Photogrammetry and laser scanning course for beginners

CTU in Prague Faculty of Civil Engineering,
Department of Geomatics

Photogrammetry and laser scanning

Prof.Dr.Ing.Karel Pavelka
E-mail: pavelka@fsv.cvut.cz

Introduction

- **Photogrammetry part of the field of geodesy and cartography, which deals with the determination of geometric and positional information from image records, most often from photographic images**
- **RemoteSensing(RS) deals with non-contact detection of surface cover types and their condition**
- **Laser scanning3D scanning technology that uses laser measurements to determine the spatial coordinates of detailed points on an object.**

Introduction

Photogrammetry, RS and laser scanning are methods that provide mass localized information for technology

GIS

- Basic sources of primary information about the territory supply:
- **geodetic methods** accuracy in the order of **mm - cm**
- **photogrammetry** accuracy in **mm, cm - dm**
- **RS** accuracy in the order of **m - km**

History

Al-Hassan bin Al–Haithm (965-1039)

*

in 1032 he was the first to describe the*"camera obscura" –the central projection principe*

History

- Leonardo da Vinci (1452 1519) described the pinhole camera "
for the
construction of central projections
- 1605 Galileo Galilei invents the telescope
- 1657 Schott Kasper builds the first portable box camera
- in 1777 the invention of the light sensitive compound , AgCl
C.H.Scheele)
- theories of reconstruction of acquired perspective images :
Taylor (1715) and J.H.Lambert (1759)
- invention of photography : Niepce and Daquerre (1839
- negative positive: Talbot 1841
- the title of the photo comes from J.Herschel
- the first aerial photographs were taken by the famous French
photographer
G.F.Tournachon called Nadar) in 1858

- the first phototeodolite was constructed according to the design of A. Laussedat (1859); used in France for mapping in 1861
- photogrammetry " dates back to 1858, when the German A.Meydenbauer used the term
- G . Eastman , 1884 paper film) and its introduction in 1889 (celluloid film , first roll film camera
- C . Pulfrich Zeiss Jena) in 1901 constructed the first device for stereoscopic measurement , the stereocomparator
- E .Orel , 1909 1911 constructed the first Autostereograph since 1909 in the Carl Zeiss Jena works as " Stereoautograph "
- Th . Scheimpflug constructed in 1911 the first rectifier for transforming an inclined image of flat terrain to the scale of a map
- W .Wright was the first to take pictures from a plane in 1903
- imaging from aircraft found its application with the advent of World War I.
- In 1935, the first Kodakchrome colour film was released

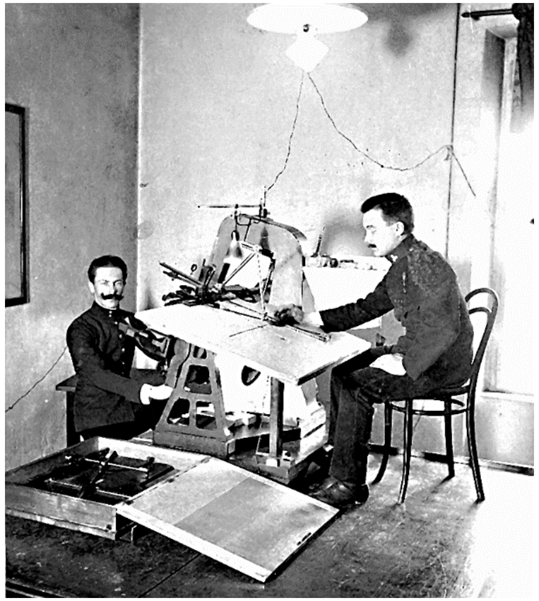
- during the World War II. some new cameras and instruments
were
constructed and methods of using photogrammetry were
developed , but
mainly for military purposes
- further development of photogrammetry occurred again
after 1945
analogue plotters
- space technology
- Seventies analytical plotters used computers
- Eighties development of digital technologies
- 1990s full transition to digital technology

