

# 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 stochastic model
- ✓ Blunder detection
- ✓ Self-calibration
- ✓ Variance component estimation

## Automation

- ✓ Coded targets
- ✓ Automated labeling

## Demo - Real Measurement & Fodis Measure<sup>3D</sup> 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<sup>3D</sup> software with panoramic images

What is a photogrammetric network design?

Why a network design is important?

Where can it be applied?

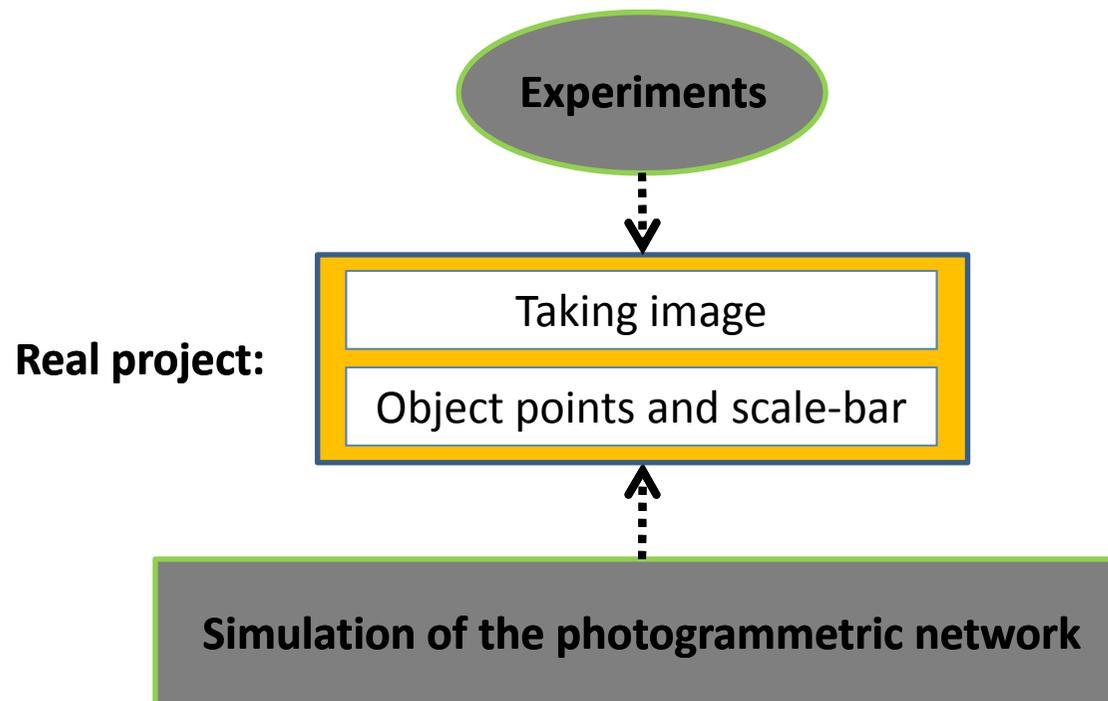
How to perform a photogrammetric network design?

### Real projects - Questions and influencing parameters

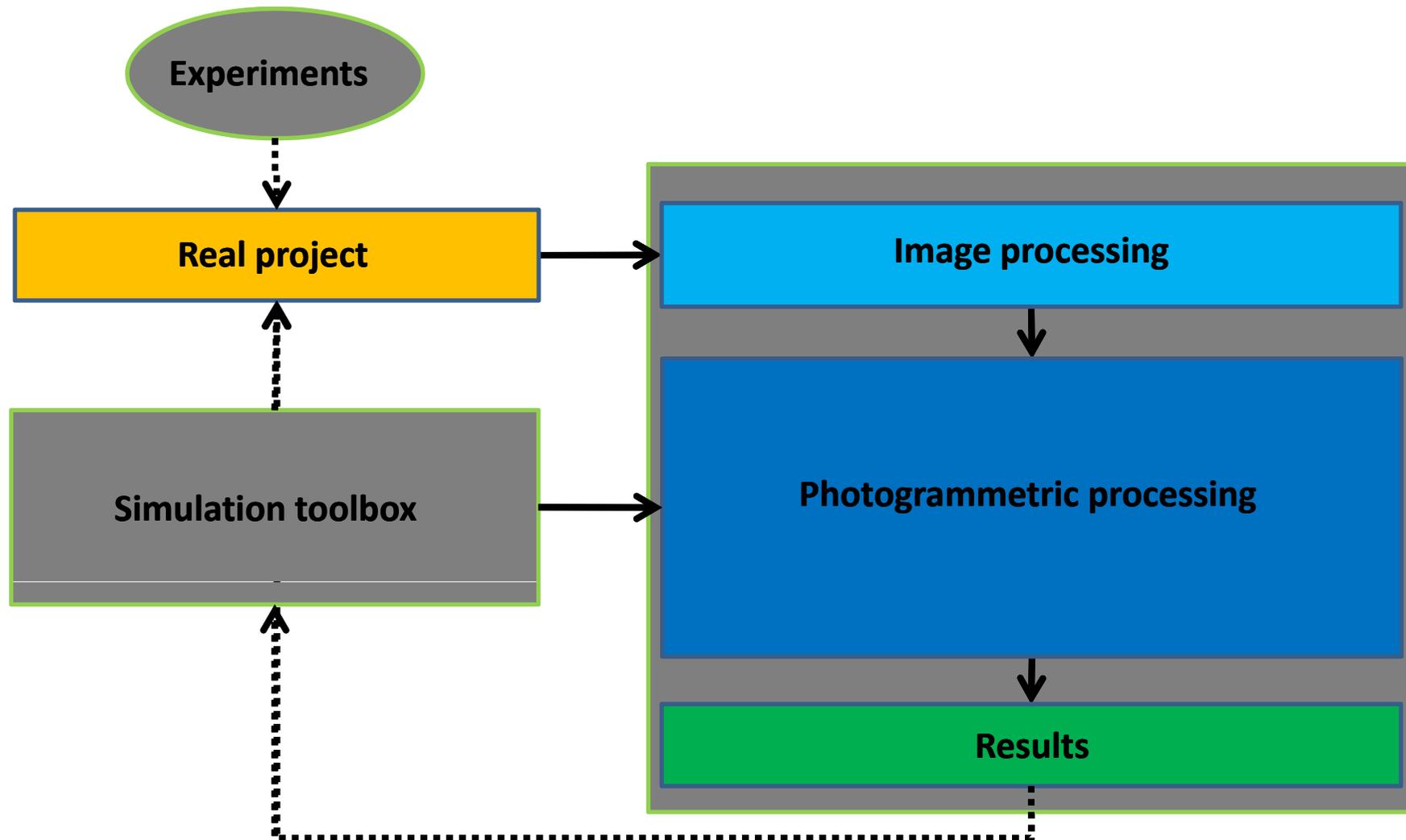
- 1) How many cameras should be used?
  - Ease of camera placement, time limits for taking images
- 2) Which camera is better to use?
  - Accuracy requirement, performance requirements
- 3) From which locations should the images be taken?
  - Accuracy requirement, visibility requirements
- 4) How many 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

