High Precision Industrial Photogrammetry (Vision Metrology)

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Outline of the lecture

Basics of network design

- ✓ Introduction
- ✓ Essential parameters to be considered before a real measurement
- ✓ Network design by simulation
- ✓ Practical example: Planck Space Telescope of ESA

Demo - Network design

Outline of the lecture

Image processing

- ✓High contrast circular targets
- ✓Target center estimation: centroid, ellipse fitting

Camera pose & 3D point coordinates estimation

- ✓Relative orientation
- ✓Space resection
- ✓Forward intersection (triangulation)

Bundle adjustment & self-calibration

- ✓Optimization, datum choice and stochastical model
- ✓Blunder detection
- ✓Self-calibration
- ✓Variance component estimation

Automation

- ✓Coded targets
- ✓Automated labeling

Demo - Real Measurement & Fodis Measure^{3D} software

Outline of the lecture

Panoramic imaging

- ✓Panoramic imaging technique (stitching, mirror technology, multi-head camera, panoramic camera)
- ✓Advantage and disadvantage of techniques
- ✓Mathematical model

Demo of Fodis Measure^{3D} software with panoramic images

Basics of network design

What is a photogrammetric network design?

Why a network design is important?

Where can it be applied?

How to perform a photogrammetric network design?

Real projects - Questions and influencing parameters

1) How many cameras should be used?
   - Ease of camera placement, time limits for taking images

2) Which camera is better to use?
   - Accuracy requirement, performance requirements

3) From which locations should the images be taken?
   - Accuracy requirement, visibility requirements

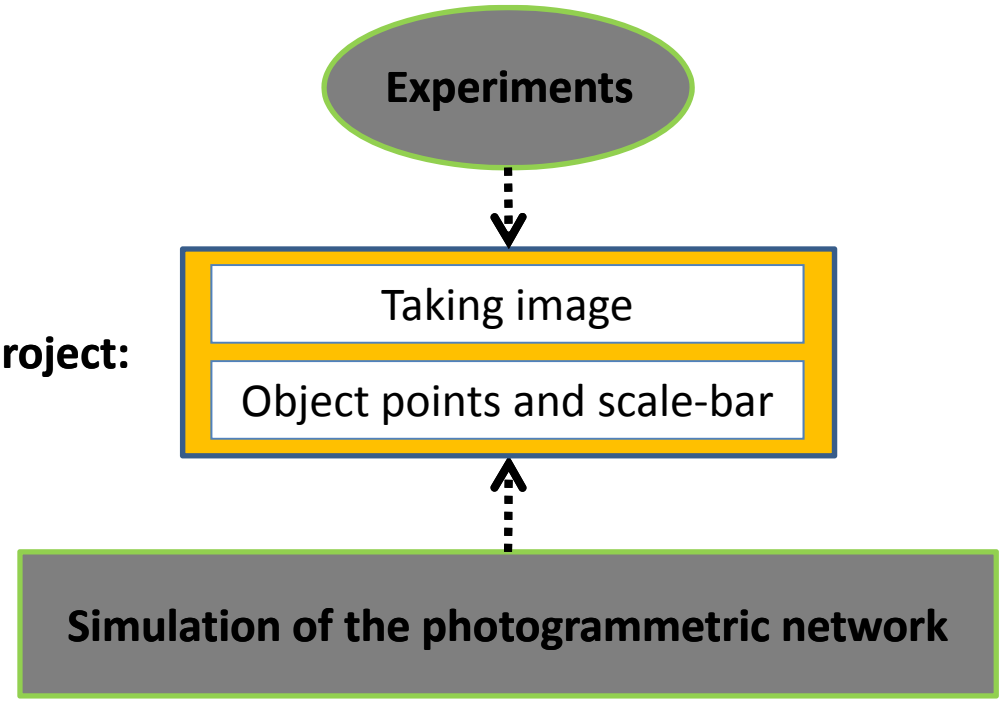
4) How many targets should be placed on the monitoring object?
   How should the targets be distributed on the monitoring object?
   - Project requirements, reliability requirements

5) How many scale-bars and where they should be located?
   - Accuracy requirement, reliability requirements

Approaches to answer the questions

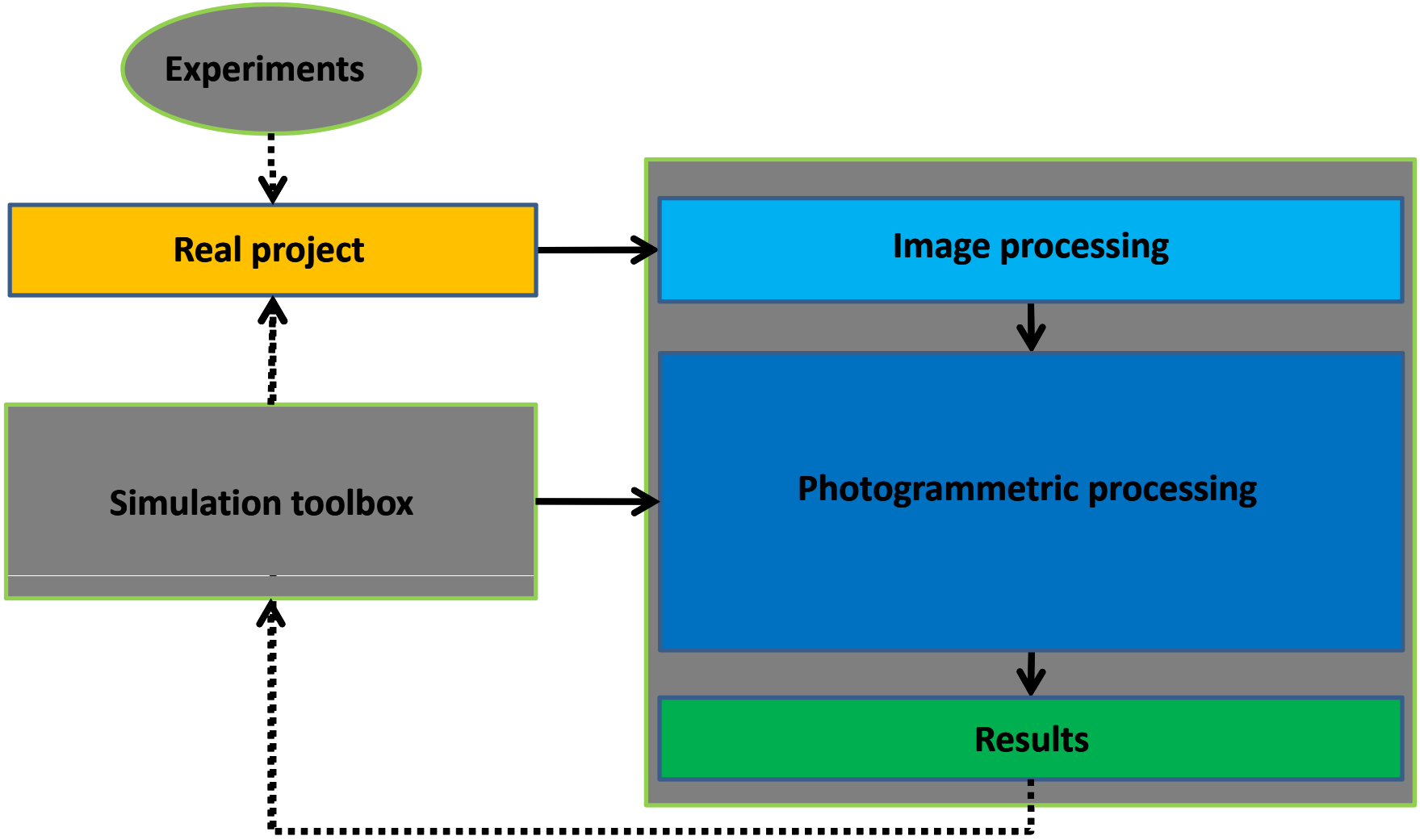
Approach 1) Requires an expert and is sufficient only for simple projects

Real project:



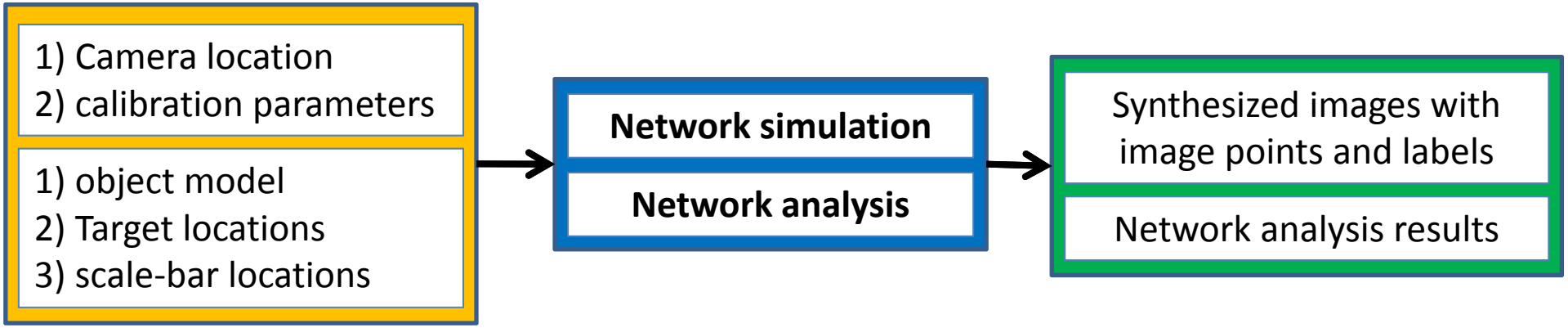
Approach 2) Requires basic knowledge of photogrammetry and is able to handle complicated projects

Basics of network design



PhotoCore simulation software package

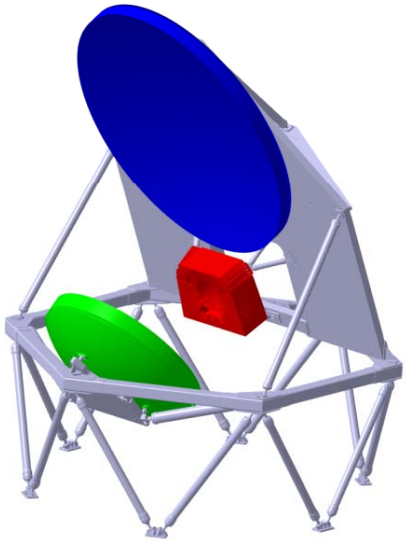
A MATLAB Toolbox which simulates a photogrammetric network and performs photogrammetric analysis.