History

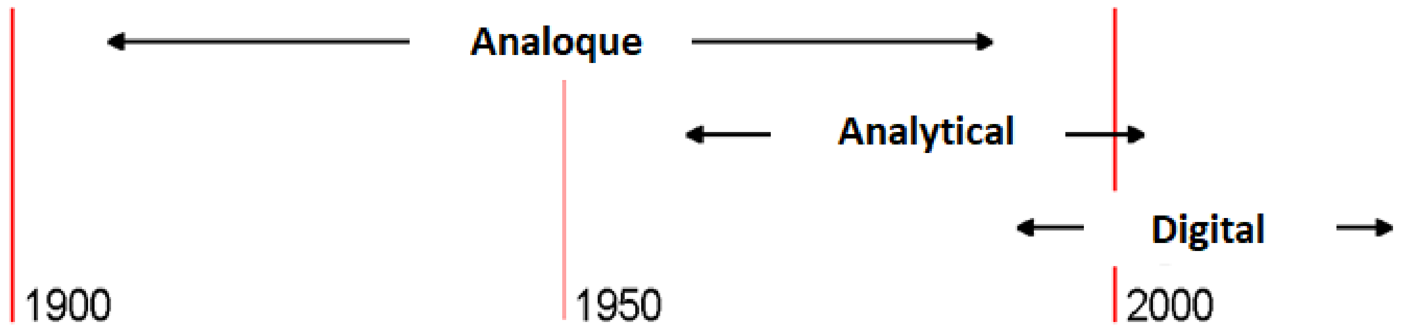
Karel Kořistka (1825 1906) professor of mathematics and geodesy , the first rector of the Royal Czech Polytechnic Institute in Prague in the school year 1864 65. Pioneer of photogrammetry in the Czech lands

K.Kořistka
got acquainted with photogrammetry on a study trip in 1862
directly with A.Laussedat and after his return from this trip he used it in Prague

World War I.



Photogrammetry subdivision
Basic stages of development: technology



Basic criteria for dividing photogrammetry
a) according to the position of the position
Terrestrial , air, satellite
b) by number and configuration of images
Single frame and multi frame : stereo or intersection
b) according to the processing technology
Analogue, analytical , digital

Use of photogrammetry (in CZ, but it is typical)

- State map works in CZ, State Administration of Land Surveying and Cadastre (ČÚZK) topographic maps (1:10
- Military topographic maps (in CZ , Army of the Czech Republic)
- Information systems state administration , GIS information layers) , digital models DMR and DMP)
- Monument care (monument care workers , architects) documentation , documents
- Construction design and construction companies) documents , documentation , determination of deformations
- Environment (in CZ, administrations of National park, protected natural area , forestry maps (in CZ, Forest Management Institute ÚHÚL), vegetation delimitation

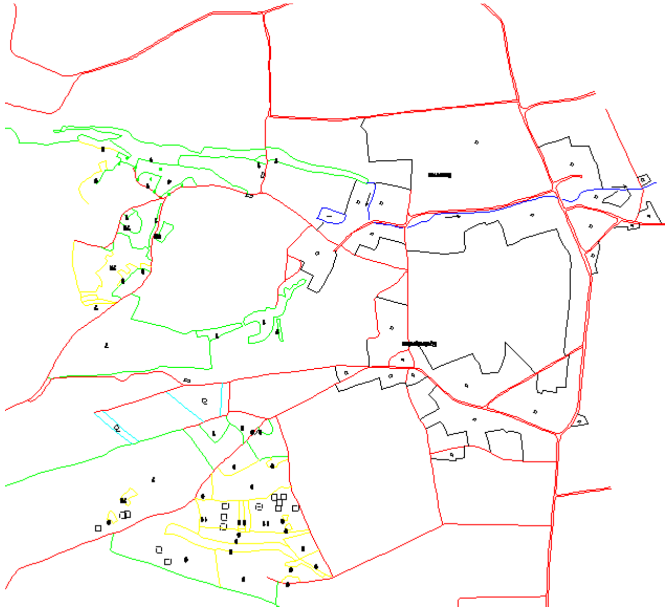
Next

Come in:

