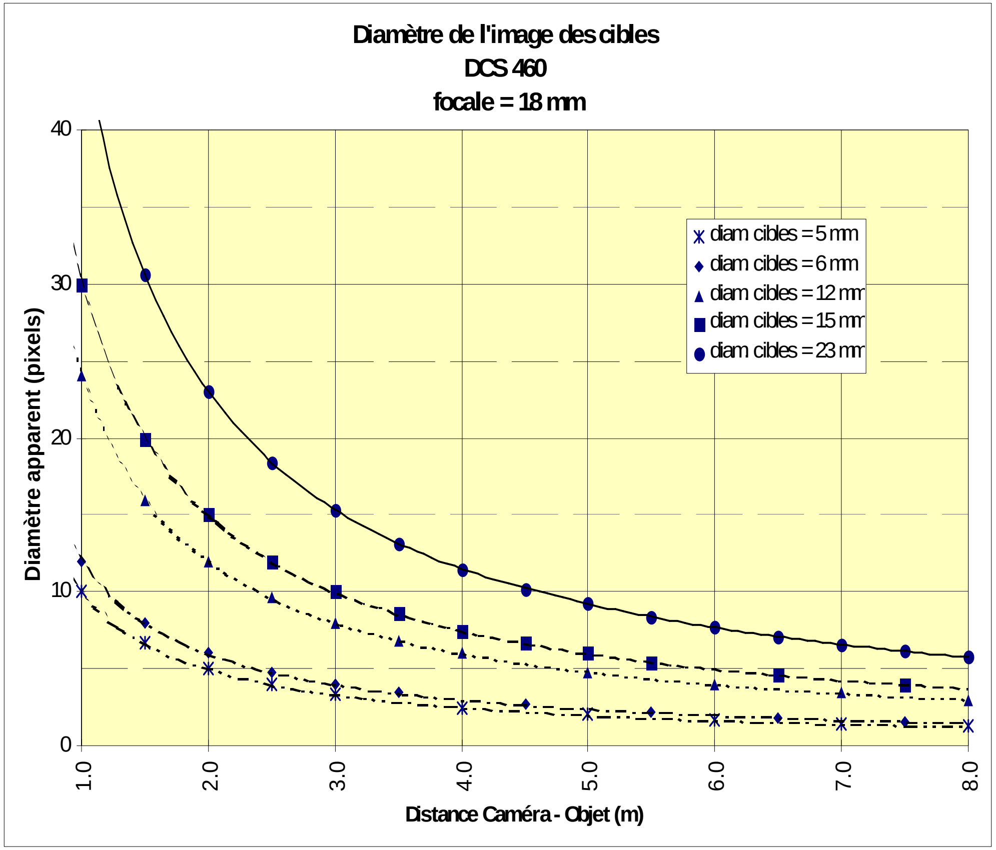
→ *THEN … good choice of the target diameters so that the offset is always less than 0.3 µm (or less)*

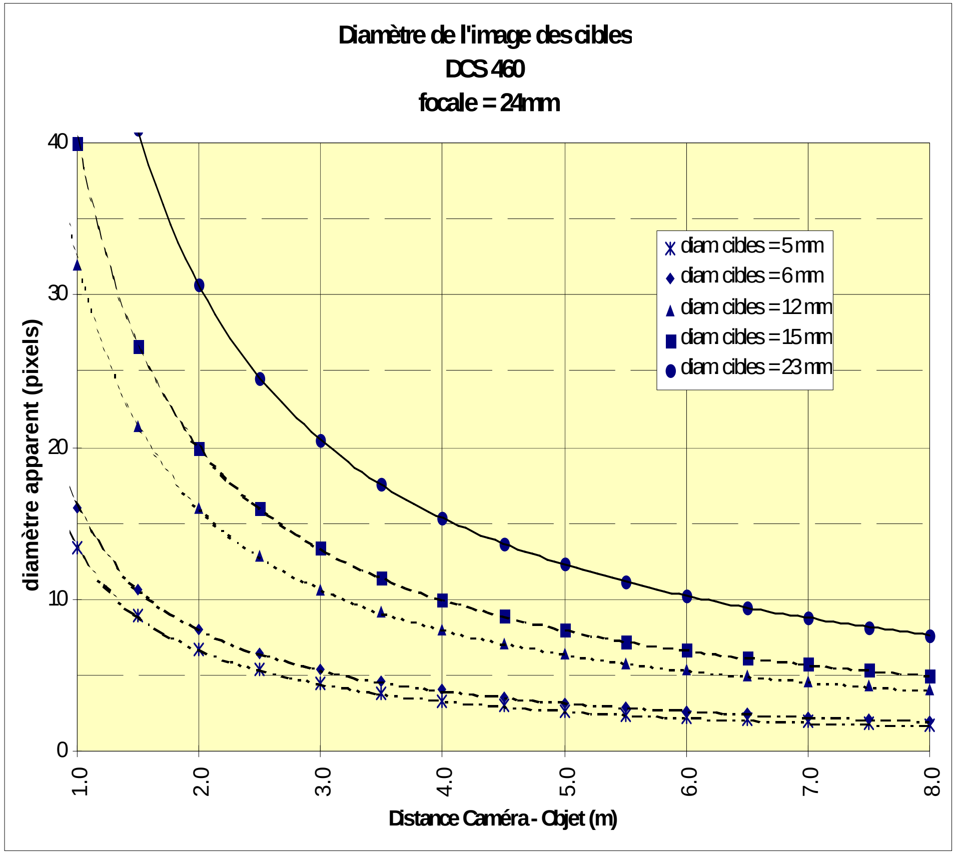
Preparatory working tables …




Estimation de l'offset
entre le centre mesuré et le centre vrai de la cible
pour une focale de 24mm et un rayon image maxi de 18mm.
Offset en microns
Angle d'incidence en grades
2m/ 6mm
2m/ 12mm
2m/ 15mm
2m/ 20mm


Estimation de l'offset
entre le centre mesuré et le centre vrai de la cible
pour une focale de 24mm et un rayon image maxi de 18mm.
Offset en microns
Angle d'incidence en grades
5m/ 6mm
5m/ 12mm
5m/ 15mm
5m/ 20mm


Diamètre de l'image des cibles
DCS 460
focale = 18 mm
Diamètre apparent (pixels)
Distance Caméra - Objet (m)
diam cibles = 5 mm
diam cibles = 6 mm
diam cibles = 12 mm
diam cibles = 15 mm
diam cibles = 23 mm
0
10
20
30
40
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0