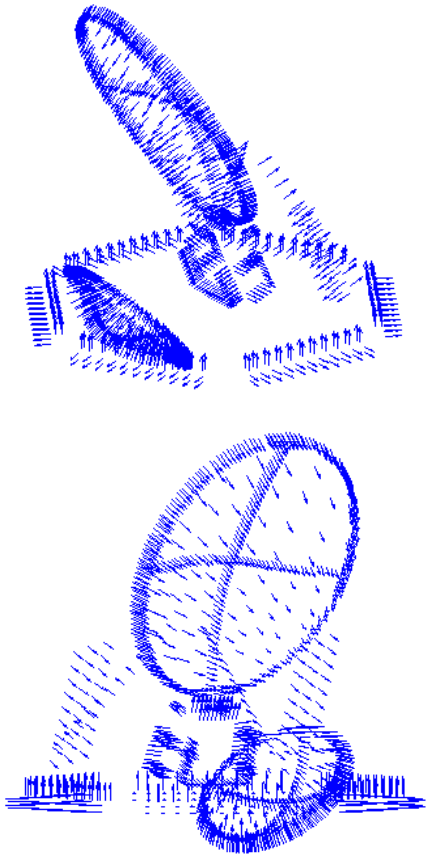
Its output includes:

– Image points, object points and synthesized images
– target size in the image space
– visibility check because of lack of reflectivity from the target
– visibility check because of obstruction
– target center shift error

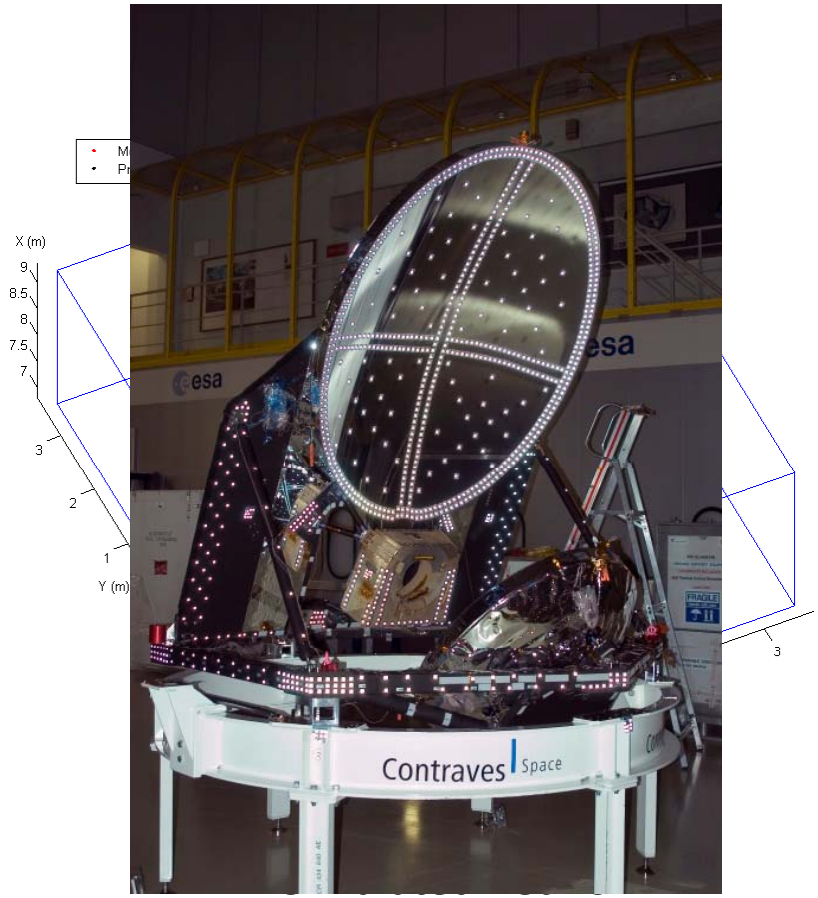
Virtual testing



CAD model of Planck Telescope
Courtesy Thales Alenia Space France



Targets and normal vectors
on CAD model



Courtesy ESA

Photogrammetric network design applied in AeroSpace

Herschel space telescope, courtesy European Space Agency (ESA)

Demo of network design

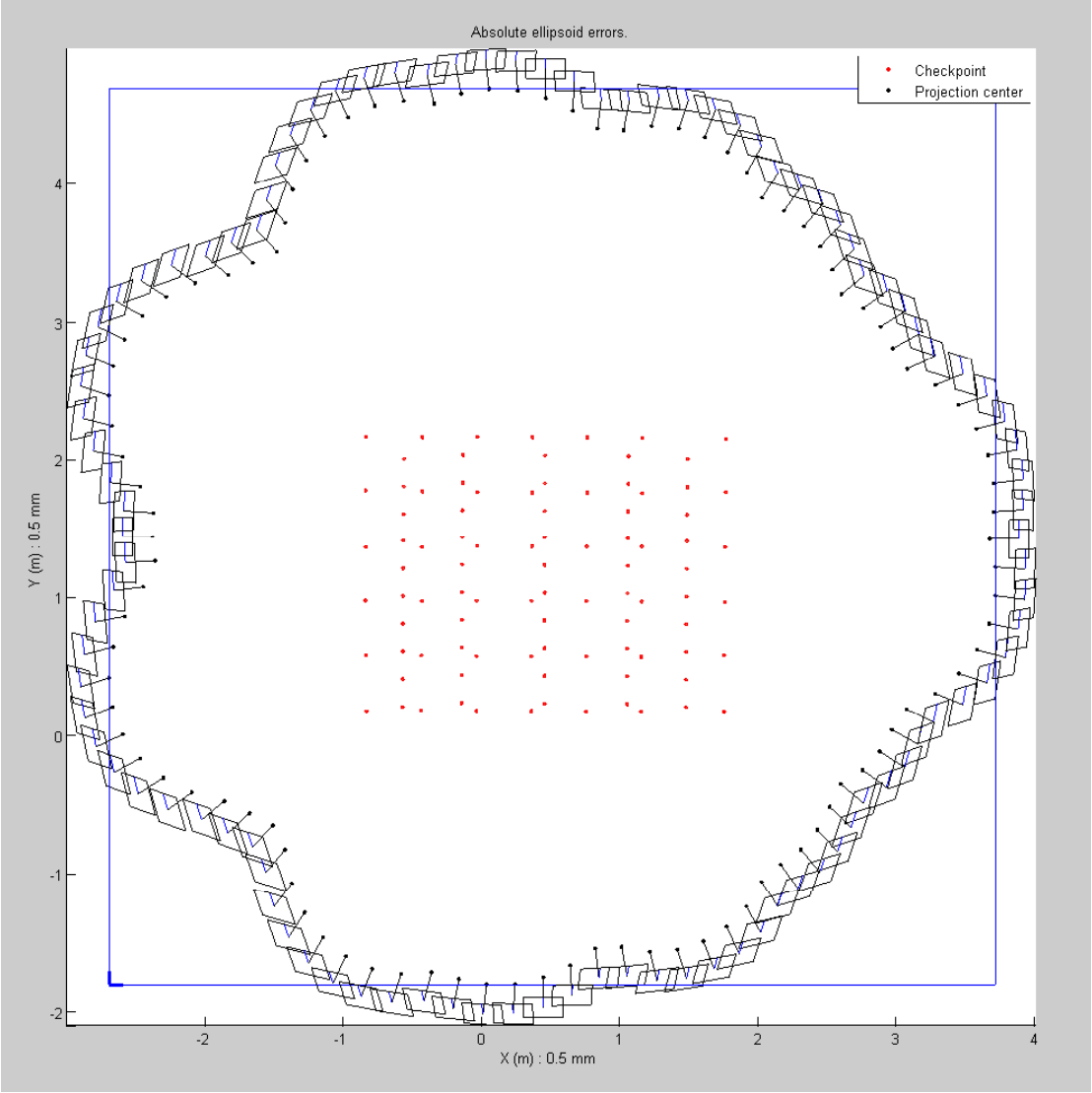
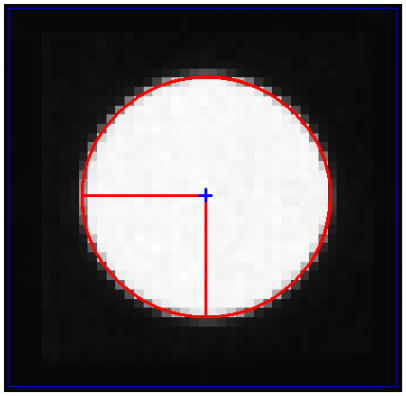


Image processing – Target detection

The given images are processed to detect round shape targets and locate the target in the image. The target detection of *PhotoCore 3D* is based on sub-pixel edge detection.