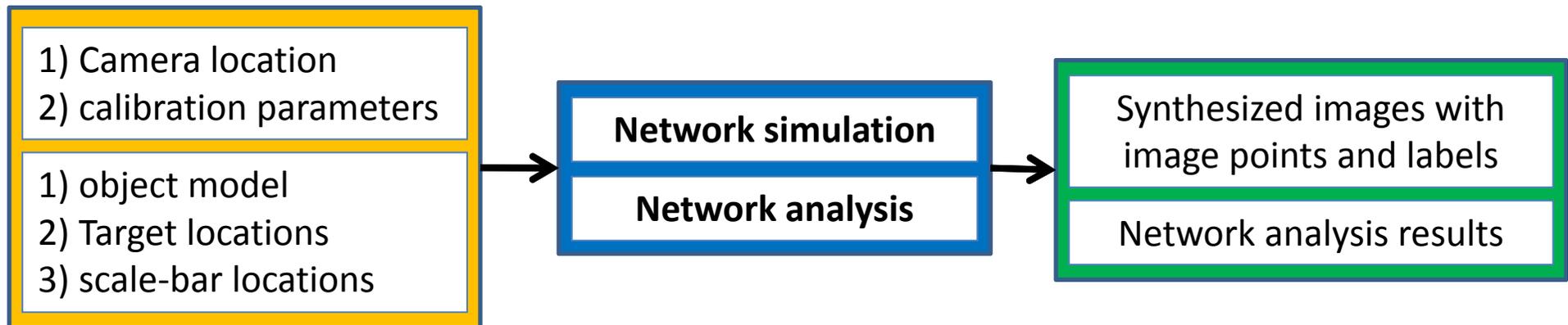


**Approach 2)** Requires basic knowledge of photogrammetry and is able to handle complicated projects



### PhotoCore simulation software package

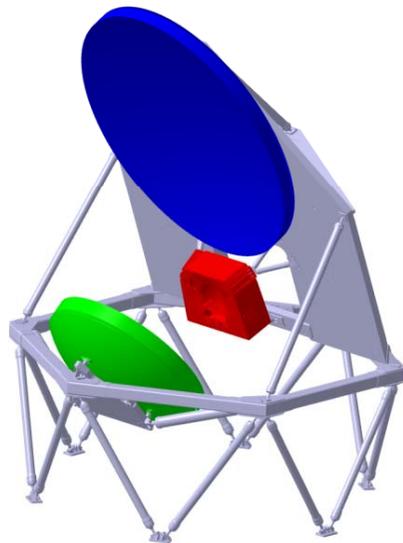
A MATLAB Toolbox which simulates a photogrammetric network and performs photogrammetric analysis.



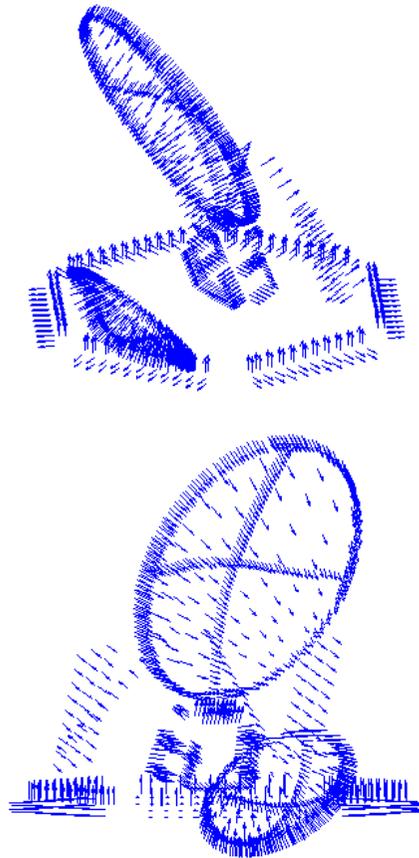
Its output includes:

- 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

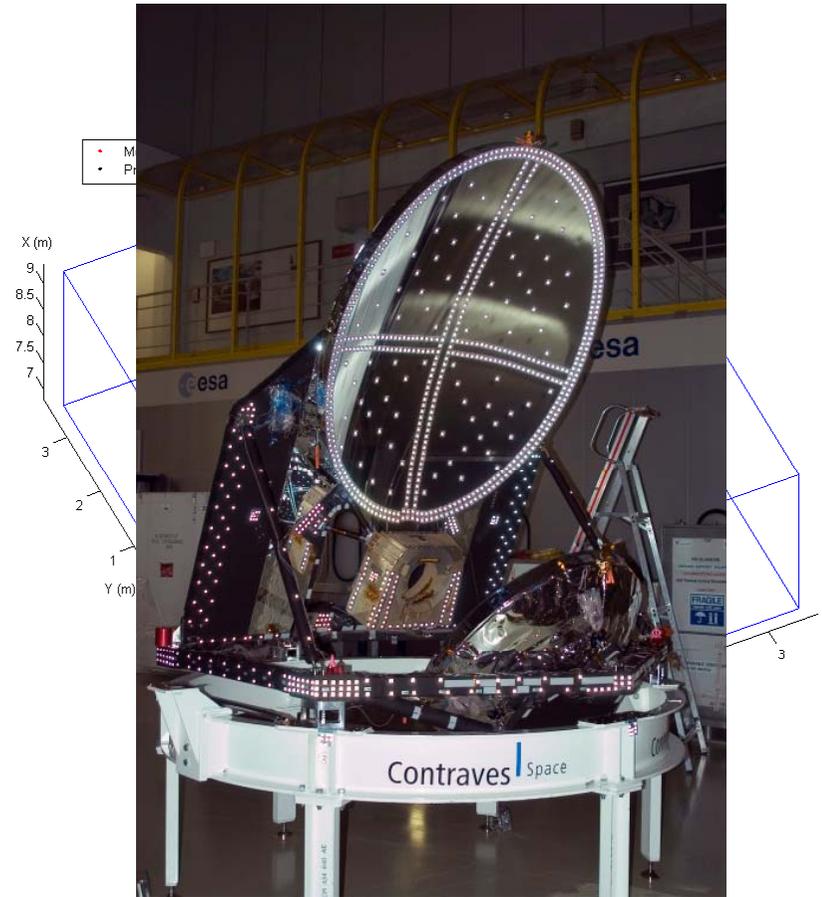
## Virtual testing



CAD model of Planck Telescope  
Courtesy Thales Alenia Space France



Targets and normal vectors  
on CAD model



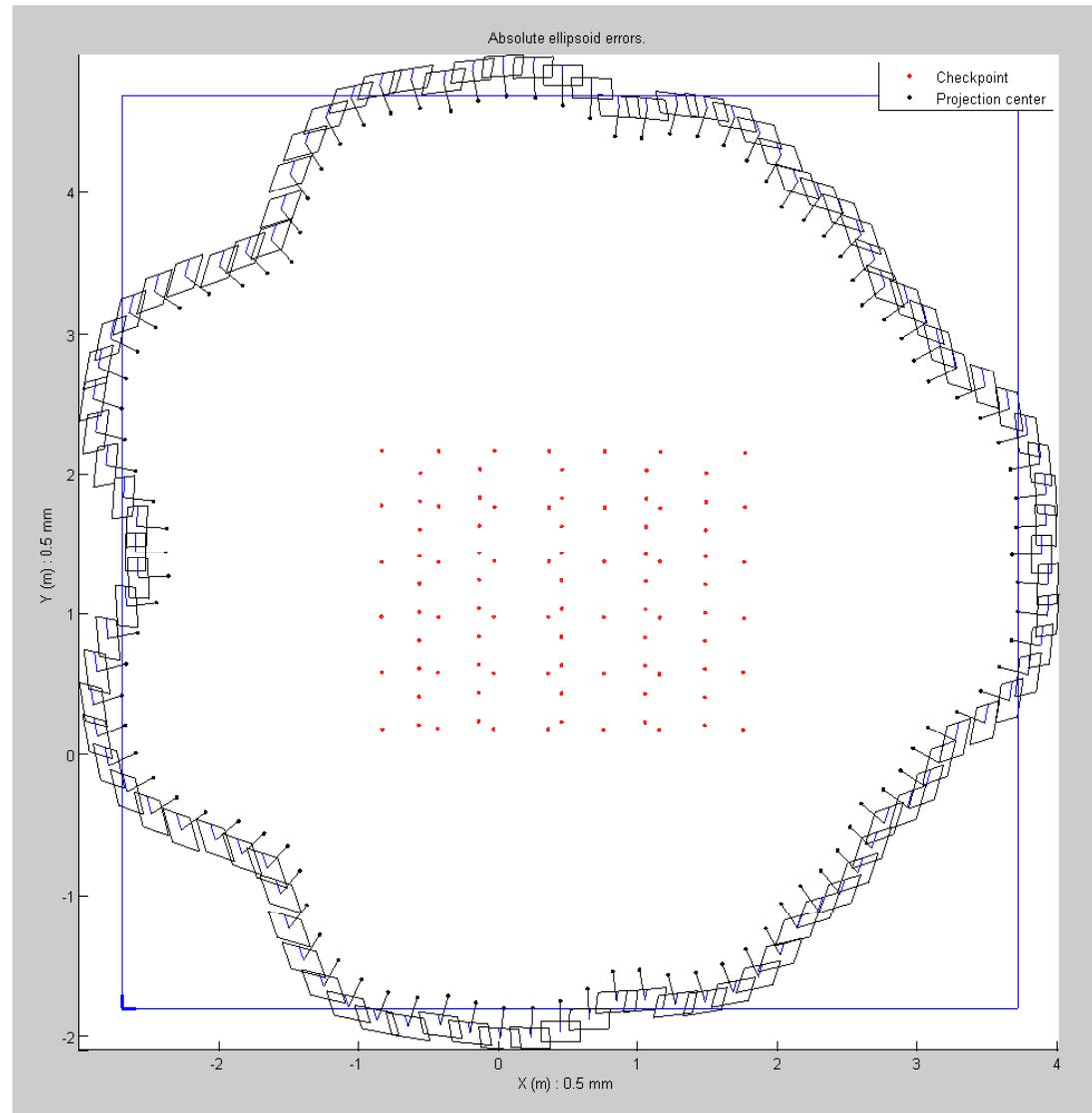
Courtesy ESA

## Photogrammetric network design applied in AeroSpace



Herschel space telescope, courtesy European Space Agency (ESA)

# Demo of network design

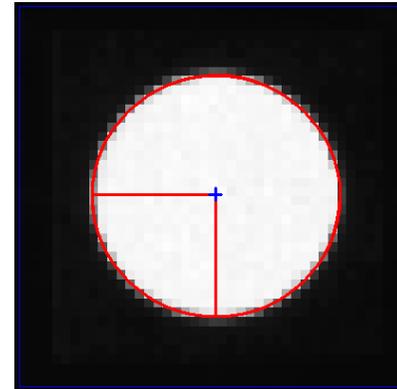


### Image processing – Target detection

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

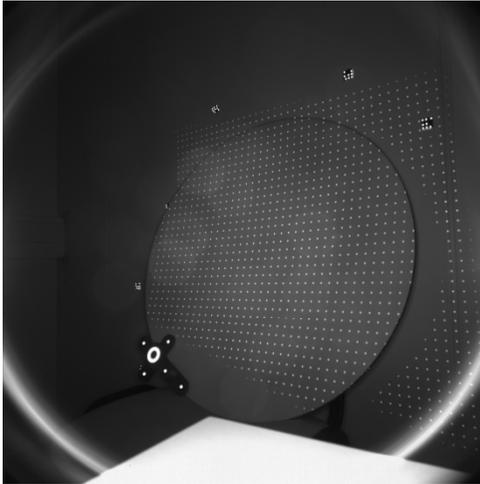


#### Accuracy potential:

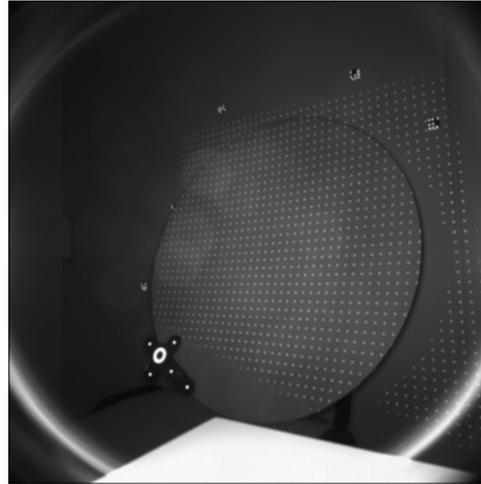
With flat-retro reflective targets: 0.003 pixel (~0.042 micron if pixel size is 14 microns)

With high contrast projected targets: 0.001 pixel (~0.014 micron if pixel size is 14 microns)

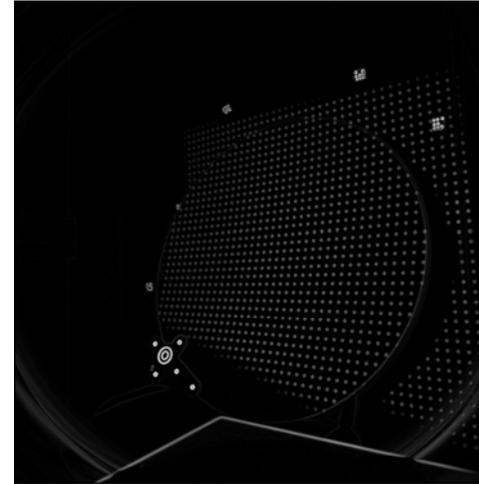
## Image processing – Target detection and chaining