Diamètre de l'image des cibles
DCS 460
focale = 24mm
diamètre apparent (pixels)
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diam cibles = 6 mm
diam cibles = 12 mm
diam cibles = 15 mm
diam cibles = 23 mm
0
10
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40
1.0
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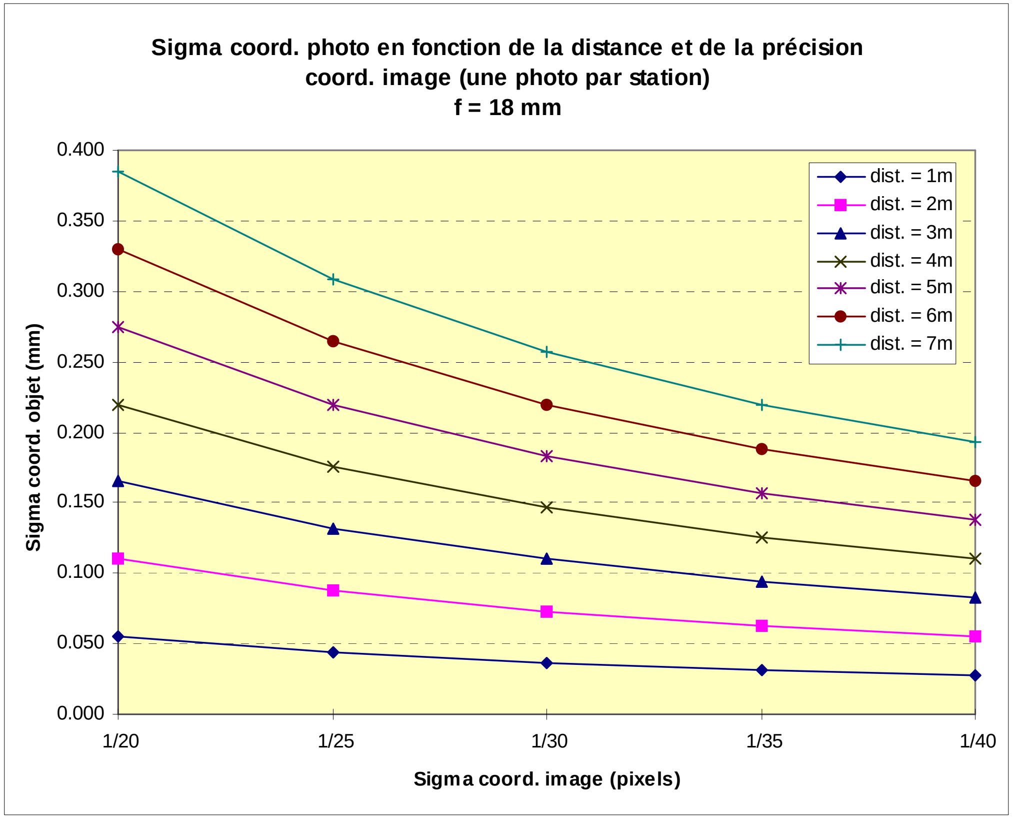
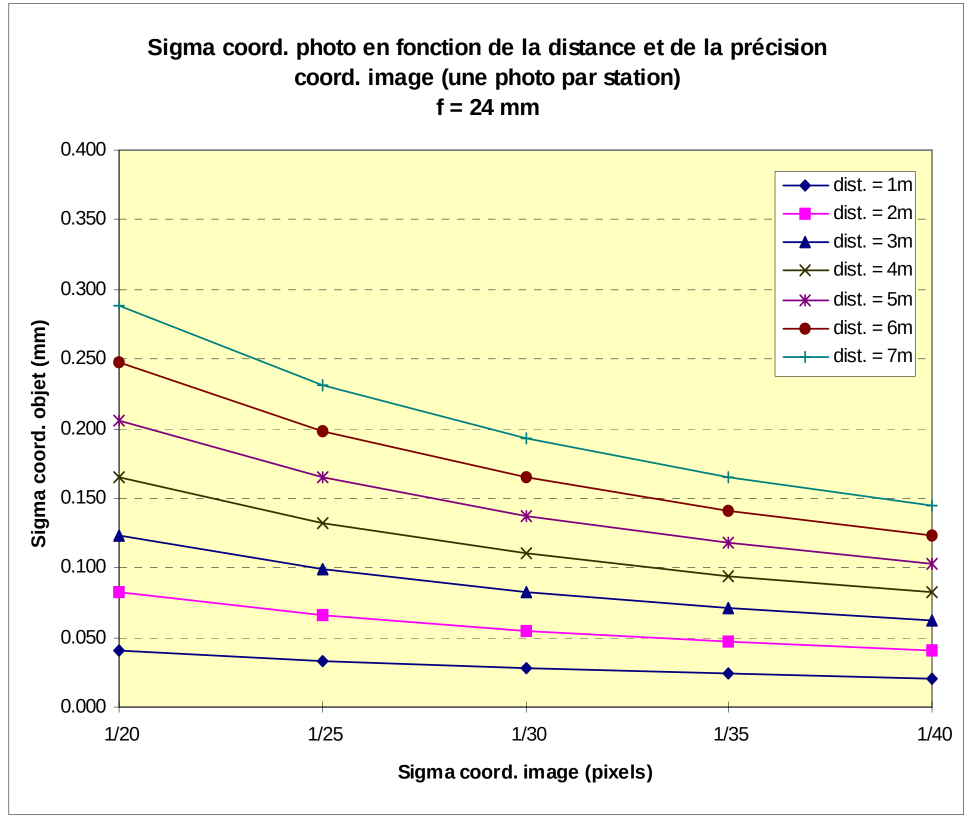
3.0
4.0
5.0
6.0
7.0
8.0


Sigma coord. photo en fonction de la distance et de la précision coord. image (une photo par station)
f = 18 mm
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
Sigma coord. objet (mm)
1/20
1/25
1/30
1/35
1/40
Sigma coord. image (pixels)
dist. = 1m
dist. = 2m
dist. = 3m
dist. = 4m
dist. = 5m
dist. = 6m
dist. = 7m


Sigma coord. photo en fonction de la distance et de la précision coord. image (une photo par station)
f = 24 mm
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
Sigma coord. objet (mm)
1/20
1/25
1/30
1/35
1/40
Sigma coord. image (pixels)
dist. = 1m
dist. = 2m
dist. = 3m
dist. = 4m
dist. = 5m
dist. = 6m
dist. = 7m

A numerical example … practical BUT theoretical BUT … gives an help !!