Methods of target localization:

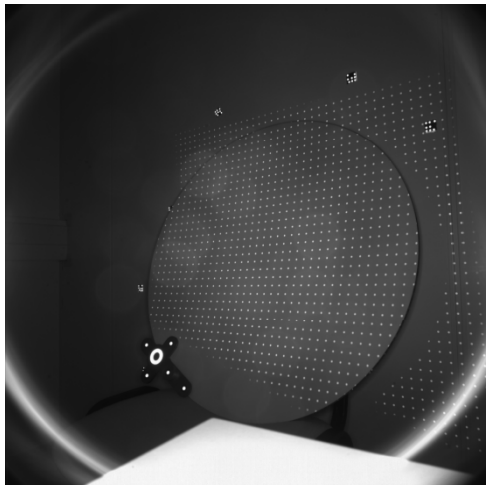
1) Centroid algorithm
2) Best-fit ellipse to the sub-pixel detected edges



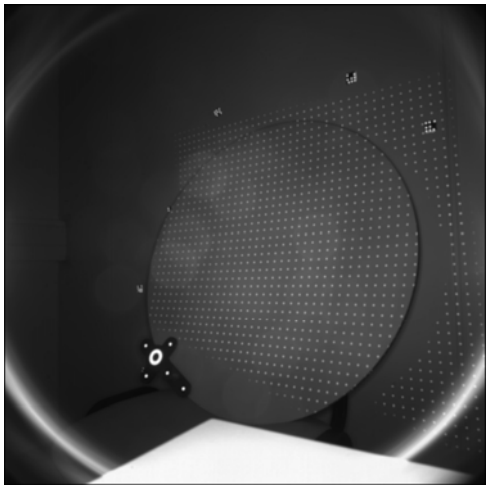
Accuracy potential:

With flat-retro reflective targets: 0.003 pixel (~0.042 micron if pixel size is 14 microns)
With high contrast projected targets: 0.001 pixel (~0.014 micron if pixel size is 14 microns)

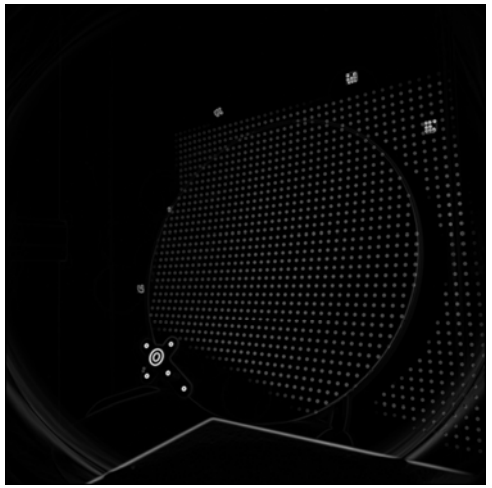
Image processing – Target detection and chaining