- **spatial planning 3D building models**
- **water management floods , Runoff profiles**
- **inventory and monitoring mines , quarries , landfills, landslides**
- **mechanical engineering precision control , deformation**
- **rehabilitation medicine , biomechanical applications etc.**

Use of photogrammetry in mapping

Original photogrammetric vertical image is similar to map



Reasons for using photogrammetry

⇒ minimising field work

-

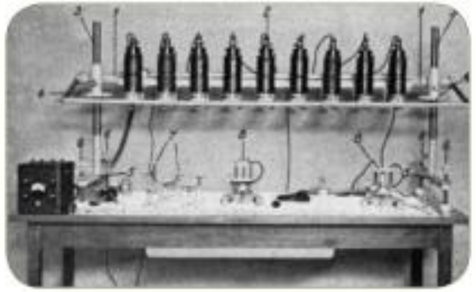
- economics

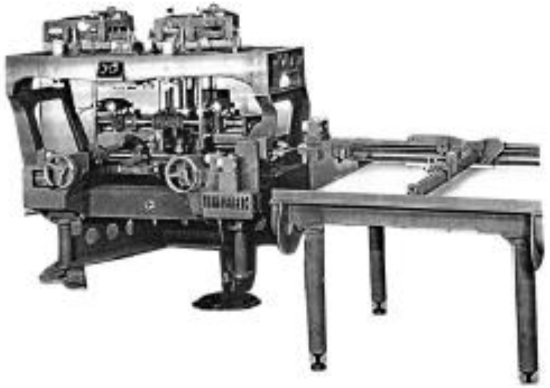
-

- speed

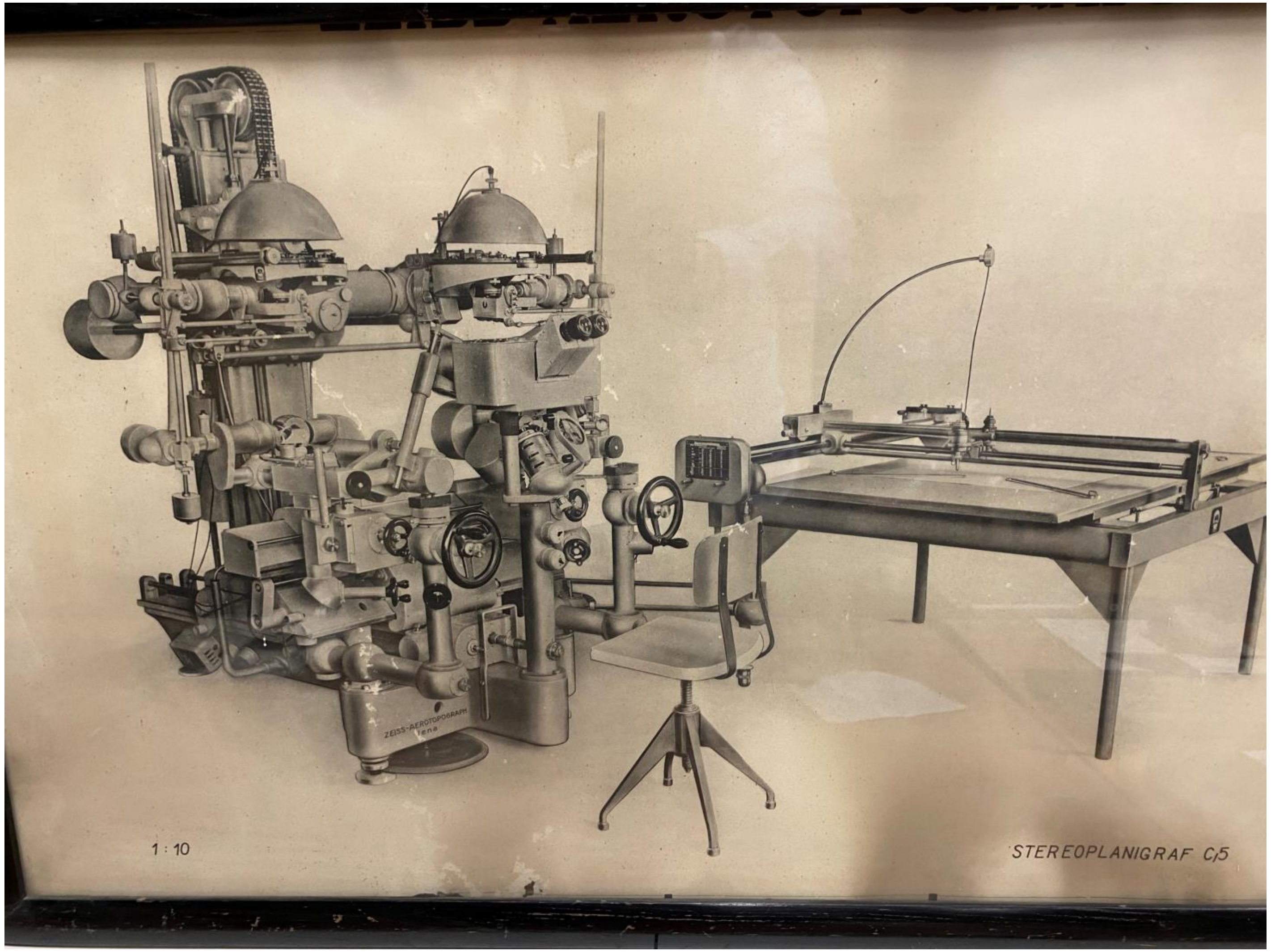
- overall time saving
- cost saving
- documentary value of the images time series
- higher resolution of the images compared to the map digital orthophoto