1- **Sig obj = 0.040 mm** **Sig img = 0.3 µm → WHAT WE WANT**

↳ uncertainty ratio / 'scale factor' → ***130***

2- **f = 24 mm**

↳ RECOMMENDED recording distance → ***L = 3.2 m***

↳ part of viewed object → ***2.5 m × 3.7 m***

3- We fix the distance in between consecutive cameras stations at b=2/3 of the recording distance L

→ b = 2/3 * 2.8 = 2.1 m

↳ uncertainty in depth = 0.060 mm

4- **Target diameters :**

Minimum > 6 mm **Maximum < 23 mm (OFFSET 0.19 microns)**

↳ Choice : 12 or 15 mm

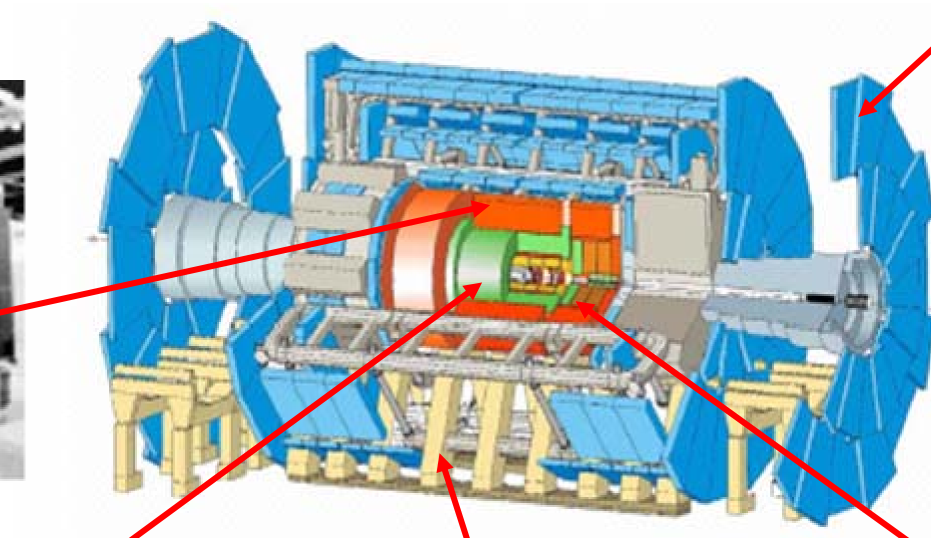
The image diameter will be AT LEAST 10 pixels → correct

The offset will be between 0.05 and 0.08 microns

ALSO SIMULATION WITH 3DSTUDIO FOR DIFFICULT CONFIGURATION …

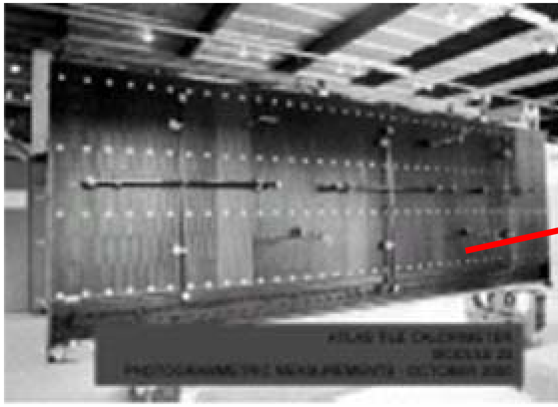
Some examples (1)

ATLAS : Diameter 25 m Lenght 42 m Weight 8000 t



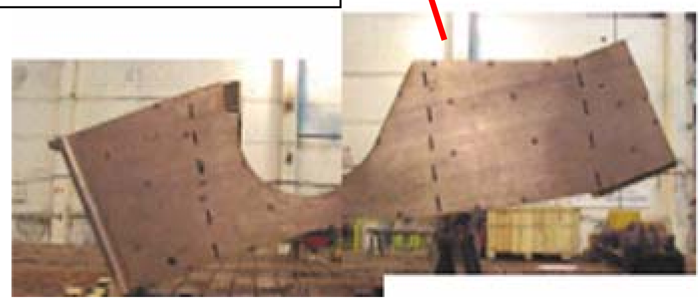
6 wheels, 25 m diameter

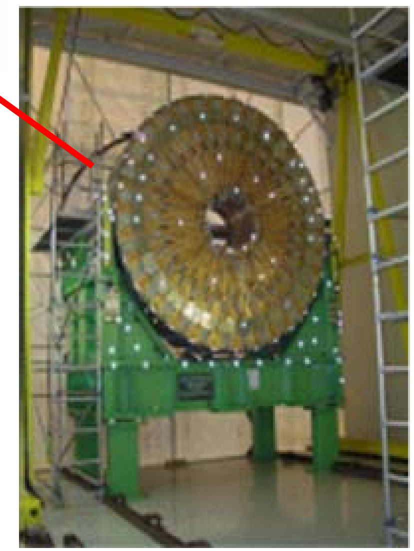
192 modules



18 modules / wheel , 2 wheels

18 pieces : 6 m long

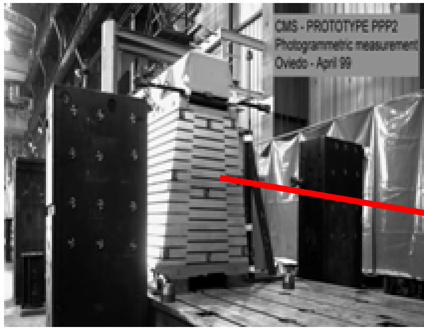


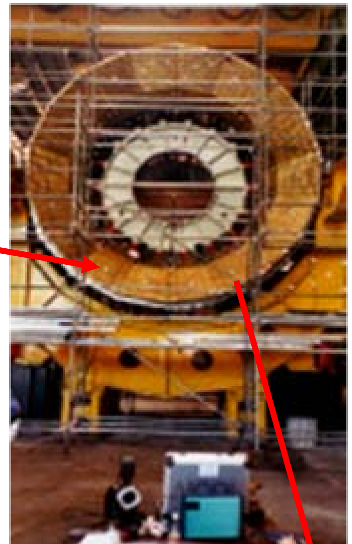


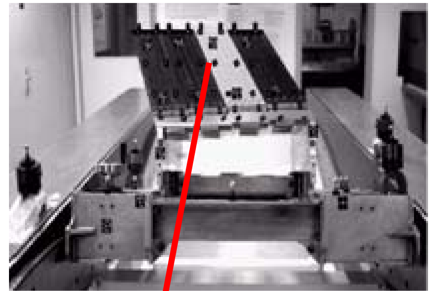
32 modules / wheel, 4 wheels

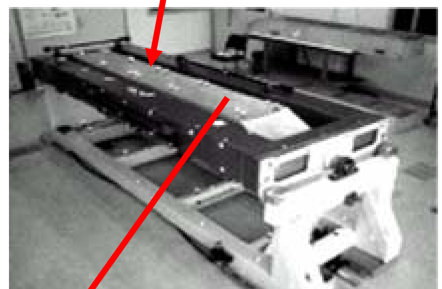
Some examples (2)