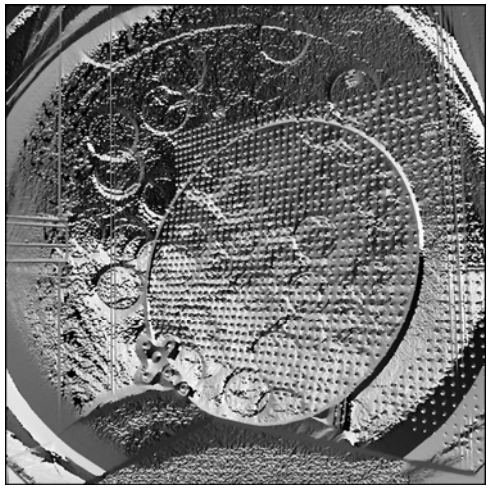
1) Original image



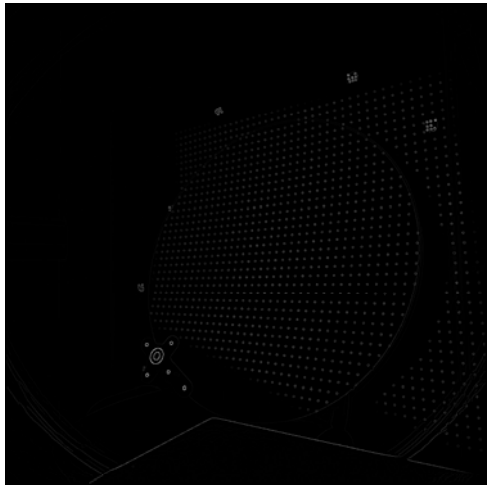
2) Smoothed image



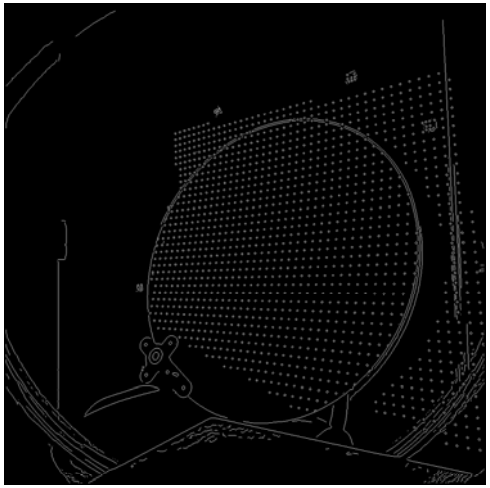
3) First derivative image



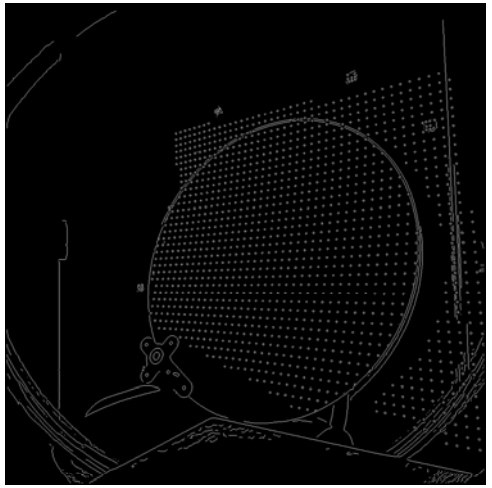
4) Orientation image



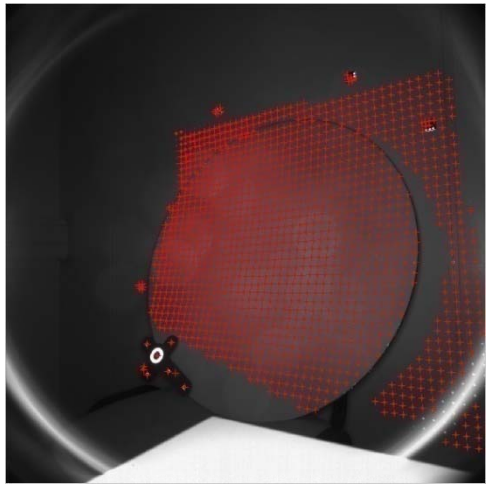
5) Non-maximum suppression



6) Edges

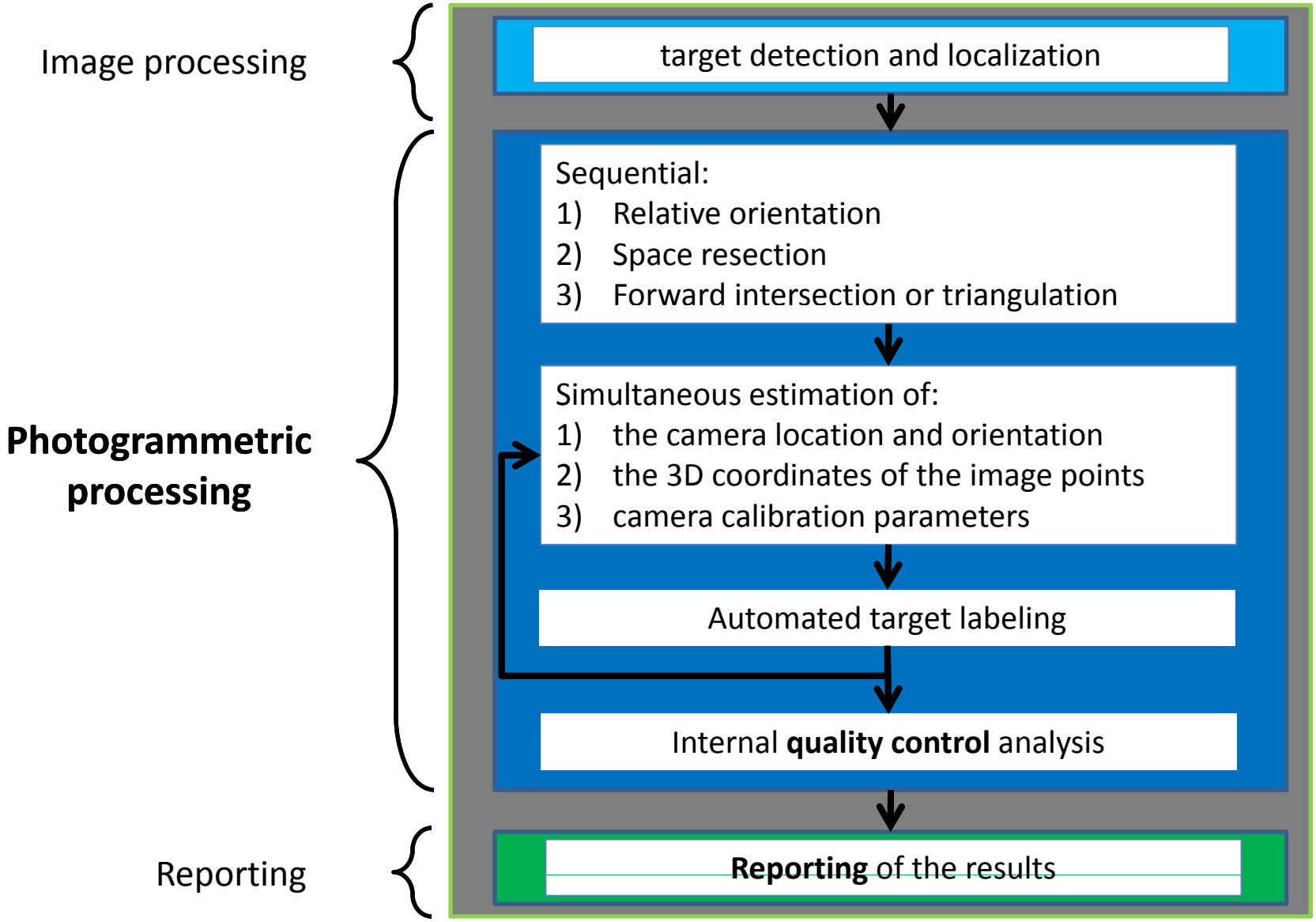


7) Edge thinning



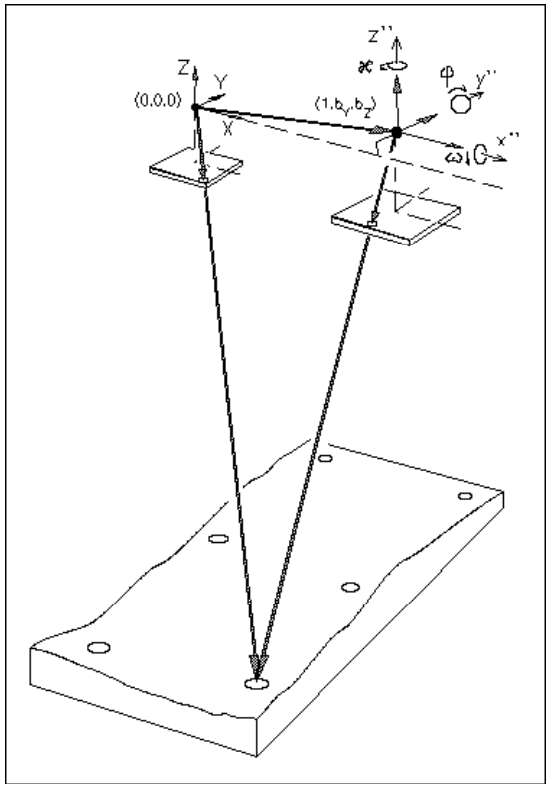
10) Target centers

Photogrammetric processing

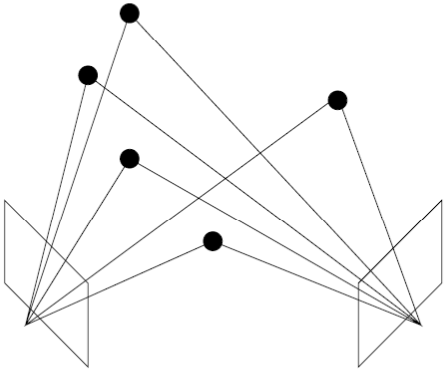


Camera pose & 3D point coordinates estimation

Sequential:
1) **Relative orientation**
2) Space resection
3) Forward intersection or triangulation



Relative orientation with five point algorithm



$$q'^{\top} F q = 0$$

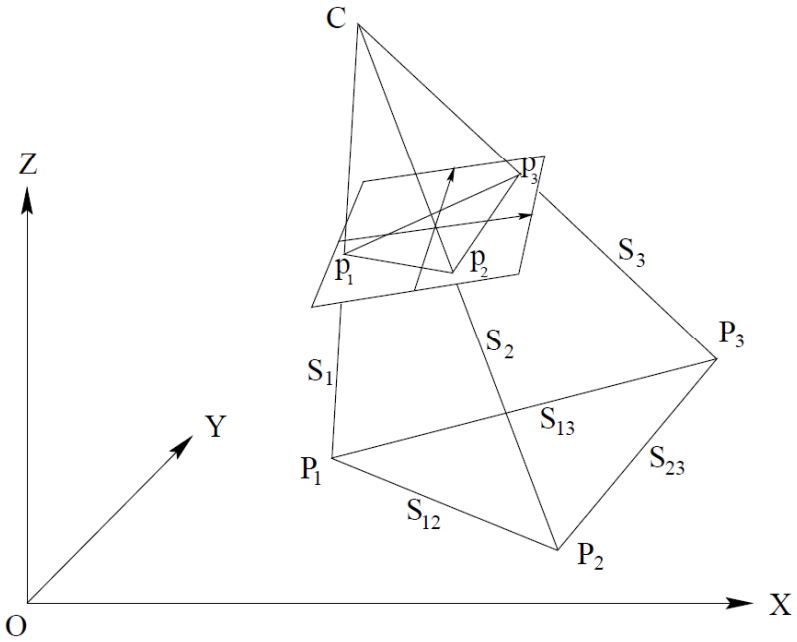
$$det(F) = 0$$

$$2EE^{\top}E - trace(EE^{\top})E = 0$$

Camera pose & 3D point coordinates estimation

Sequential:
1) Relative orientation
2) Space resection
3) Forward intersection or triangulation

Space resection with 4 points

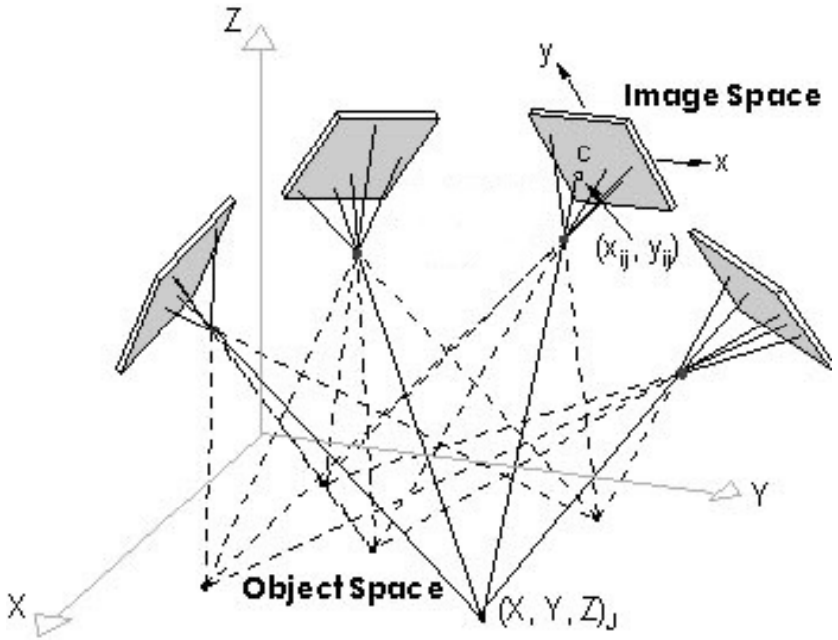


1) Estimation of scale factor of each ray
2) Estimation of orientation parameters
3) Selection of the correct solution with the 4th point

Camera pose & 3D point coordinates estimation

Sequential
1) Relative orientation
2) Space resection
3) **Forward intersection or triangulation**

Forward intersection or triangulation



Input:
- ✓ Exterior orientation parameters
- ✓ Corresponding image points
- ✓ Calibration parameters