From analoque photogrammetry to the digital technology





Stereoplanigraph, 1930-1950



DPW (digital photogrammetric Workstation (1990- today)

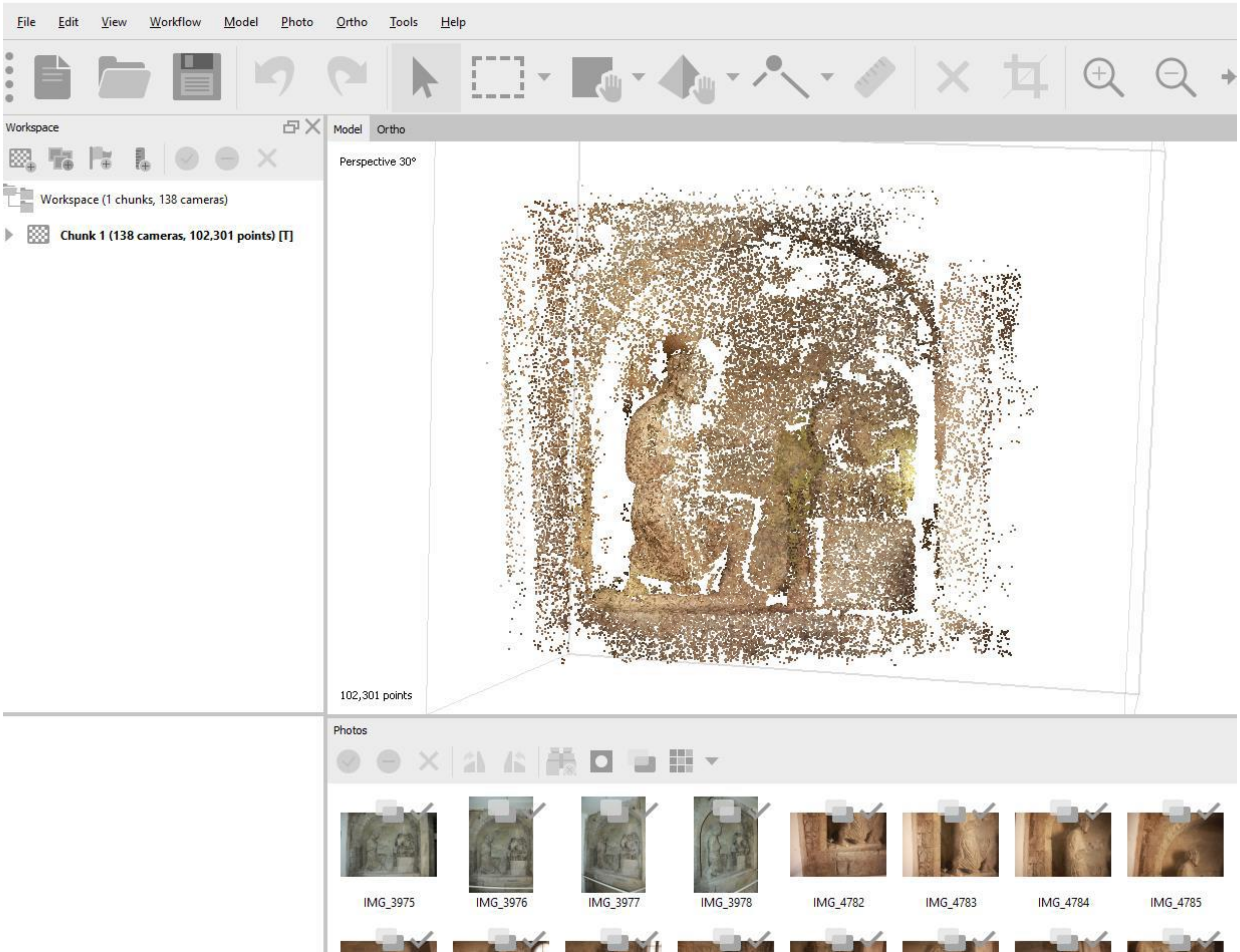
Stereo DWP

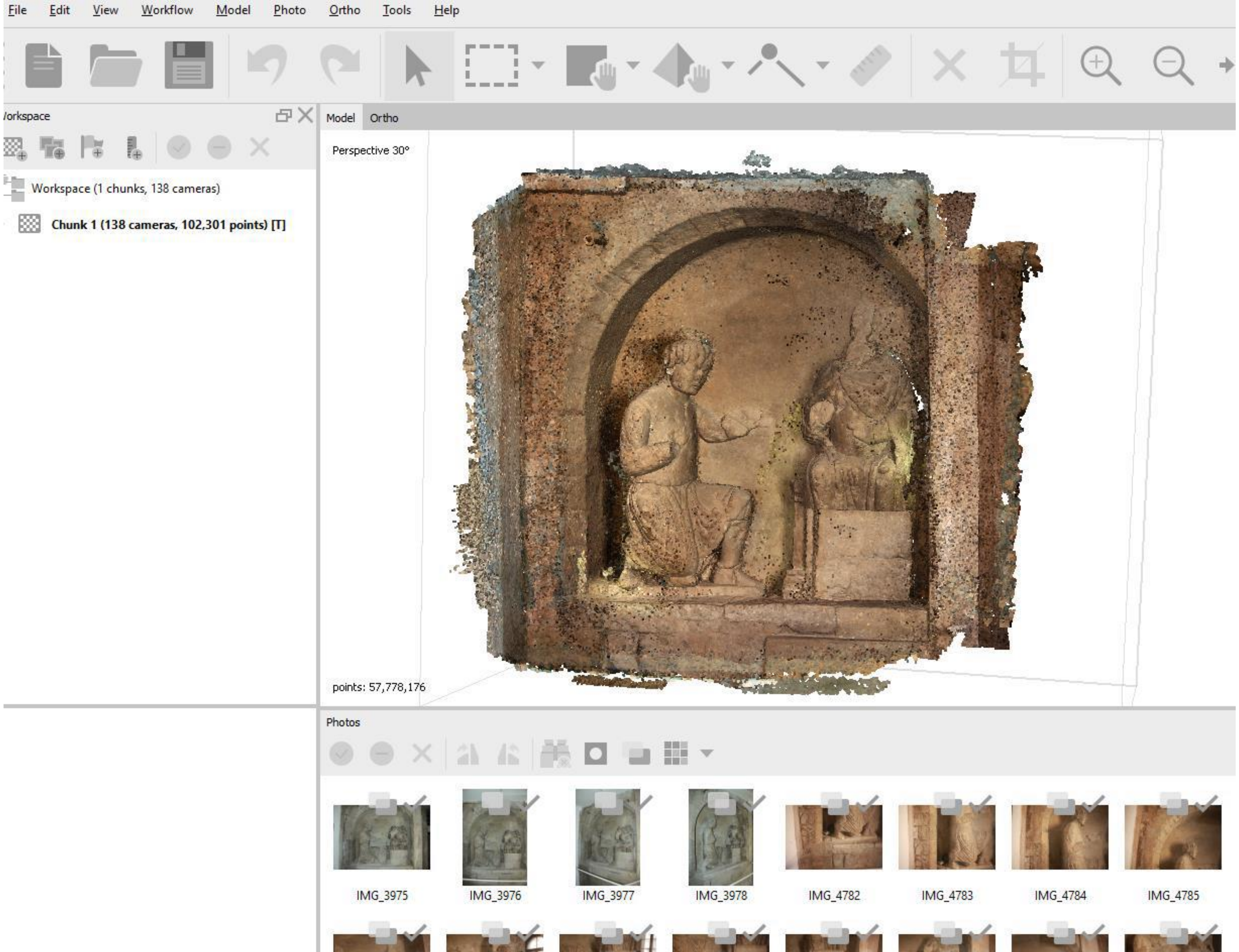
Digital (automated) photogrammetry (after 2010)