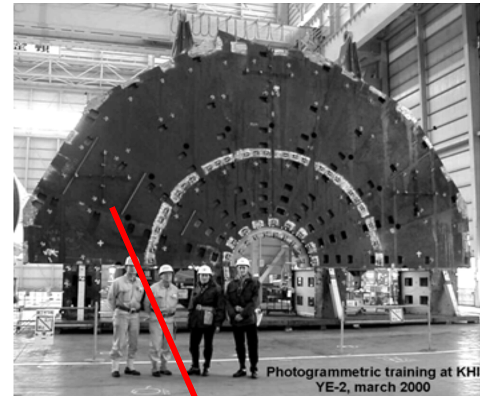
CMS : Diameter 15 m Lenght 22 m Weight 14500 t



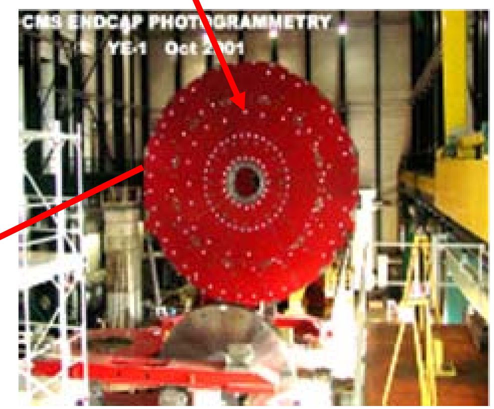


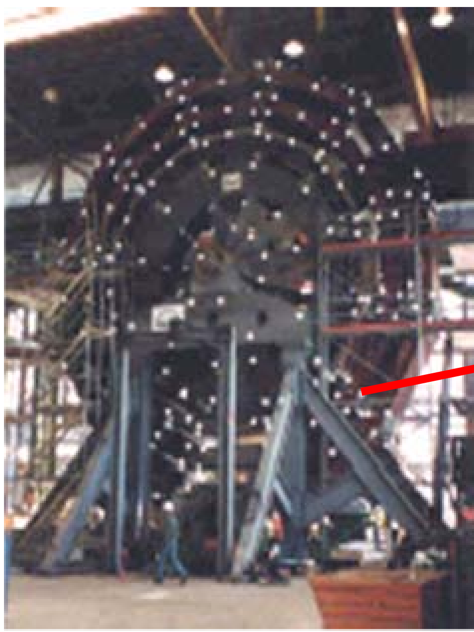


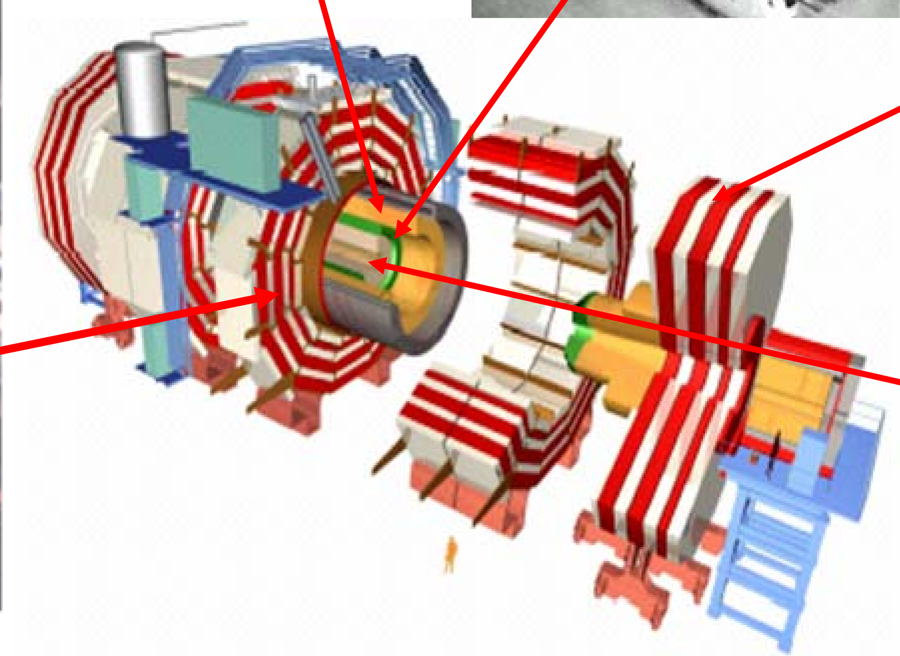




module and pre-assembly







A very good and significant example … assembly and deformations

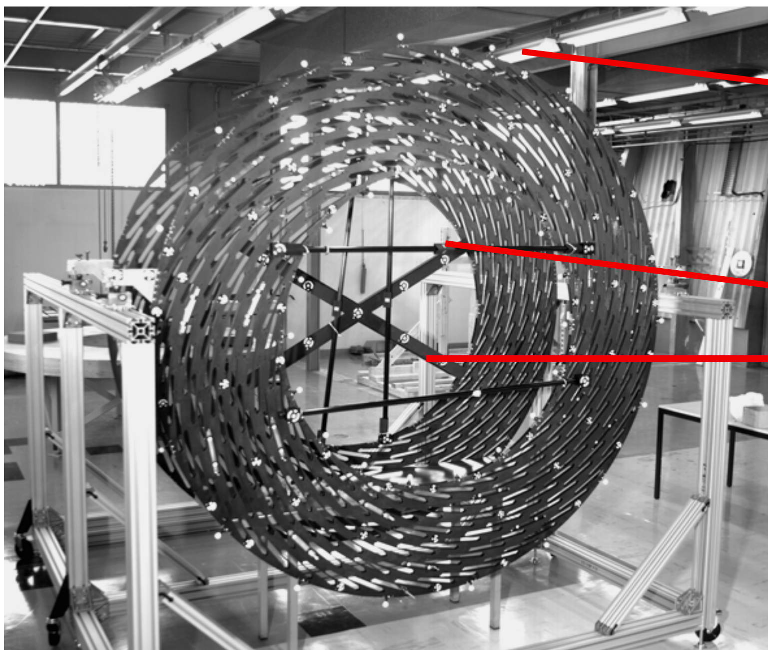
CENTRAL TRACKER : carbon fiber wheel – 2.5 m

304 points, 14141 observations, 1443 inconnues, 87 images
→ < 1 hour : photos plus results

EXTREME POINTS (mm)

Point	X	Y	Z	Rayint	ÕX	ÕY	ÕZ	
125	1315.643	407.032	252.307	12	0.020	0.035	0.019	NewPt
126	-1314.309	407.271	252.486	14	0.019	0.028	0.016	NewPt
601	214.532	-394.180	1215.964	38	0.014	0.015	0.011	NewPt
618	-214.331	-394.798	1215.828	40	0.014	0.015	0.011	NewPt

SigmaO image co-ordinates : 0.000461
RMS- X : 0.017 mm RMS- Y : 0.027 mm RMS- Z : 0.015 mm