Output:
- ✓ 3D coordinates of the corresponding image points

Bundle adjustment & self-calibration

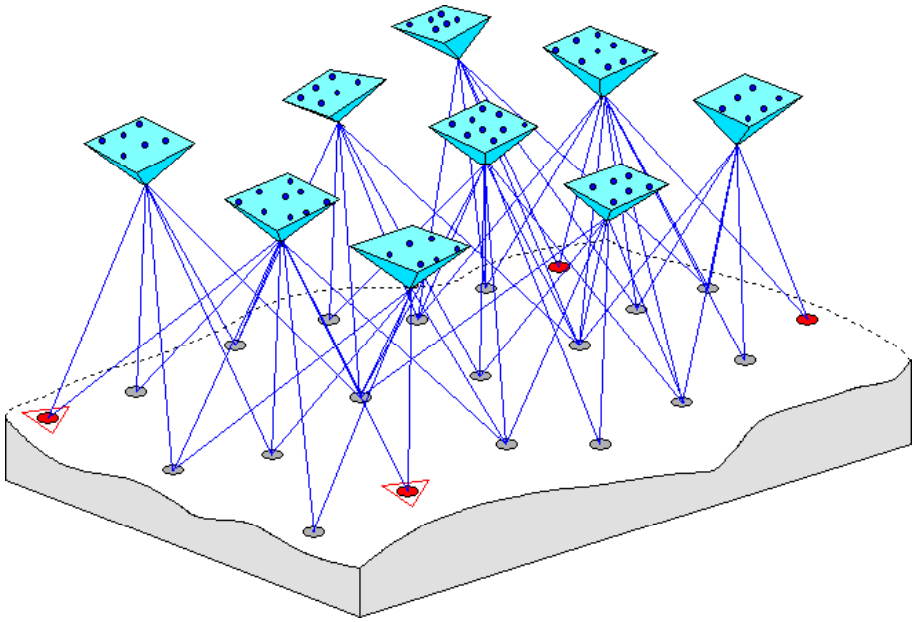
Simultaneous estimation of:
1) the camera location and orientation
2) the 3D coordinates of the image points

3) camera calibration parameters

Requirement: initial values

Associated concepts:

- ✓ Optimization methods
- ✓ Mathematical/stochastical model
- ✓ Reduced Normal Equation (RNE)
- ✓ Datum definition
- ✓ Total Error Propagation (TEP)
- ✓ Limited Error Propagation (LEP)
- ✓ Blunder detection



Bundle adjustment & self-calibration

Optimization method:

- ✓ Least squares: L2 ... Delivers quality analysis matrices
- ✓ Least absolutes: L1 ... Less sensitive to blunders

Datum choice with:

- ✓Inner constraints / free network
- ✓External constraints: control points

Bundle adjustment & self-calibration

Gauss-Markov model

$$\mathrm{E}\{L\} = A \cdot X$$

$$\Delta\{L\} = P^{-1} \cdot \sigma_0^2$$

With **datum** constraints

$$D \cdot X = 0$$

Linearized observation equation

$$L + V = A \cdot X$$

Variation function or object function

$$\phi = V^T \cdot P \cdot V + 2K_1^T \cdot (L + V - A \cdot X) + 2K_2^T \cdot (D \cdot X - 0)$$

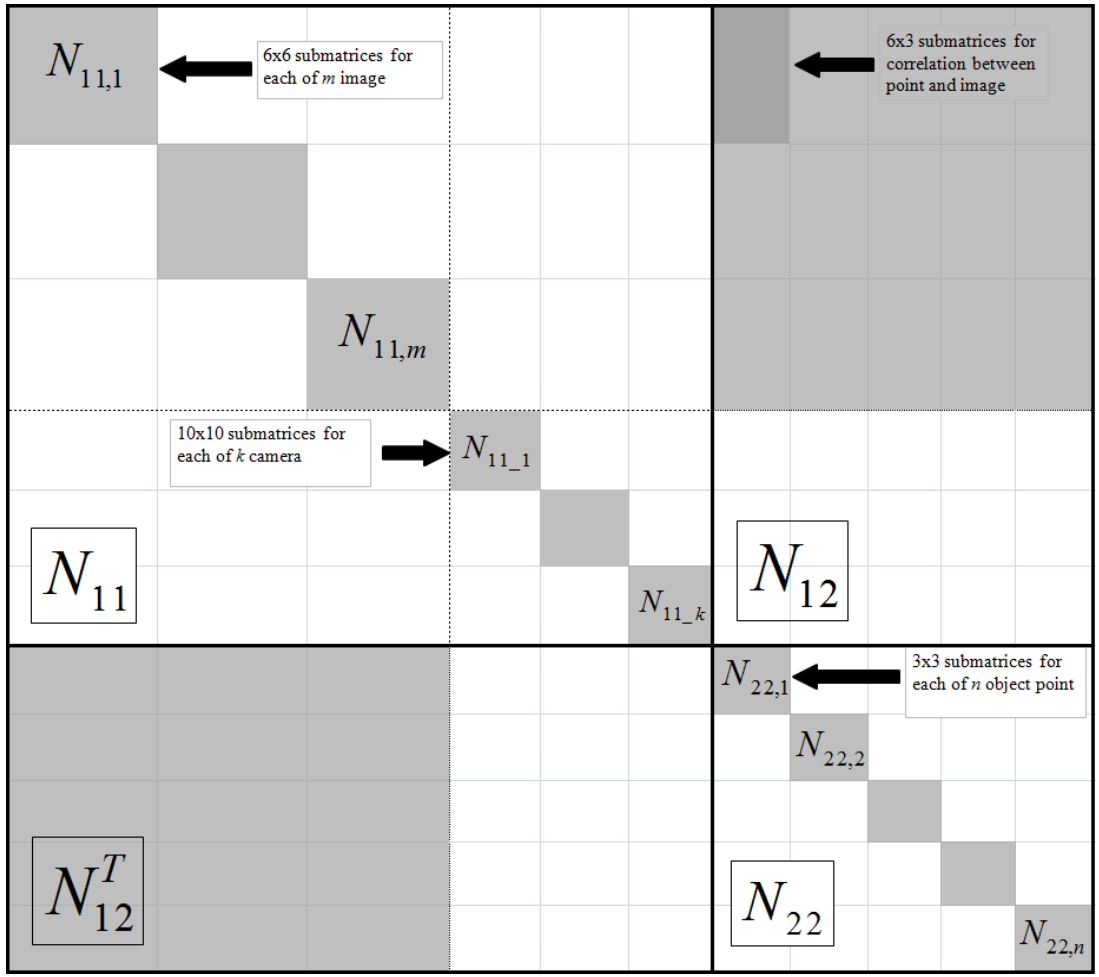
Solution with Lagrange method

$$X = (A^T \cdot P \cdot A + D^T \cdot D)^{-1} \cdot (A^T \cdot P \cdot L)$$

Cofactor matrix

$$Q = (A^T \cdot P \cdot A + D^T \cdot D)^{-1} - H^T \cdot (H \cdot D^T \cdot D \cdot H^T)^{-1} \cdot H$$

Normal equation

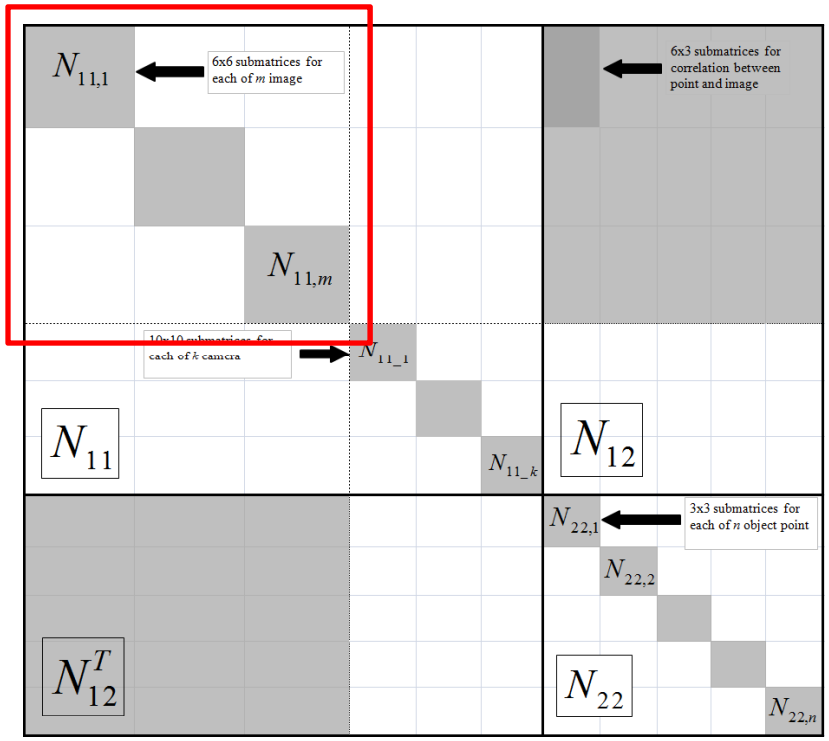


- ✓ Total Error Propagation
- ✓ Limited Error Propagation

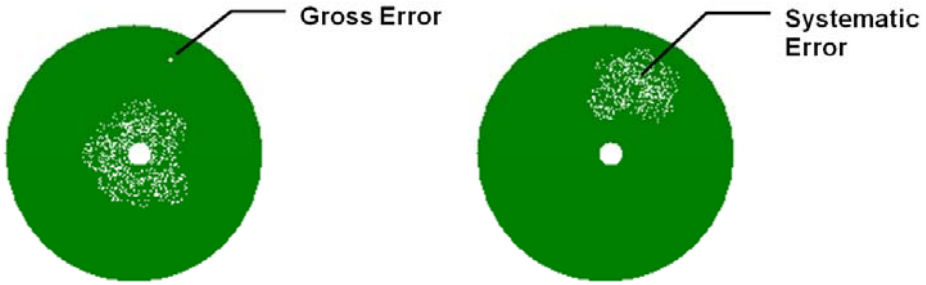
Advantage of bundle adjustment with Reduced Normal Equation (RNE):

- ✓Increases computation speed because of less CPU operation
- ✓Less computer memory consumption
- ✓Better numerical stability