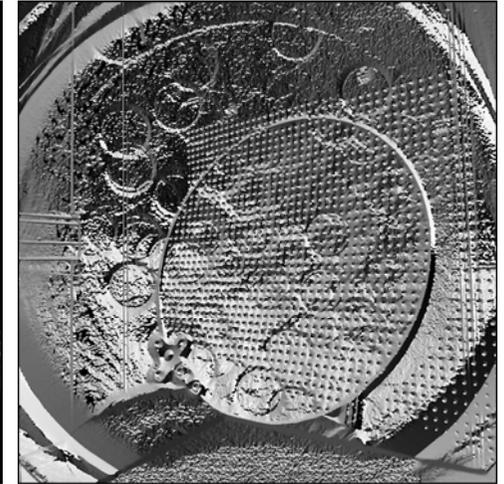
1) Original image



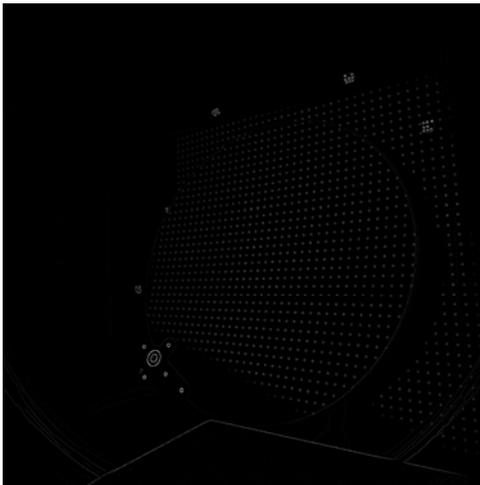
2) Smoothed image



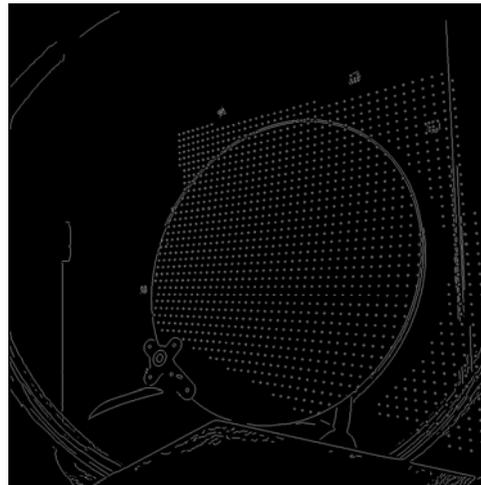
3) First derivative image



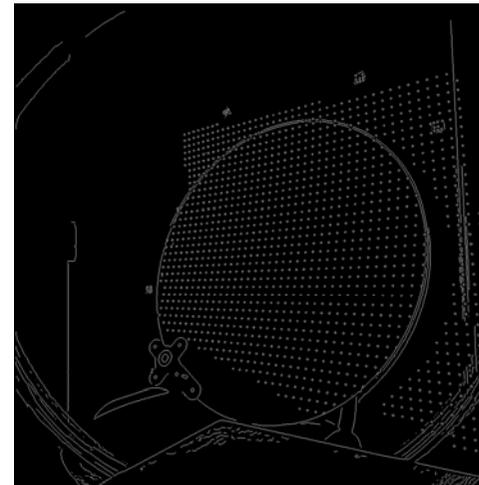
4) Orientation image



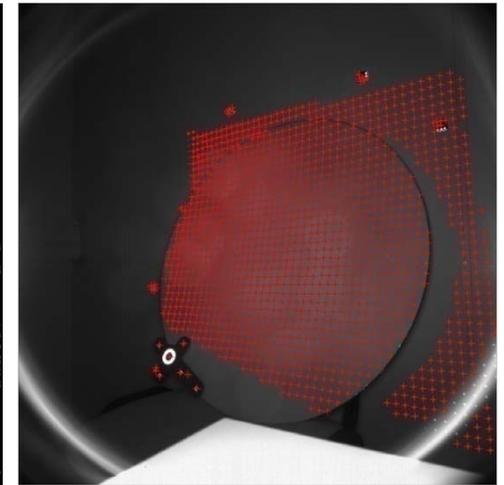
5) Non-maximum suppression



6) Edges

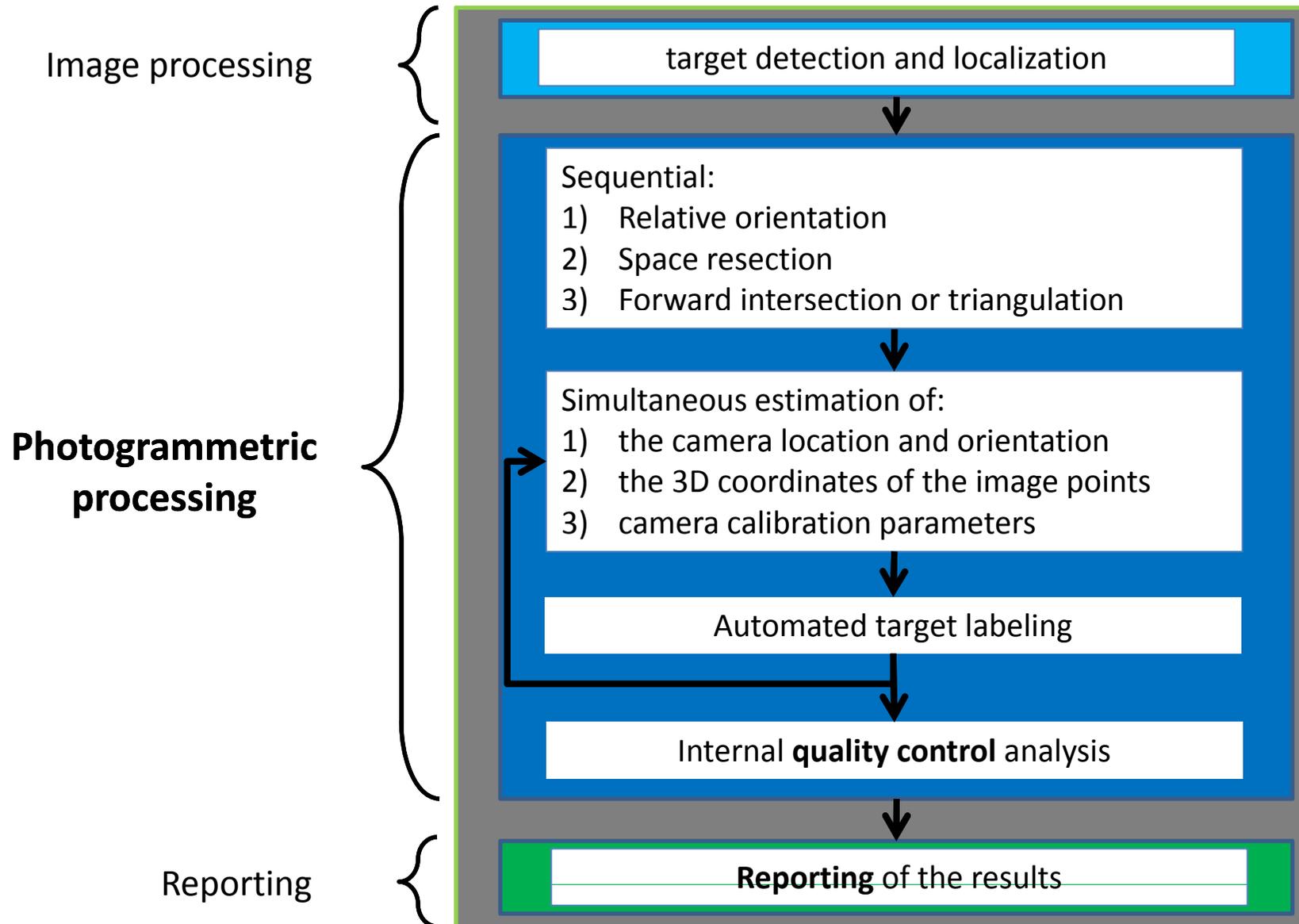


7) Edge thinning



10) Target centers

# Photogrammetric processing

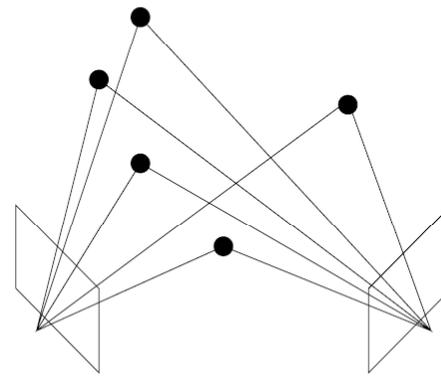
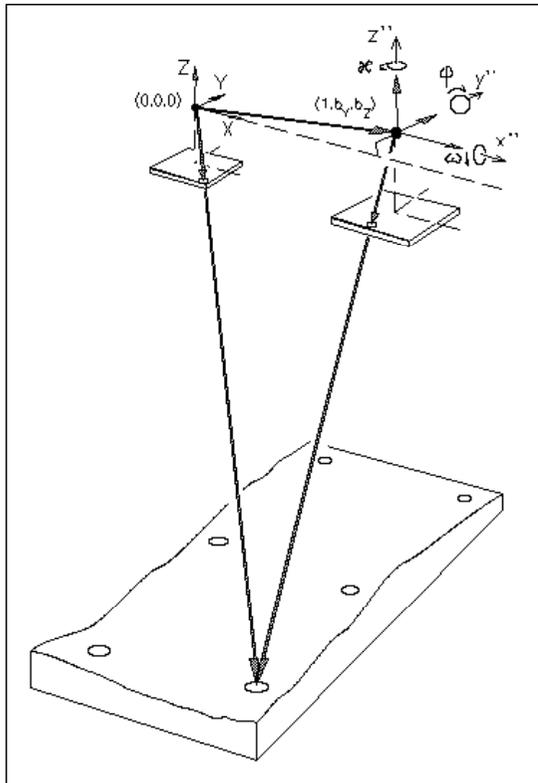


# Camera pose & 3D point coordinates estimation

Sequential:

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

Relative orientation with five point algorithm



$$q'^T F q = 0$$

$$\det(F) = 0$$

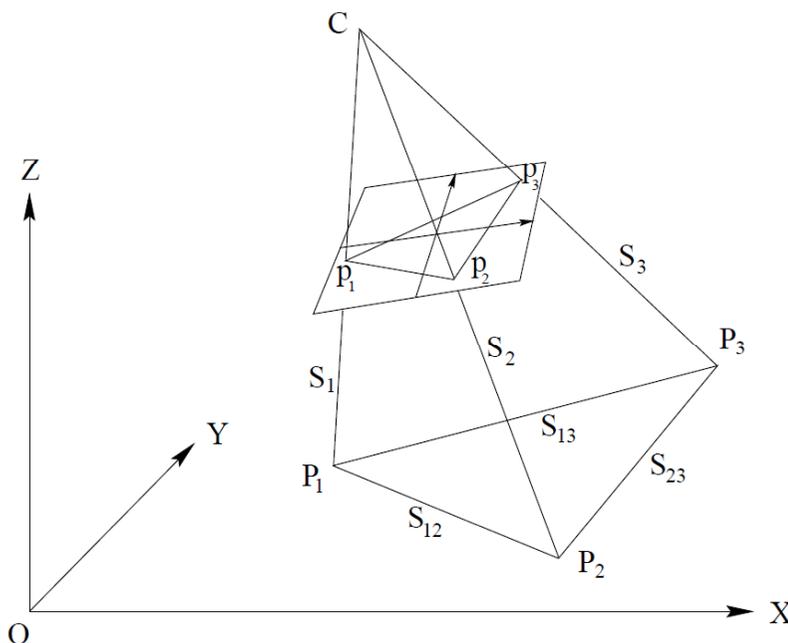
$$2EE^T E - \text{trace}(EE^T)E = 0$$

## Camera pose & 3D point coordinates estimation

Sequential:

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

Space resection with 4 points



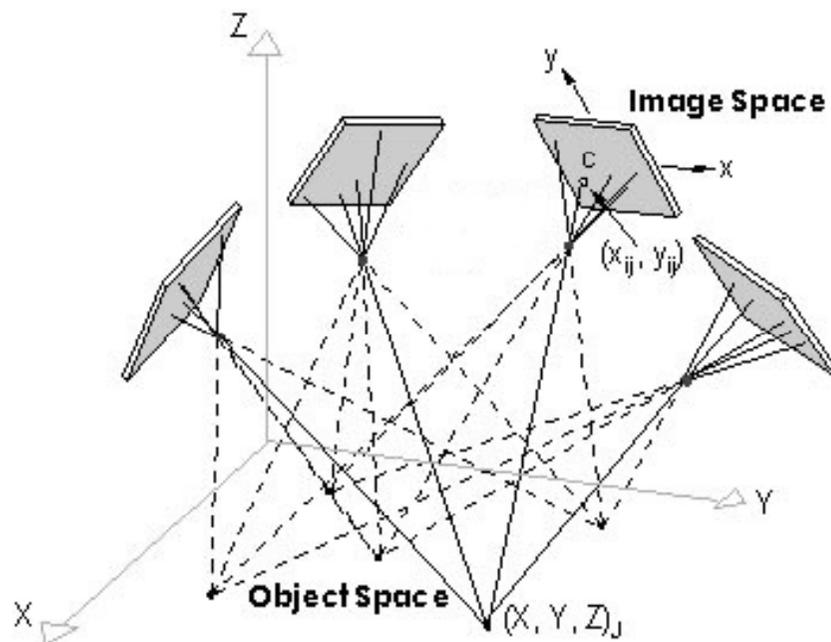
- 1) Estimation of scale factor of each ray
- 2) Estimation of orientation parameters
- 3) Selection of the correct solution with the 4<sup>th</sup> point

## 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

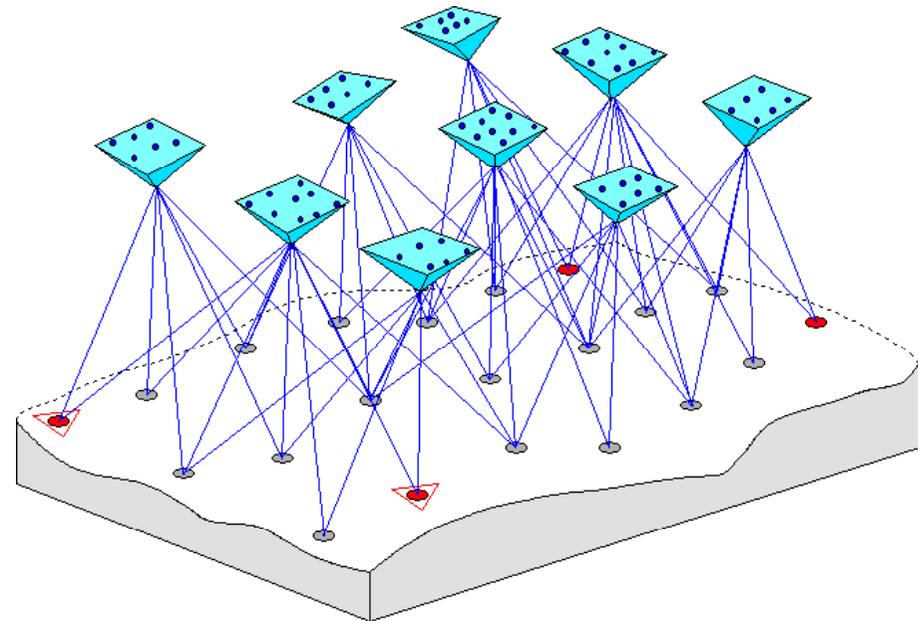
**Simultaneous** estimation of:

- 1) the camera location and orientation
- 2) the 3D coordinates of the image points
- 3) camera calibration parameters

Associated concepts:

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

Requirement: initial values



## 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

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

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

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

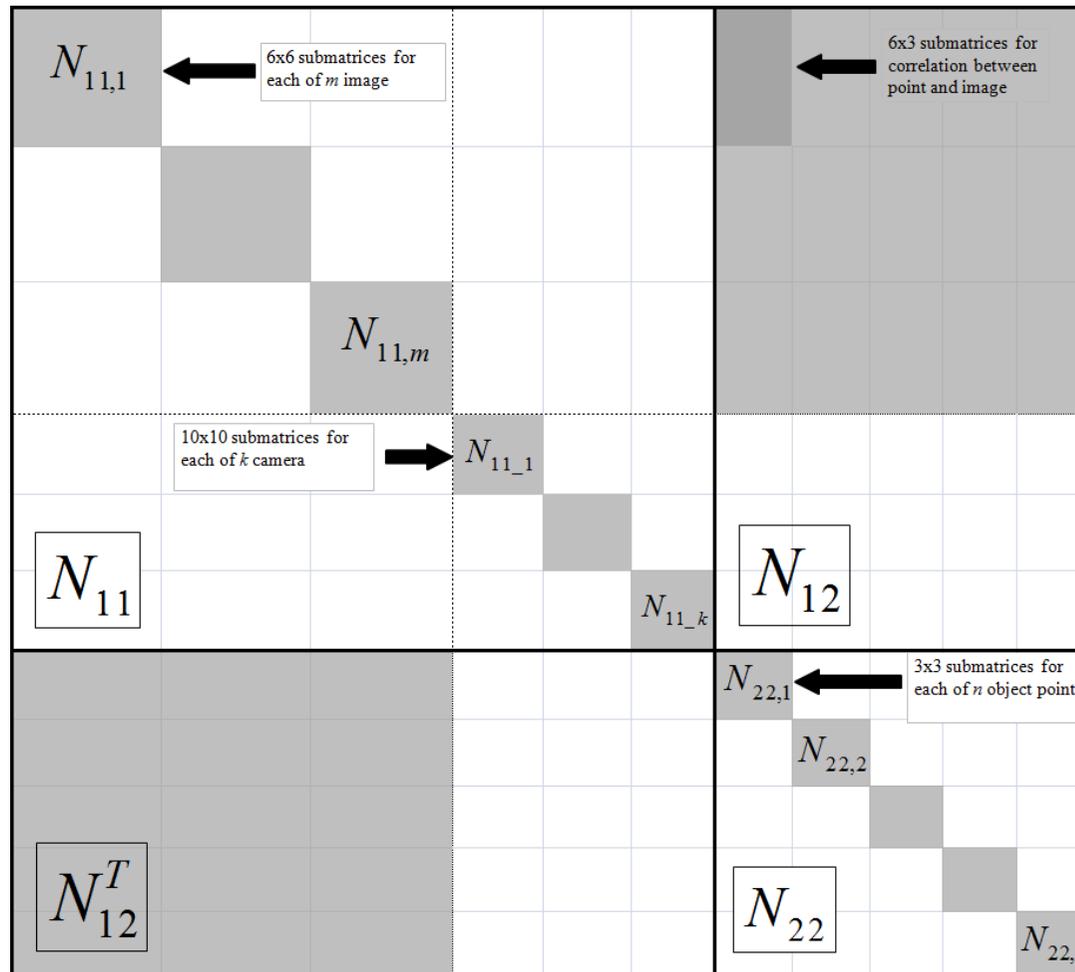
$$X = (A^T \cdot P \cdot A + D^T \cdot D)^{-1} \cdot (A^T \cdot P \cdot L)$$