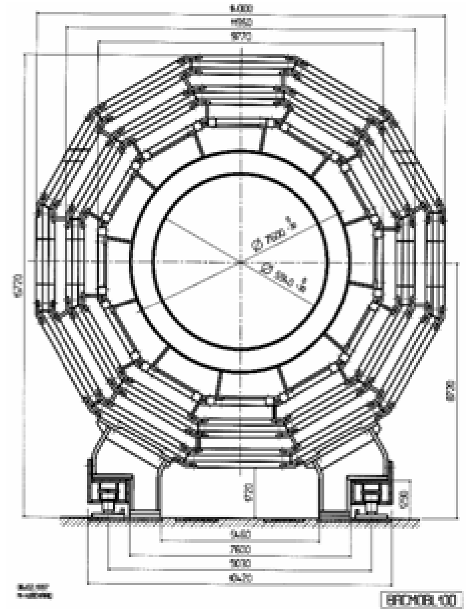


rétroreflective spheres

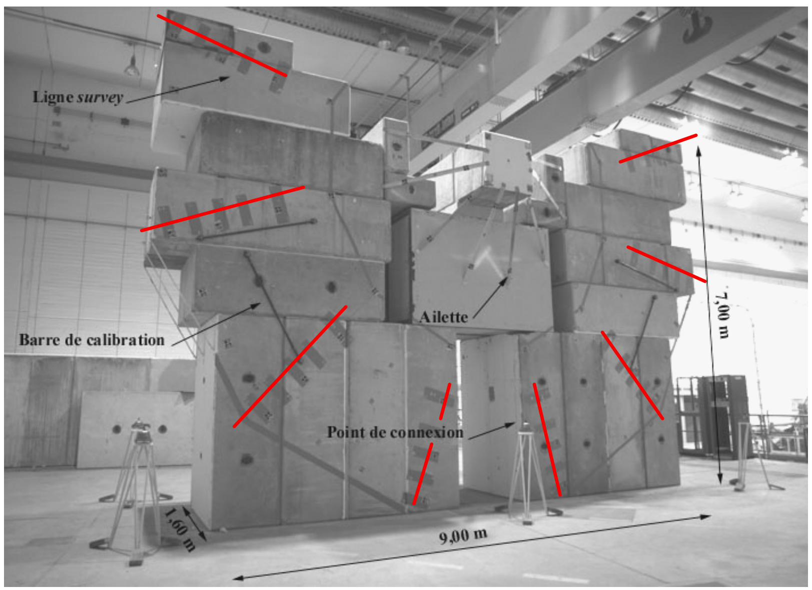
Scale bars

Original approach … CMS ring barrel yoke

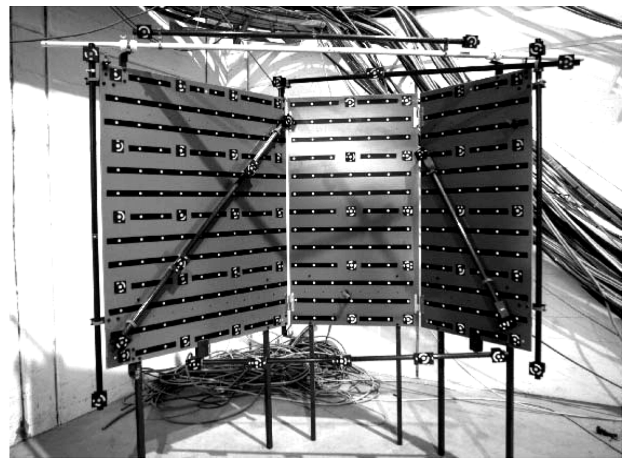
CONSTRAINTS IN FACTORY :
- Ø 14 m but top 18 m from the floor … connection of the 2 faces
- required precision … better than 1 mm in XYZ
- immobilization time as short as possible



⇨ **SIMULATION NEEDED ⇨ MOCK-UP {**
- validation of the method
- test of specific equipment
- adapted procedure



CERN MODEL … scale 65 %



PORTABLE BENCH … control of the camera calibration

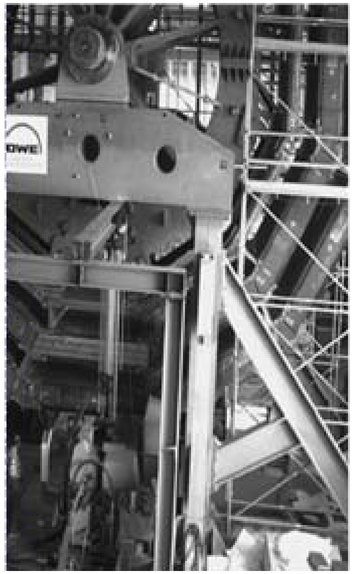
...the real object

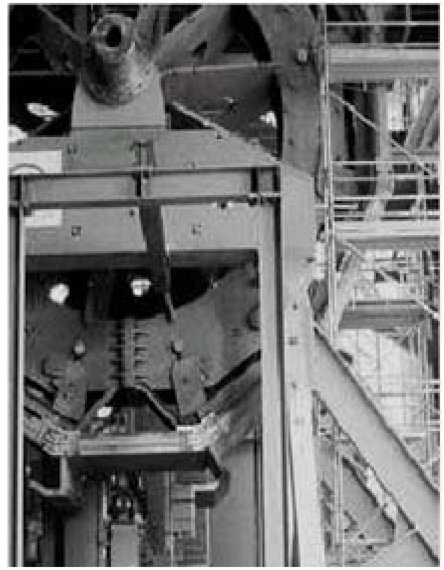
270 photos/4h30/500 points … 100 µm … control long distances

40 mm retro targets in reference holes with …

points hidden by feet and scaffoldings

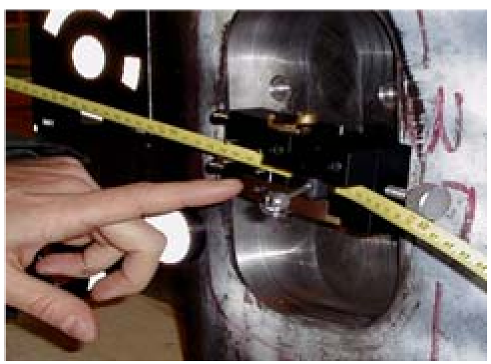
shooting distances : 12 m to object, 18m from floor





… 12 cm coded foil around plus spheres

Blunder detection important : separation object / environment



long distances measured with a control tension device and calibrated tape

SX = 0.091 mm SY = 0.082 mm SZ = 0.145 mm

Arising problems and a wishing list …

Time table …

→ **Preparation : targets plus scale bars, distance measurements if any → > 50 % but once !**