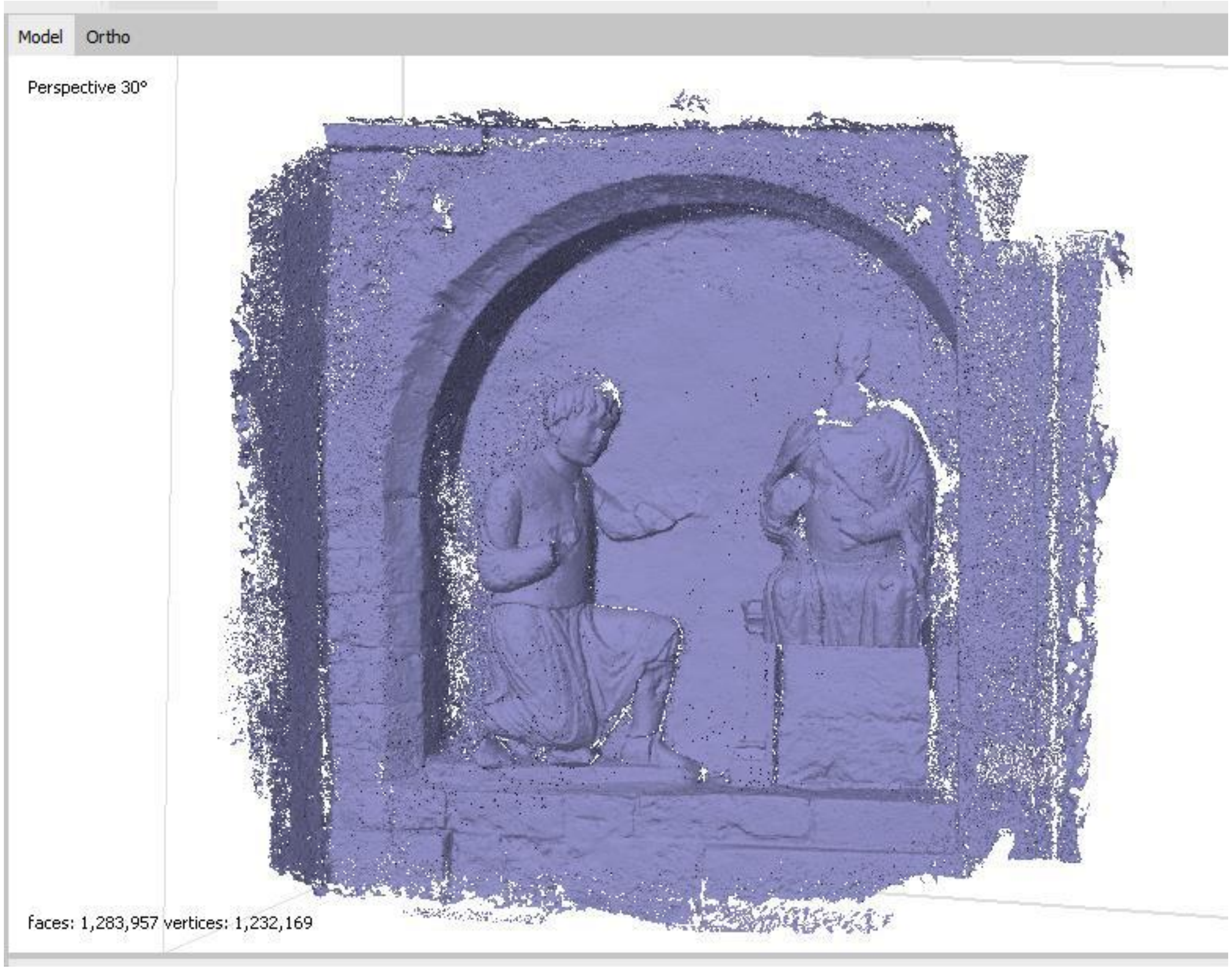
Image correlation principle
Agisoft Photoscan-Metashape,
Zephyr 3D, pix4D, 123catch, aj.)
SfM+ MVS (structure from motion
and multi view stereo)