Cofactor matrix

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

# Bundle adjustment & self-calibration

## Normal equation



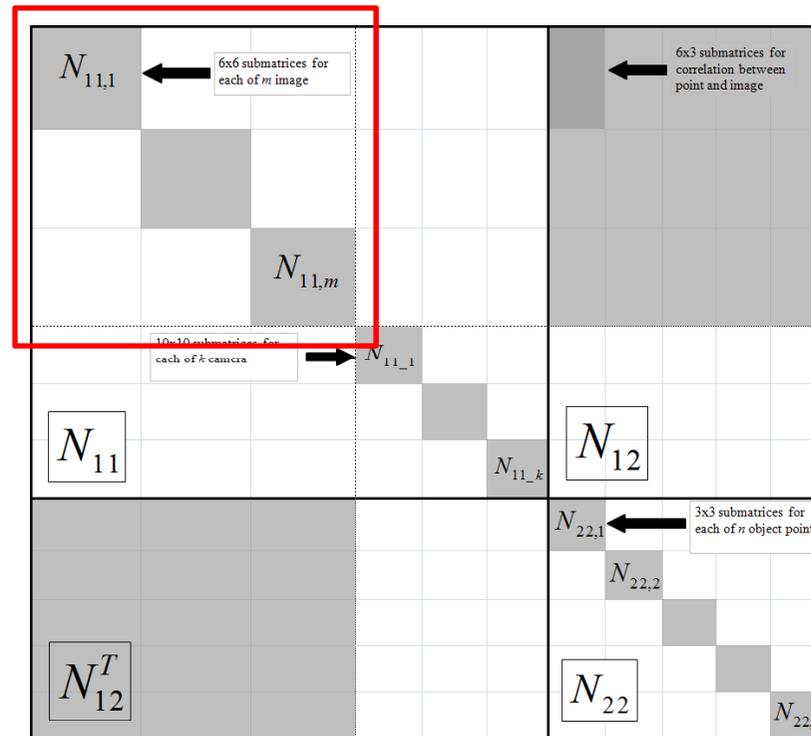
- ✓ Total Error Propagation
- ✓ Limited Error Propagation

## Bundle adjustment & self-calibration

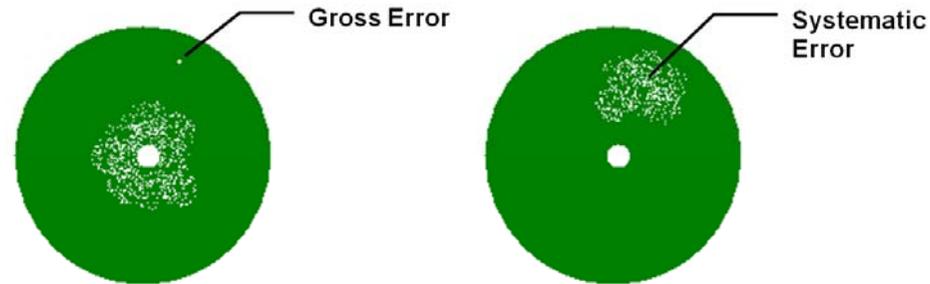
Advantage of bundle adjustment with Reduced Normal Equation (RNE):

- ✓ 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

$$w_i = \frac{-v_i}{\sigma_{v_i}} \quad \text{with} \quad \sigma_{v_i}^2 = \sigma_0^2 q_{v_i v_i}$$

$q_{v_i v_i}$  ...  $i$ th 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

## Bundle adjustment & self-calibration

Contribution of observations

Variance component estimation (VCE)

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

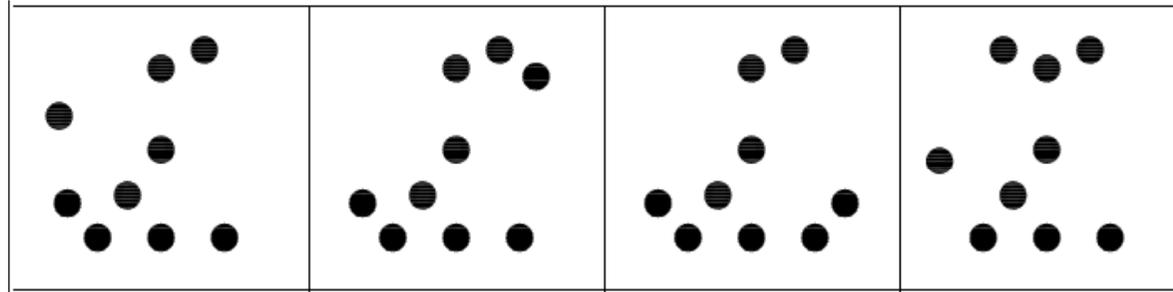
$$\hat{\sigma} = N^{-1}r$$

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

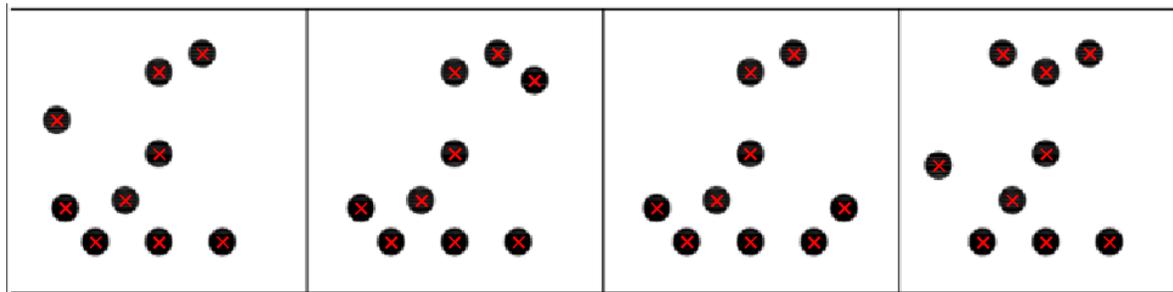
With  $r_k = \frac{1}{2} \hat{v}^T C_l^{-1} Q_k C_l^{-1} \hat{v}$