→ **Measurement : photo taking, data transfer → 20 % / 30 % … D2X NIKON WITH WIRELESS**

→ **Calculation up to 3D co-ordinates → < 20 % … WIRELESS / 3DSTUDIO …**

Logistics and equipment …

→ **Specific targets + supports if any must be designed and fabricated → delay for the measurement**

→ **Targets must be available for different dimensions and recording distances → investment**

→ **Risk of damages of targets in industrial environment → regular control and cleaning**

→ **Needs of a quite versatile and adapted tooling box**

THEREFORE …

- **higher resolution, better stability (see next), speeding up the data transfer**
- **avoiding retro-reflective materials : possible with manual / semi-automated process …**

Specific tests … 'OLD' CAMERAS DCS660 … BUT CALIBRATION PROCESS

- in some cases, internal accuracy **optimistic** w.r.to the external information (scale bars …)
- **DCS660** non-metric camera … Nikon lenses **…** shelf products → **TO-DAY D2X**
- **stability** of the camera and its interior orientation is a **real question specifically when** large sized projects image acquisition (example : CMS yoke … 300 photos … 5 hours)

TESTS DETECTION MOVEMENTS OF THE INTERIOR ORIENTATION …

- instability of the DCS … interior orientation … different for each image

literature : distortion fixed
- **… principal point/focal length within a priori standard deviations (Maas)**
- **… principal point free, focal length fixed (Beyer)**

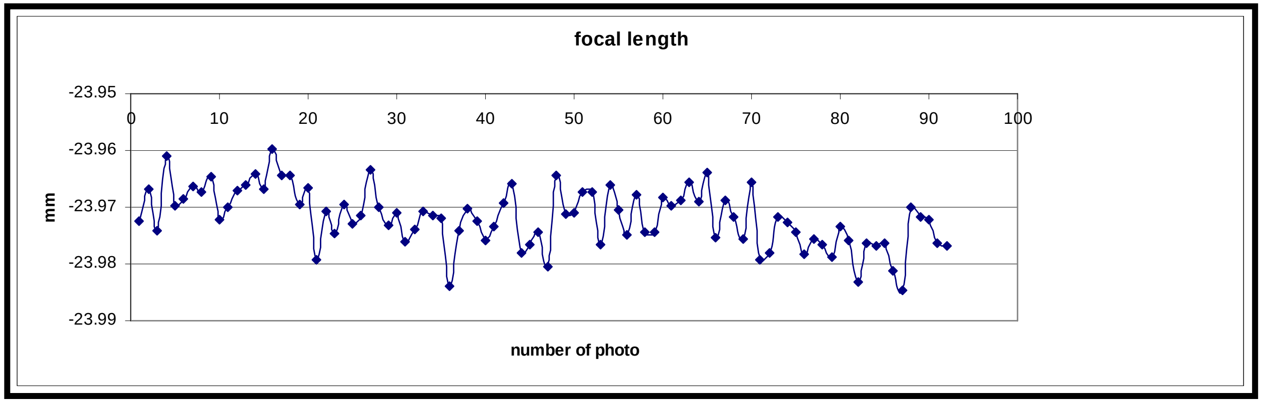
- our approach … software CDW can attach one camera per image

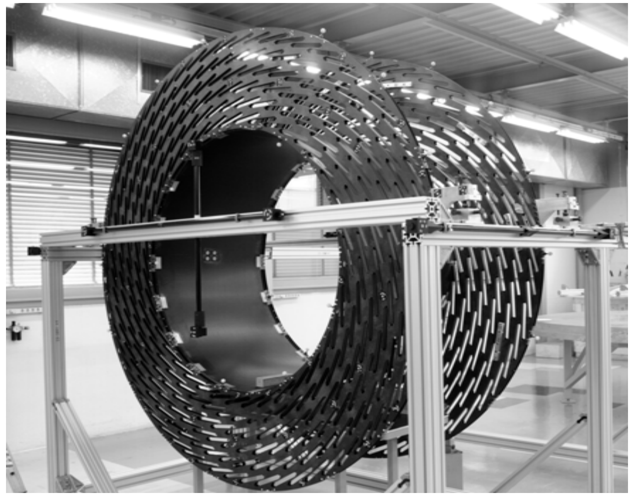
⇨ principal point and focal length free for each image,

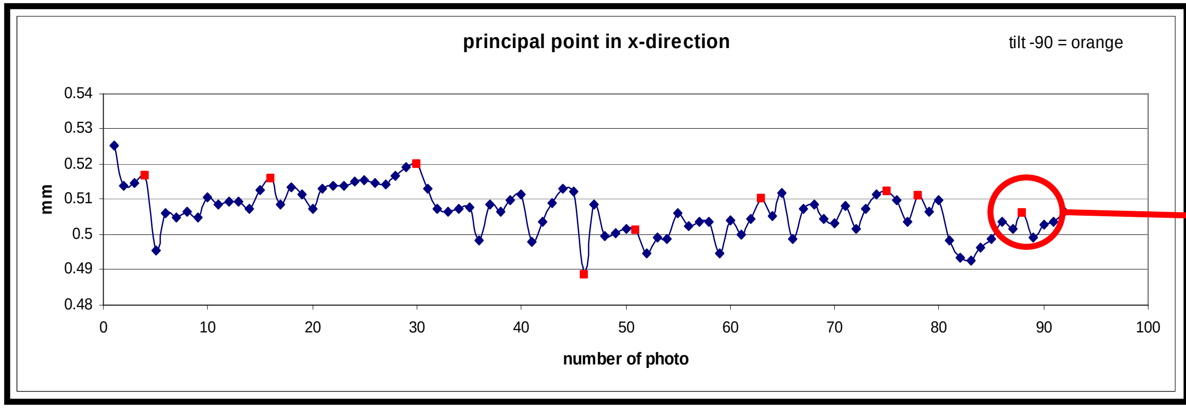
⇨ distortion invariant for the block

Test 1 …

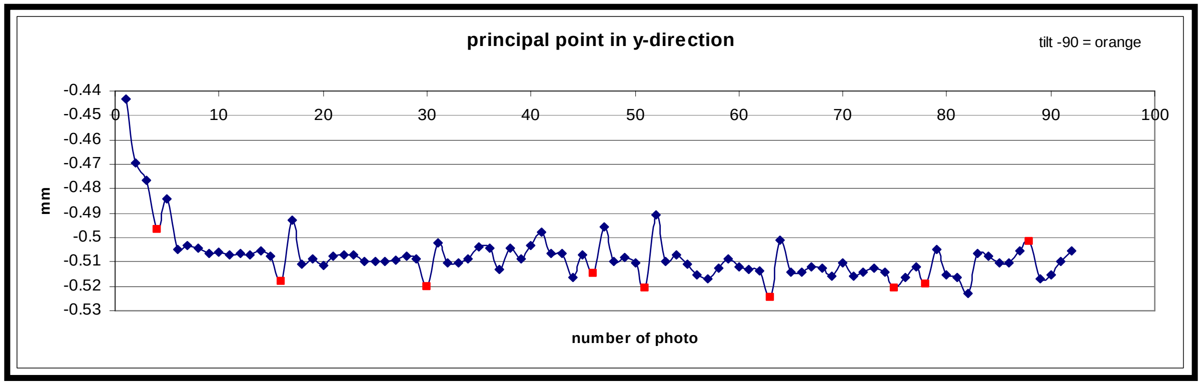
DCS 660 … results on a ring-shaped object 2.5 m diameter