Largest block of RNE



Blunder detection



Baarda data snooping method

$$w_i = \frac{-v_i}{\sigma_{v_i}} \quad \text{with} \quad \sigma^2_{v_i} = \sigma^2_0 q_{v_i v_i}$$

$$q_{v_i v_i} \ldots \text{ith diagonal element of } Q_{vv}$$

With geometrically strong network, Root Mean Squares (RMS) of Residuals is a good approximation of:

$$\sigma_{v_i}$$

Calibration models:

1) 11 parameters of Ebner ... Aerial photogrammetry and model-based adjustment
2) 44 parameters of Gruen ... Aerial photogrammetry and photo-based adjustment
3) **8 parameters of Brown + 2 parameters ... Close range**

$$\Delta x = dx_0 - \frac{\bar{x}}{c} dc - S_x \bar{x} + a \bar{y} + \bar{x}(r^2 k_1 + r^4 k_2 + r^6 k_3) + (r^2 + 2\bar{x}^2) p_1 + 2\bar{x}\,\bar{y}\, p_2$$

$$\Delta y = dy_0 - \frac{\bar{y}}{c} dc - a \bar{x} + \bar{y}(r^2 k_1 + r^4 k_2 + r^6 k_3) + (r^2 + 2\bar{y}^2) p_2 + 2\bar{x}\,\bar{y}\, p_1$$

Where $r = \sqrt{\bar{x}^2 + \bar{y}^2}$, $\bar{x} = x - x_0$, $\bar{y} = y - y_0$ and with

S_x	affinity parameter
a	shear parameter
k_1, k_2, k_3	parameters of radial symmetrical lens distortion
p_1, p_2	parameters of decentering lens distortion
c.....	Camera constant
dc	correction to the camera constant
x_0, y_0	shift of principal point
dx_0, dy_0	correction to the shift of principal point

Contribution of observations

Variance component estimation (VCE)

$$L + V = AX, \quad C_L = \sum_{k=1}^{p} \sigma_k Q_k$$

$$\hat{\sigma} = N^{-1} r$$

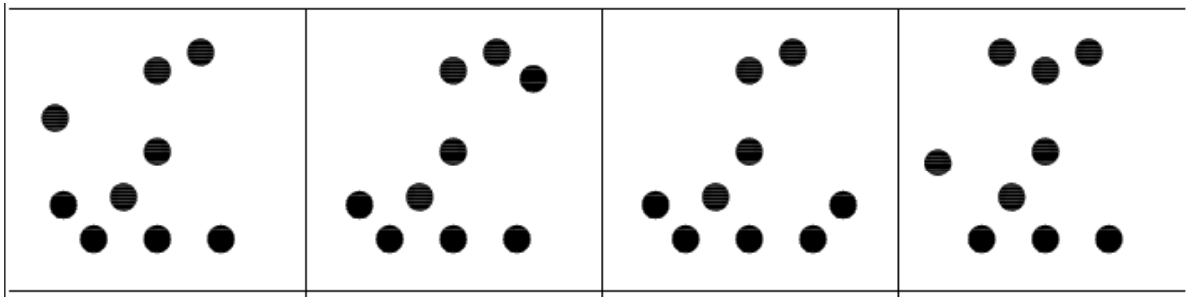
$$n_{kl} = \frac{1}{2} \mathrm{tr}(Q_k C_l^{-1} P_A^{\perp} Q_l C_l^{-1} P_A^{\perp})$$

With $$r_k = \frac{1}{2} \hat{v}^T C_l^{-1} Q_k C_l^{-1} \hat{v}$$

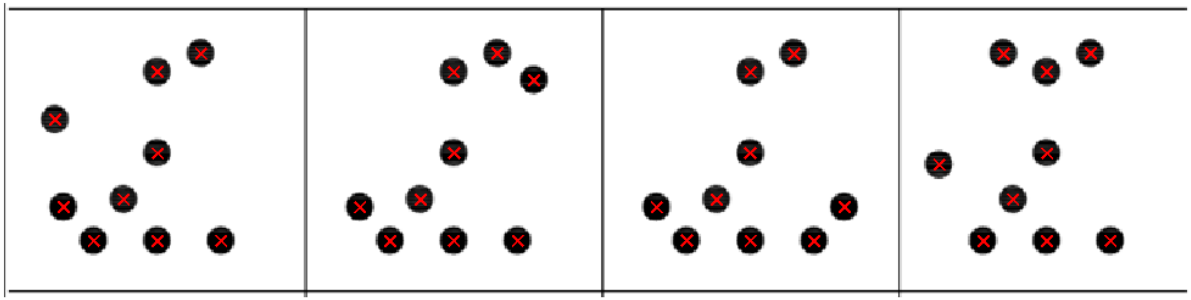
$$P_A^{\perp} = I - A(A^T C_l^{-1} A)^{-1} A^T C_l^{-1}$$

Automation

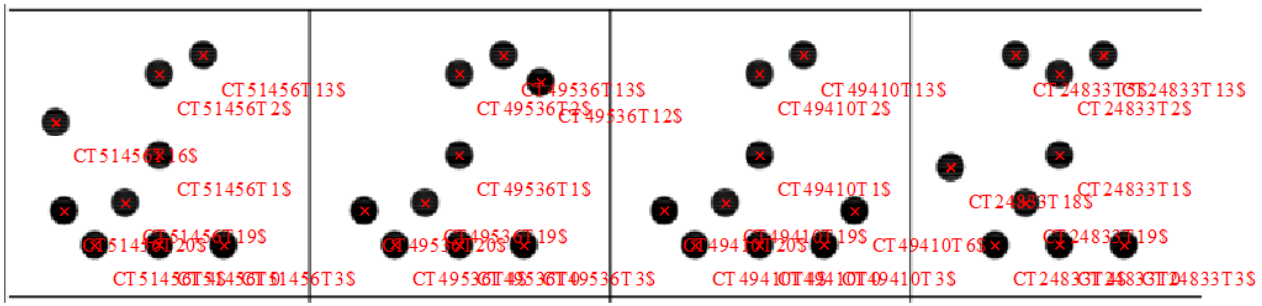
Coded targets



Target center detection



Recognition of coded targets



Automation

Automated labeling:

- ✓Labeling the non-labeled image points
- ✓Epipolar line constraint (sub-pixel accuracy)
- ✓Rapid search space of corresponding image points by clustering of images