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

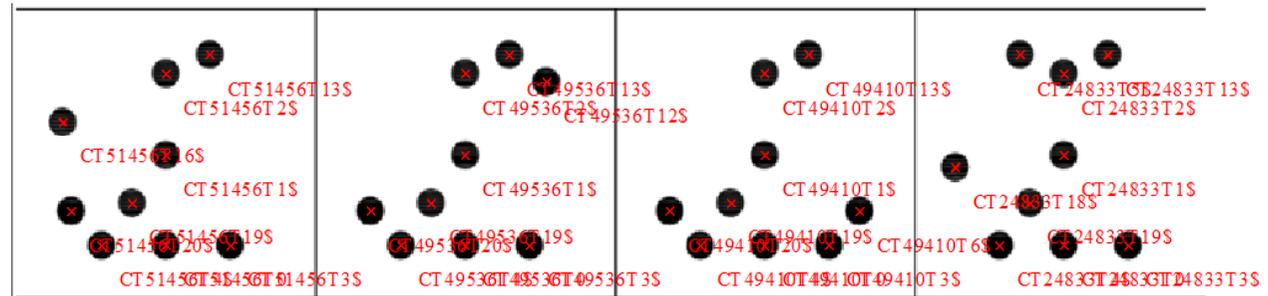
Coded targets



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

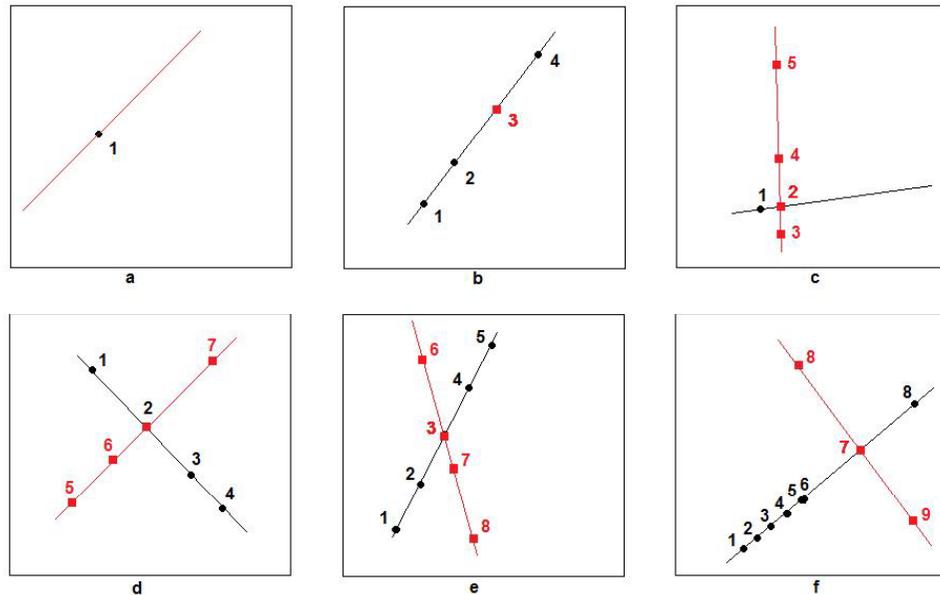


Image "a"	Image "b"	Image "c"	Image "d"	Image "e"	Image "f"
a1	b1 b2 b3 b4	c1 c2	d1 d2 d3 d4	e1 e2 e3 e4 e5	f1 f2 f3 f4 f5 f6 f7 f8
a1	<b>b3</b>	<b>c2 c3 c4 c5</b>	<b>d2 d5 d6 d7</b>	<b>e3 e6 e7 e8</b>	<b>f7 f8 f9</b>
a1	<b>b3</b>	<b>c2</b>	<b>d2</b>	<b>e3</b>	<b>f7</b>

# Demo Real Measurement & Fodis Measure<sup>3D</sup> software

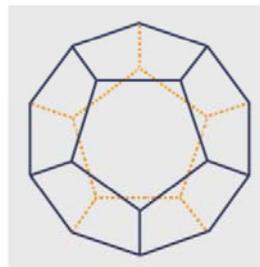
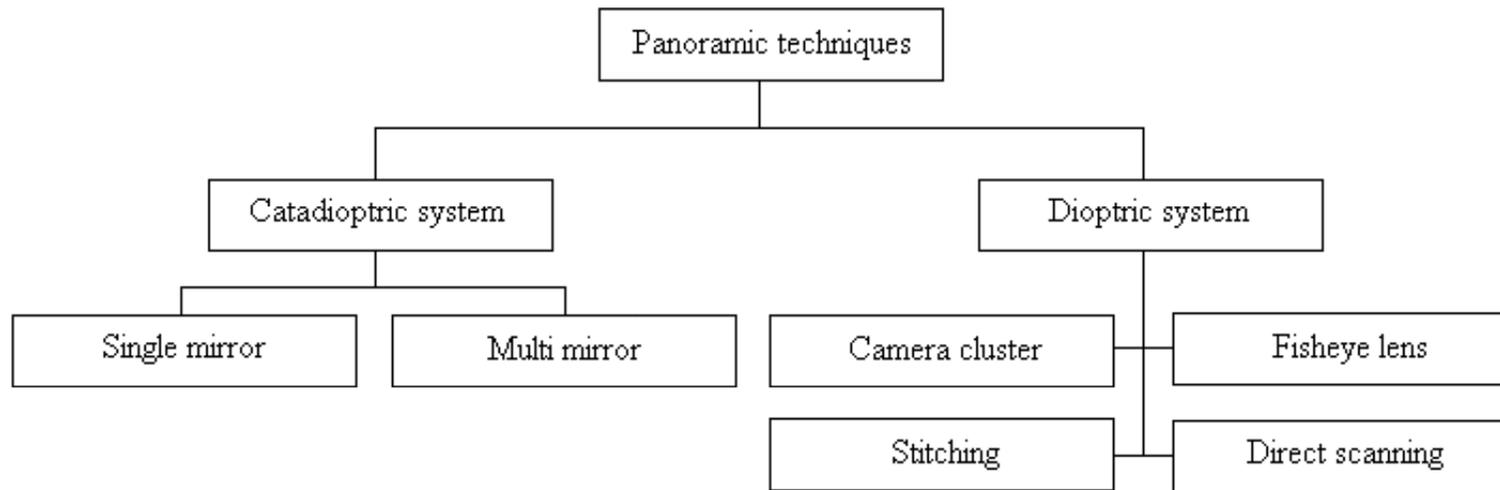
The screenshot displays the Fodis Measure<sup>3D</sup> software interface. The main window shows a 3D point cloud of a desk scene with camera positions indicated by blue and green icons. The interface includes a Project Explorer on the left, a Message Log at the bottom, and a Thumbnail View on the right. The Message Log contains the following text:

```
File Info Warn Error Show Search/Filter
Sat Apr 9 21:45:23 2011 End Auto-labeling
Sat Apr 9 21:45:25 2011 Bundle adjustment is started with 29 images, *885 object points, and a free network datum.
Sat Apr 9 21:45:32 2011 Bundle adjustment, convergent to a solution after 4 iterations.
Sat Apr 9 21:45:32 2011 Blunder detection is not active now.
Sat Apr 9 21:45:32 2011 Image point residuals: ... x: 0.12, y: 0.11 pixel
Sat Apr 9 21:45:32 2011 End bundle adjustment
Sat Apr 9 21:45:32 2011 Datum definition is partial inner constraints datum.
Sat Apr 9 21:45:32 2011 Computation time: 8.367 second(s).
Sat Apr 9 21:45:32 2011 Bundle adjustment was performed with free network datum.
Sat Apr 9 21:45:32 2011 >>> There is no scale in the network.
Sat Apr 9 21:45:32 2011 Auto process time: 28.727
Sat Apr 9 21:46:13 2011 Start Auto-labeling ...
Sat Apr 9 21:46:25 2011 Iteration 1 Total auto-labeled targets: 983
Sat Apr 9 21:46:26 2011 Iteration 2 Total auto-labeled targets: 1007
Sat Apr 9 21:46:27 2011 Iteration 3 Total auto-labeled targets: 1024
Sat Apr 9 21:46:27 2011 Iteration 4 Total auto-labeled targets: 1024
Sat Apr 9 21:46:28 2011 Auto label was done in 15.431 second(s).
Sat Apr 9 21:46:28 2011 End Auto-labeling
```

The Project Explorer on the left shows the following structure:

- Project: Reliability test
  - Specifications
    - Date/Time: 24.11.2010, 12...
    - Date of Project: 24.11.2010
    - Place: Talstrasse 20
    - Processed By: JAP
  - Frame Array Camera
    - Sensor 1: Nikon D90
      - Parameter Setting
        - 1 DSC\_1782.JPG
        - 2 DSC\_1783.JPG
        - 3 DSC\_1784.JPG
        - 4 DSC\_1785.JPG
        - 5 DSC\_1786.JPG
        - 6 DSC\_1787.JPG
        - 7 DSC\_1788.JPG
        - 8 DSC\_1789.JPG
        - 9 DSC\_1790.JPG
        - 10 DSC\_1791.JPG
        - 11 DSC\_1792.JPG
        - 12 DSC\_1793.JPG
        - 13 DSC\_1794.JPG
        - 14 DSC\_1795.JPG
        - 15 DSC\_1796.JPG
        - 16 DSC\_1797.JPG
        - 17 DSC\_1798.JPG
        - 18 DSC\_1799.JPG
        - 19 DSC\_1800.JPG
        - 20 DSC\_1801.JPG
        - 21 DSC\_1802.JPG
        - 22 DSC\_1803.JPG
        - 23 DSC\_1804.JPG
        - 24 DSC\_1805.JPG

# Panoramic imaging



(a)



(b)



(c)