CAMERA TURN UPSIDE DOWN



focal length and principal point … 30-40 µm in both directions … 70 µm … the first 10 photos

20 µm principal point movement … co-ordinates by up to 0.5 µm …

test 2 … results

test 1 … possible causes

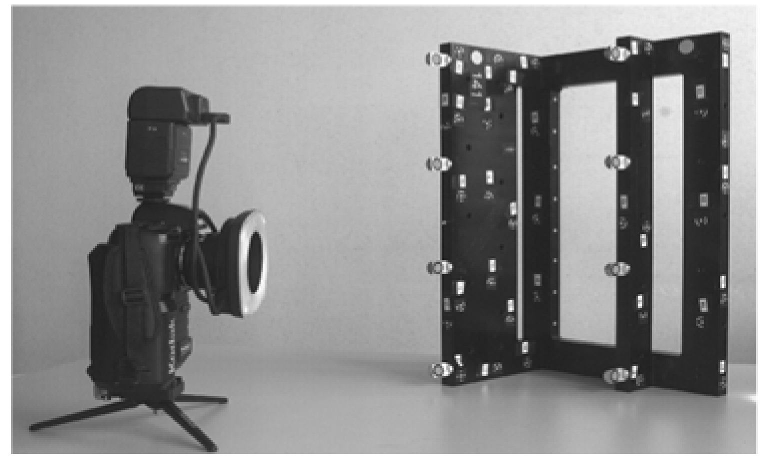
- camera transporting upside down and then turned by 180 ^{0} …
- not an electronic or temperature effect (PCMCIA card)
- not easy to keep same tilt (charging, changing cards, climbing …)

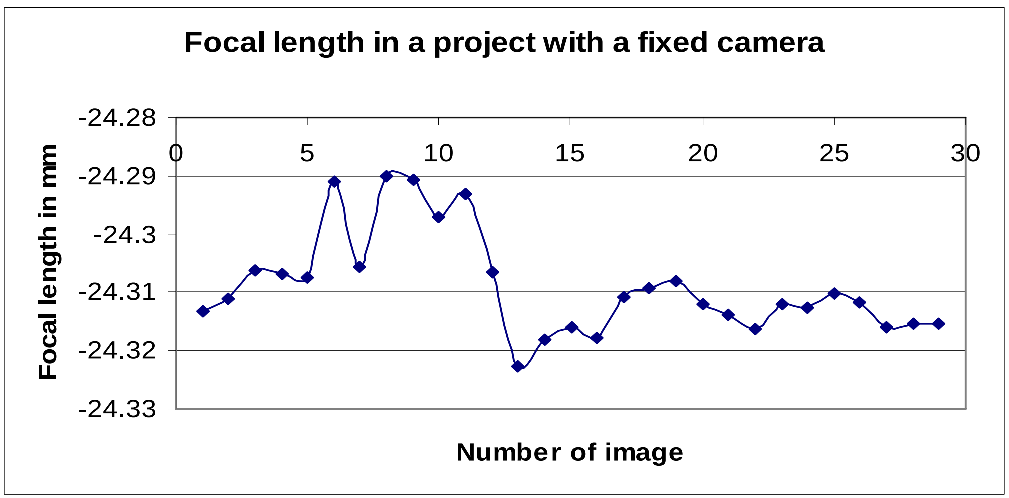
- as if specific internal orientation parameters related to a given handling of the camera …

⇨ test 2 … fixed camera

… small but rigid moving object

… no deformations camera + object



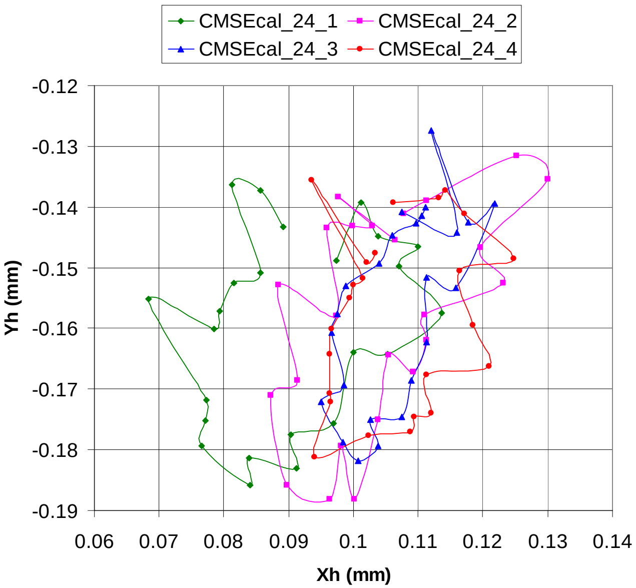


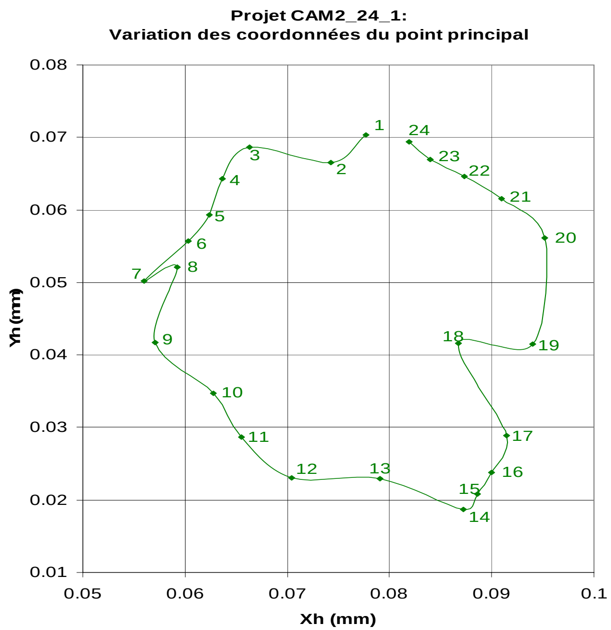
- focal length changes same range as test 1, and stable 2 µm when same camera/object relative position (see 6, 8, 9 and 27, 28, 29),