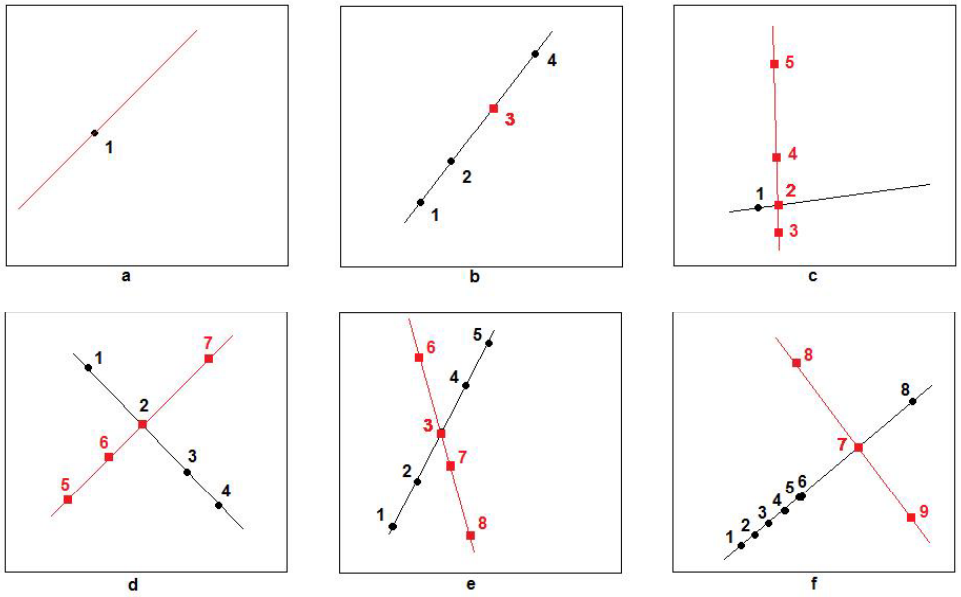
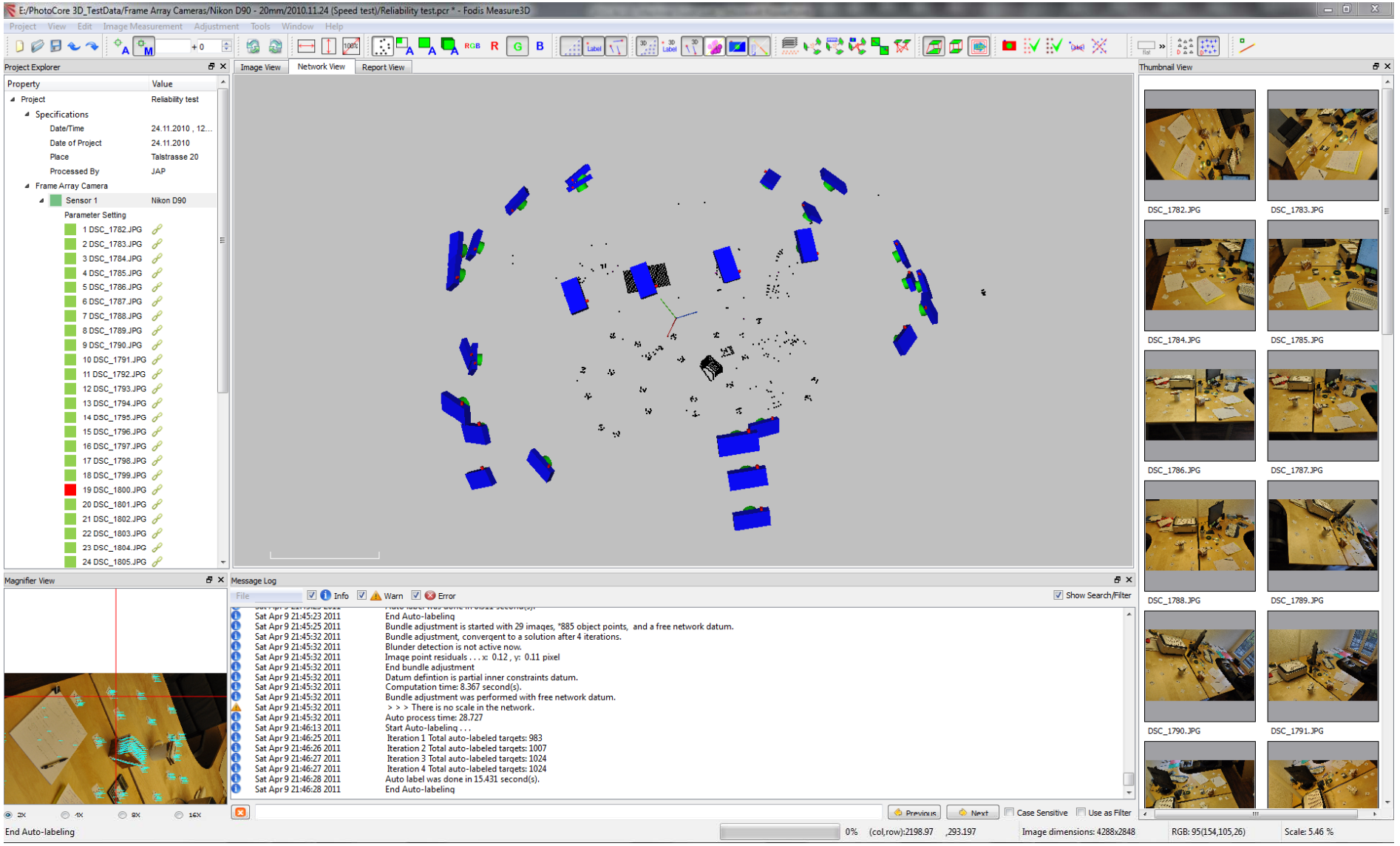
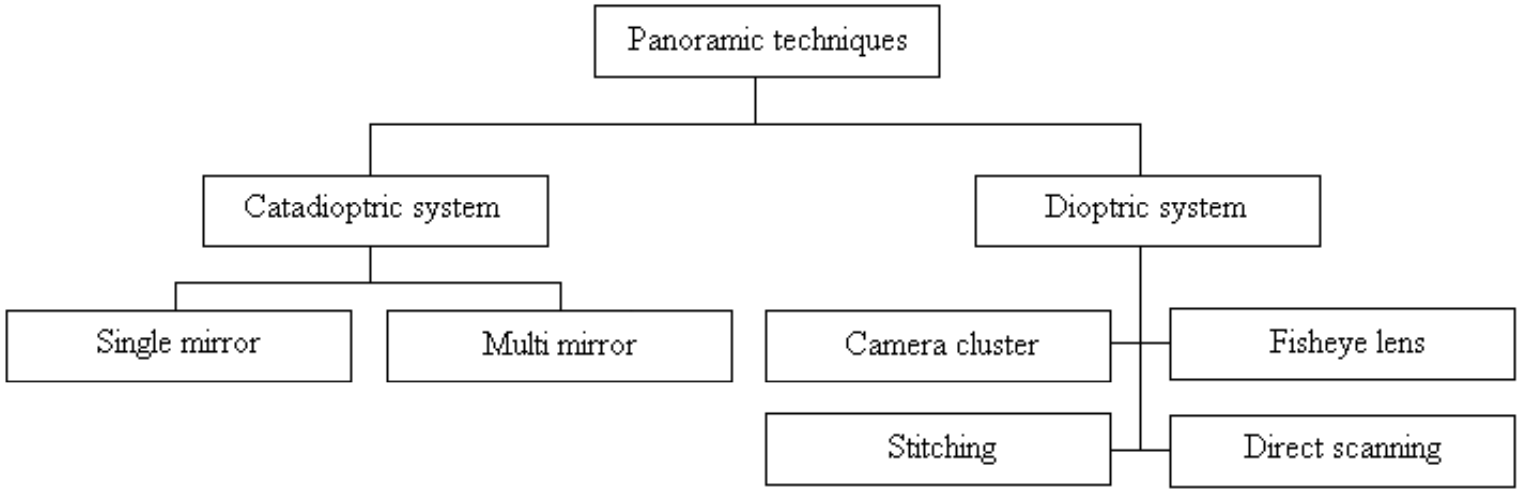


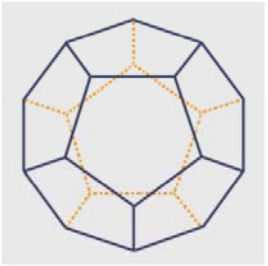
Image “a”	Image “b”	Image “c”	Image “d”	Image “e”	Image “f”
a1	b1 b2 b3 b4	c1 c2	d1 d2 d3 d4	e1 e2 e3 e4 e5	f1 f2 f3 f4 f5 f6 f7 f8
a1	b3	c2 c3 c4 c5	d2 d5 d6 d7	e3 e6 e7 e8	f7 f8 f9
a1	**b3**	**c2**	**d2**	**e3**	**f7**

Demo Real Measurement & Fodis Measure^{3D} software



Panoramic imaging





(a)

(b)

(c)

Panoramic imaging

Panoramic imaging

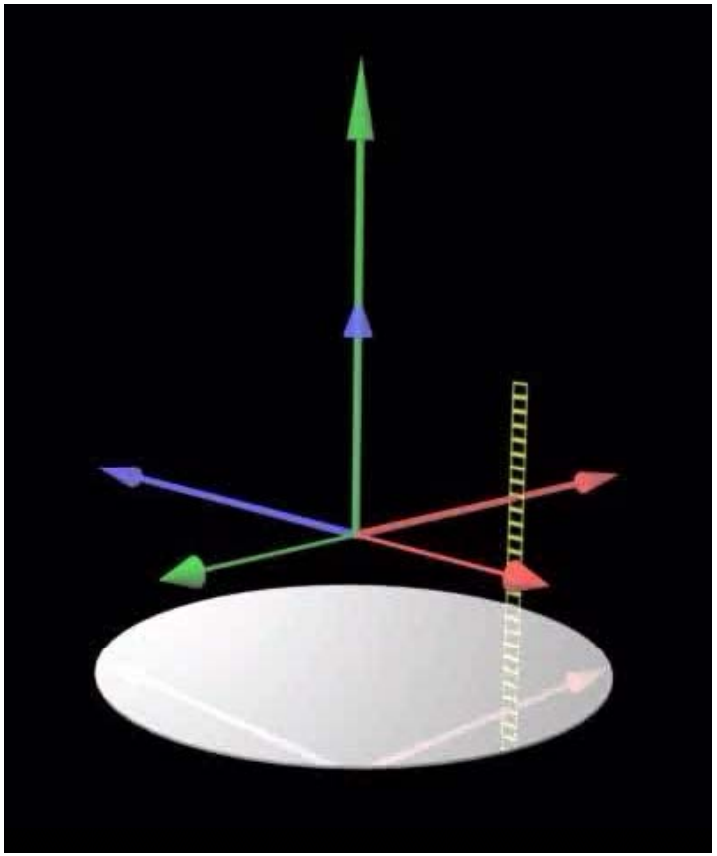
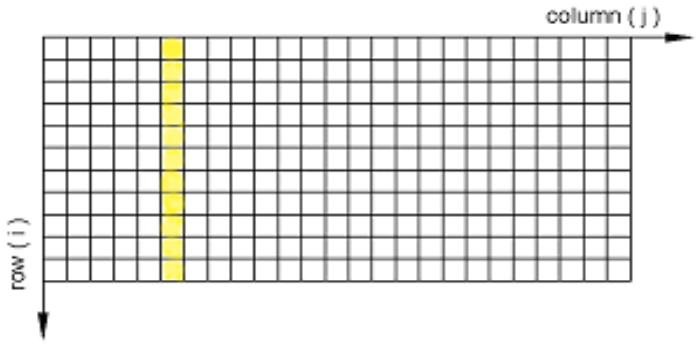


Image format for example:
7,500 pixel × 40,000 pixel (45 mm lens)