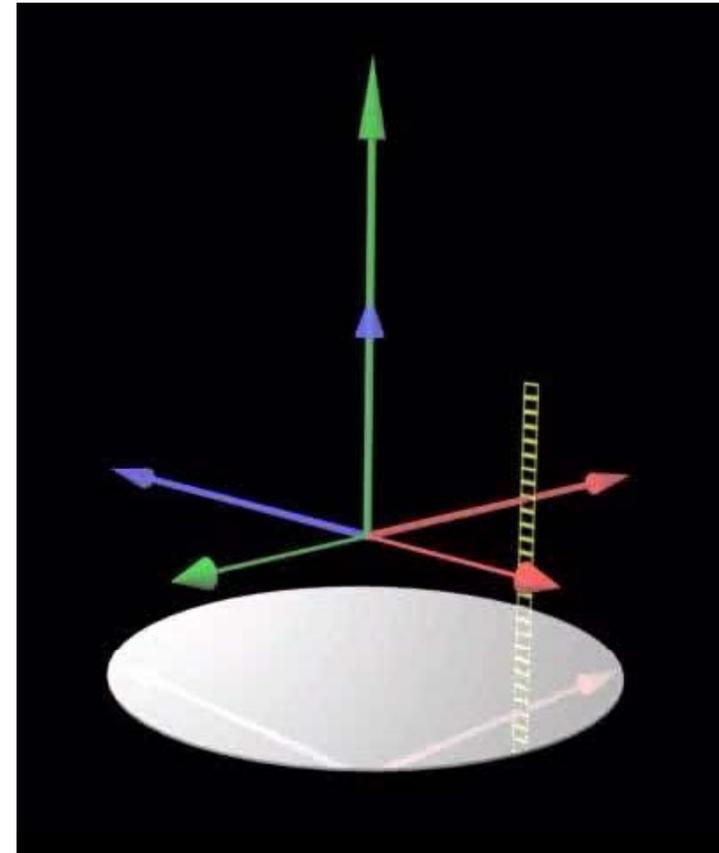
# Panoramic imaging





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

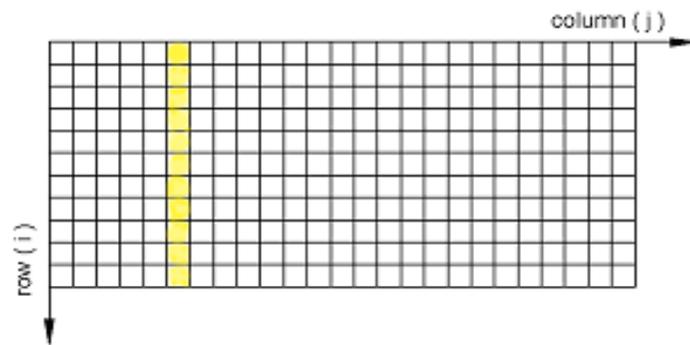
Pixel size: 8 microns



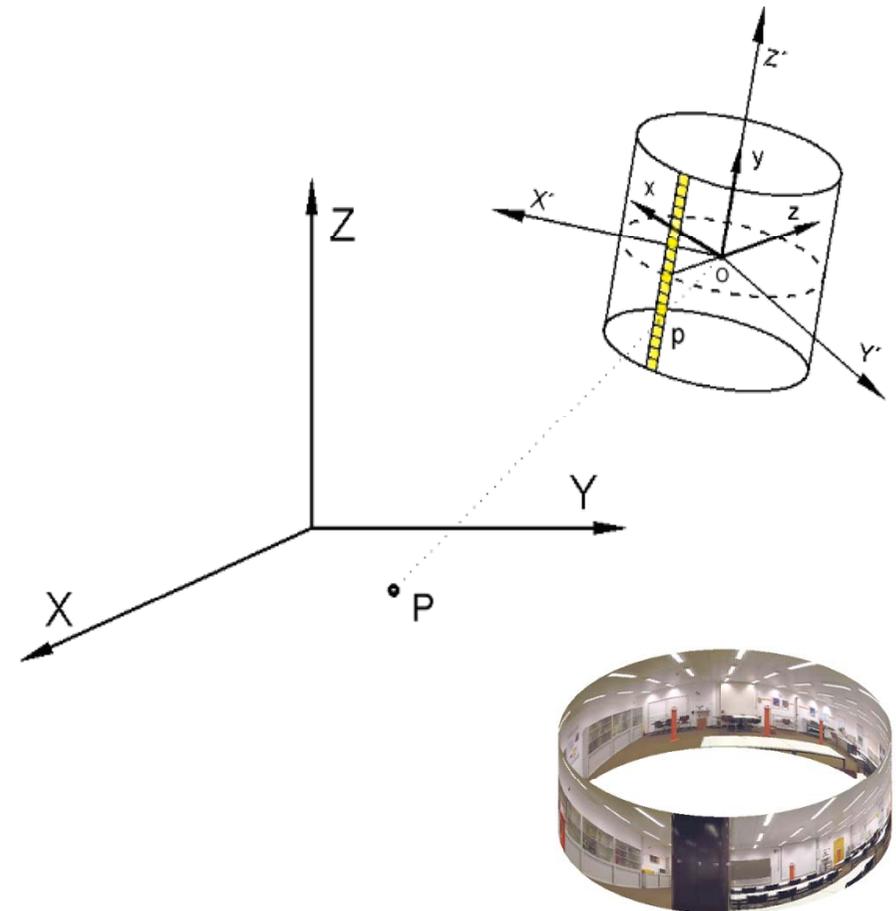
## Panoramic imaging

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

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

Collinearity equation

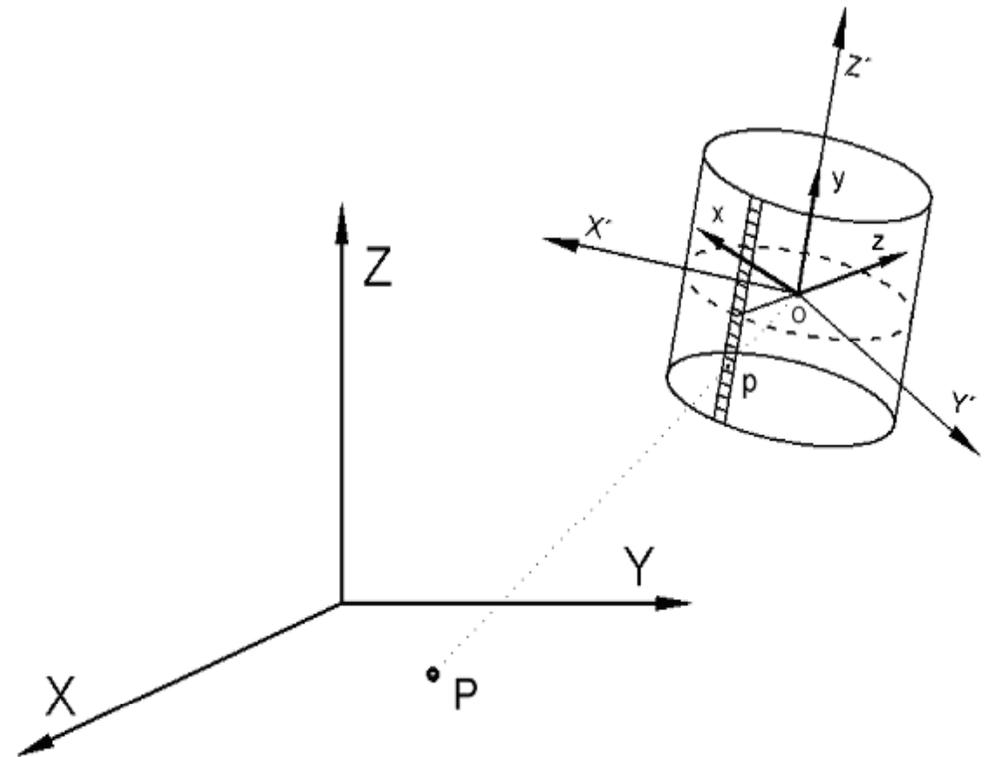
$$T = \begin{pmatrix} 0 & 0 & -1 \\ -1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \quad y = \left(i - \frac{N}{2}\right) P_y \quad \theta = j P_x$$

## Panoramic camera - Mathematical model

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

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

**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