Another test

Principle point movement w.r.to the rotation angle of the camera around its optical axis

Circular and symmetric object with depth + limited camera positions, 4 times 24 photos → 1 each 15° … 6 ensembles different cameras + lens 24 mm → some results





Common project …

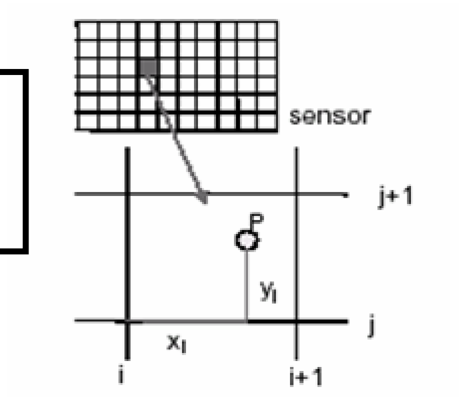
The Institute for Applied Photogrammetry – University of Applied Sciences Oldenburg + AICON & CERN … analyse industrial projects, modelisation interior orientation parameters

Parameters	Modelisation CDW	Modelisation Oldenburg
Principle distance	f	f
Co-ord. Principle point	x_H, y_H	x_H, y_H
Radial-symmetric lens distorsion	A_1, A_2, A_3	A_1, A_2, A_3
Tangential and asymmmetric distorsion	B_1, B_2	Finite Elements Correction Model Grid-based correction model
Affinity and sheering	C_1, C_2	
Unflatness of the sensor and errors	None	

Image-variant parameters and Finite elements Correction model (**T.Luhmann / W.Tecklenburg)**

→ **at each point : a plane vector – FiBun option**

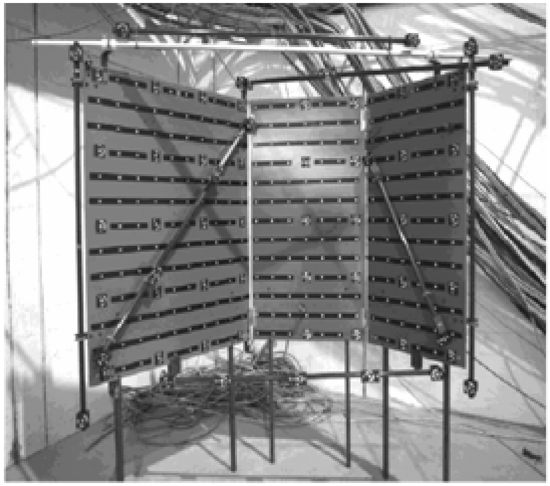
- variation of principle distance affects lens distorsion on image plane → modelled as a function of imaging angle and not of image coordinates

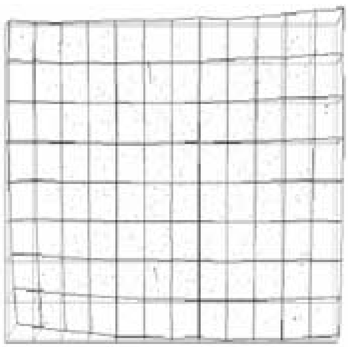


…and conclusion

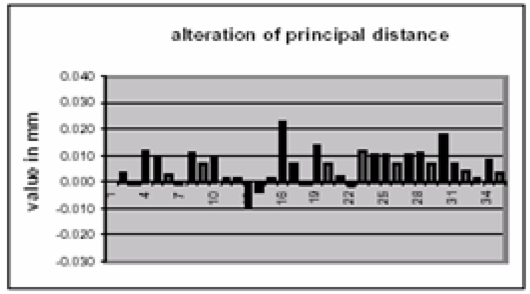
59 object points, 35 images (10 rolled), 7 scalebars (1 for scale definition)

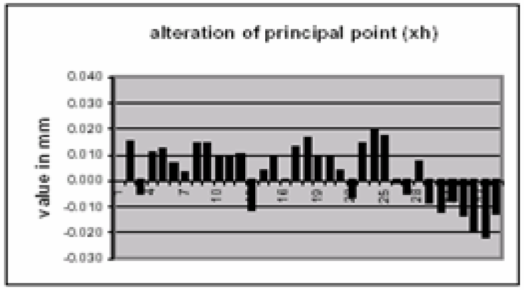
→ DCS 660 BUT process available for any camera calibration

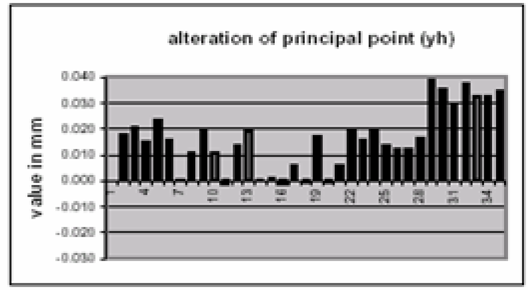


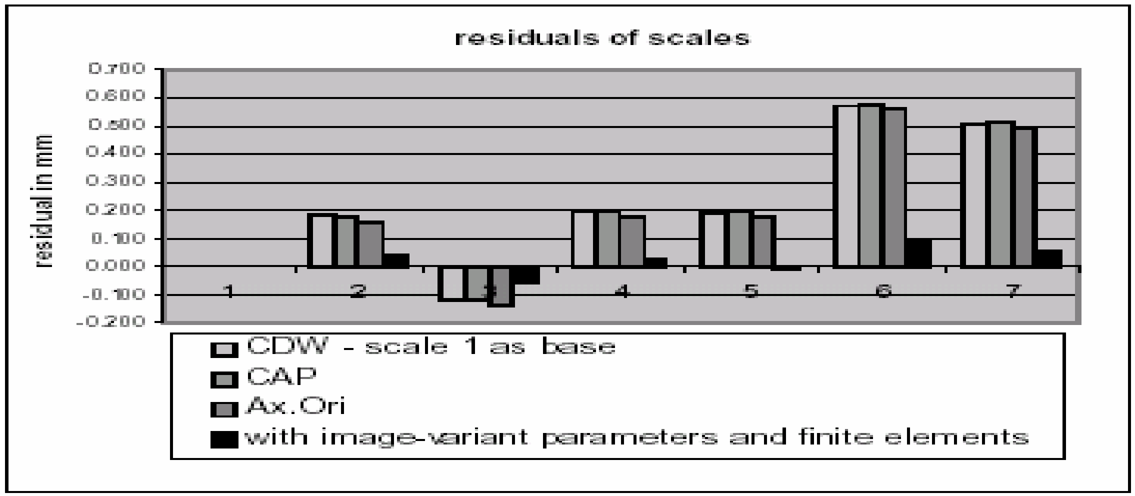


Grid : a raster-width of 2.35 mm









… instabilities : now well considered

… still influence of configuration