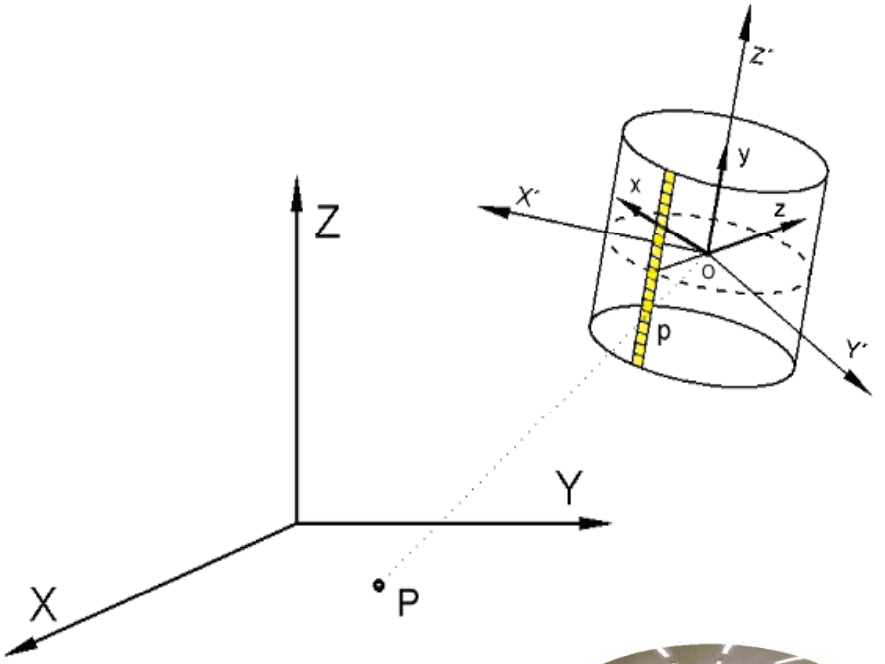
Pixel size: 8 microns

Coordinate systems:

1) Pixel coordinate system (i, j)
2) Linear Array coordinate system (x, y, z)
3) 3D auxiliary coordinate system (X', Y', Z')
4) 3D object coordinate system (X, Y, Z)



Pixel coordinate system



Panoramic camera - Mathematical model

Object coordinate system

Auxiliary coordinate system

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = M_{w,\varphi,k} \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix}$$

3D Conformal

Linear array coordinate system

Auxiliary coordinate system

$$\begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} = R_{z'}(\theta)\,\lambda\,T \begin{pmatrix} 0 \\ y \\ -c \end{pmatrix}$$

$$T = \begin{pmatrix} 0 & 0 & -1 \\ -1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \qquad y = (i - \frac{N}{2})\,P_y \qquad \theta = j\,P_x$$

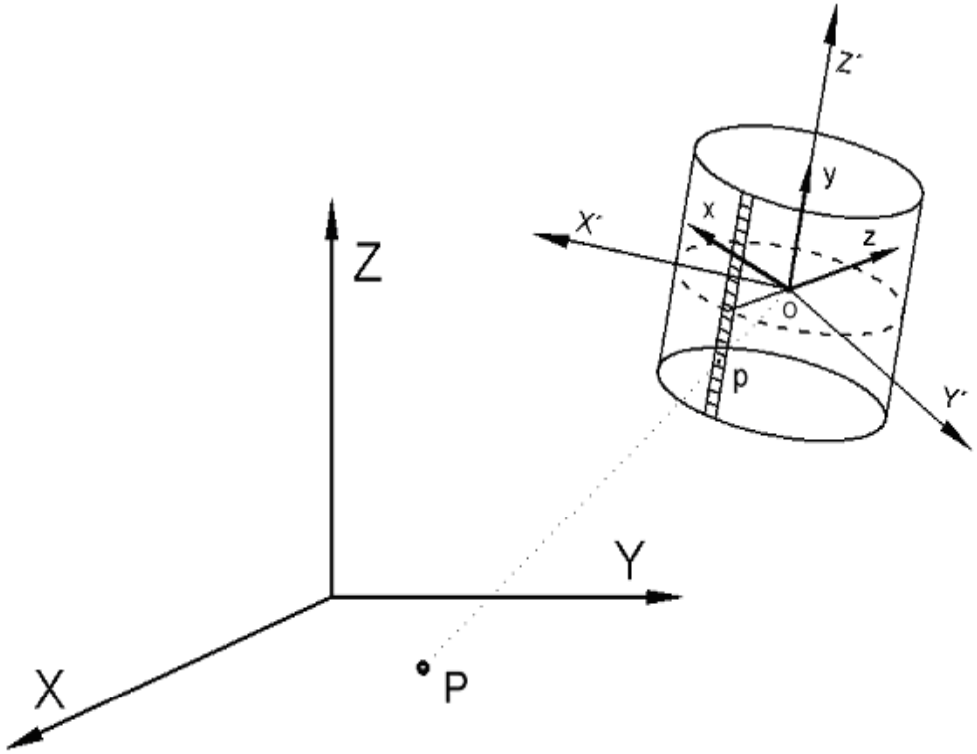
Collinearity equation

Panoramic camera - Mathematical model

$$M_{w,\varphi,k} \cdot \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Y - Z_0 \end{pmatrix} = \lambda \cdot R_{z'}^{t}(\theta) \cdot \begin{pmatrix} c \\ 0 \\ y \end{pmatrix}$$

Additional Parameters

$$y = (i - \frac{N}{2}) P_y \qquad \theta = j P_x$$



Pixel coordinate system (i, j)

3D object coordinate system (X, Y, Z)

Systematic errors for panoramic cameras

a) Stationary systematic errors

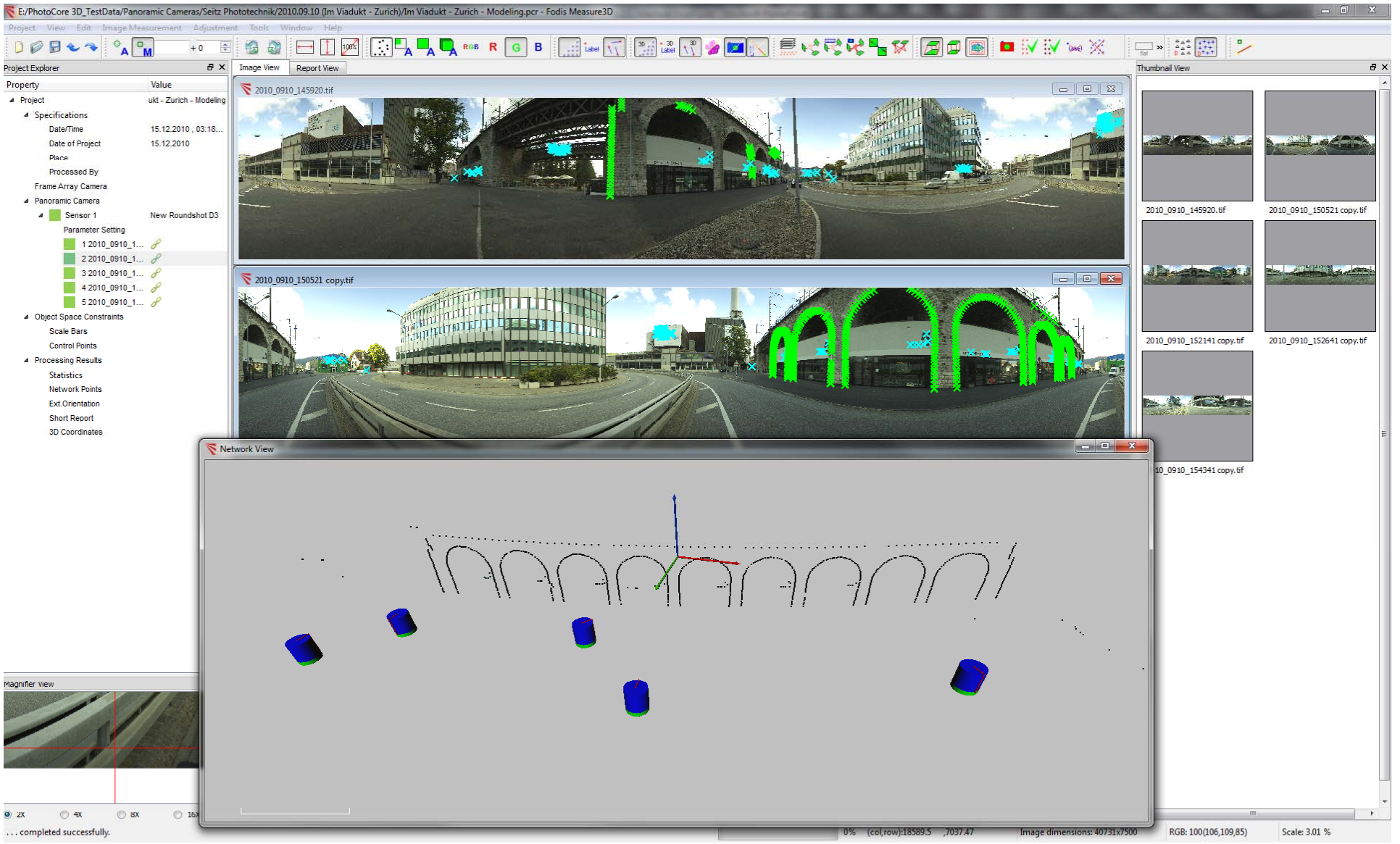
1. Errors common between frame array and panoramic cameras

   – lens distortions
   – shift of principal point
   – shift of camera constant

2. Errors only for panoramic cameras

   – the correction to the angular pixel size
   – tilt and inclination of the linear array
   – eccentricities of the projection center

b) Non-stationary systematic errors

– non-equal angular pixel size
– tumbling

Demo of software