Photogrammetry

terrestrial (hand – held)
aerial (aerial or using drones)
satellite


File Edit View Workflow Model Photo Ortho Tools Help
Workspace
Workspace (1 chunks, 138 cameras)
Chunk 1 (138 cameras, 102,301 points) [T]
Model
Ortho
Perspective 30°
102,301 points
Photos
IMG_3975
IMG_3976
IMG_3977
IMG_3978
IMG_4782
IMG_4783
IMG_4784
IMG_4785


File Edit View Workflow Model Photo Ortho Tools Help
/orkspace
Workspace (1 chunks, 138 cameras)
Chunk 1 (138 cameras, 102,301 points) [T]
Model Ortho
Perspective 30°
points: 57,778,176
Photos
IMG_3975
IMG_3976
IMG_3977
IMG_3978
IMG_4782
IMG_4783
IMG_4784
IMG_4785


Model
Ortho
Perspective 30°
faces: 1,283,957 vertices: 1,232,169

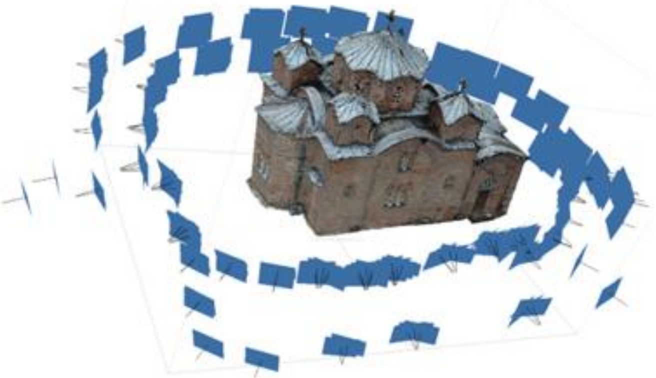
Case study –combined documentation of a historical object

- photogrammetry (terrestrial, drone)
- laser scanning
- mobile laser scanning
- VR

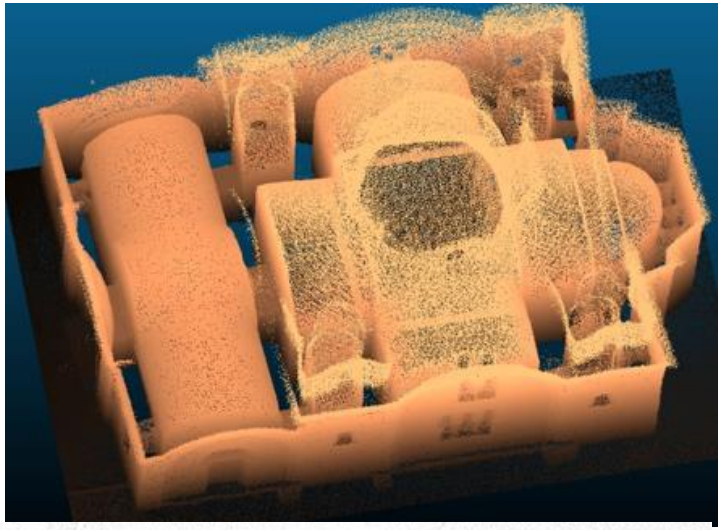
Used instruments

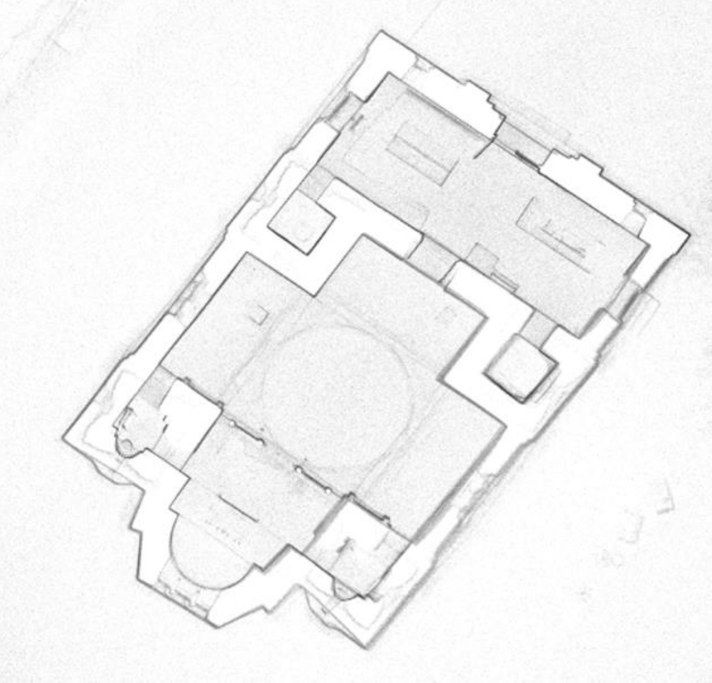

Perspective 30°
Snap: Axis, 2D
faces: 5,270,156 vertices: 2,648,118
Z
X
Y

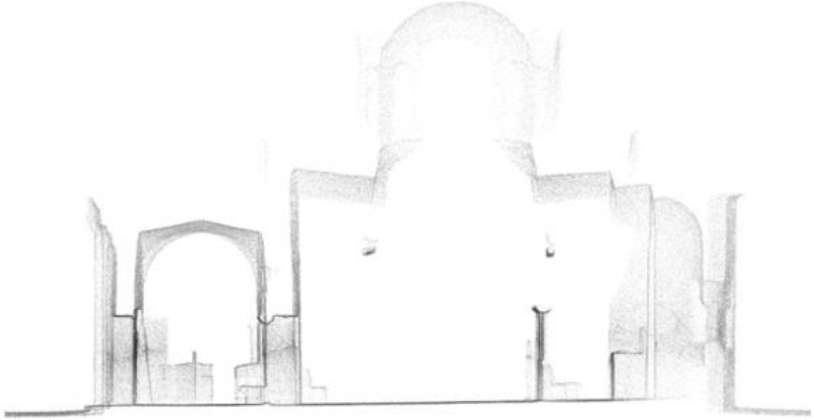
Sv. Panteleimon, Skopje

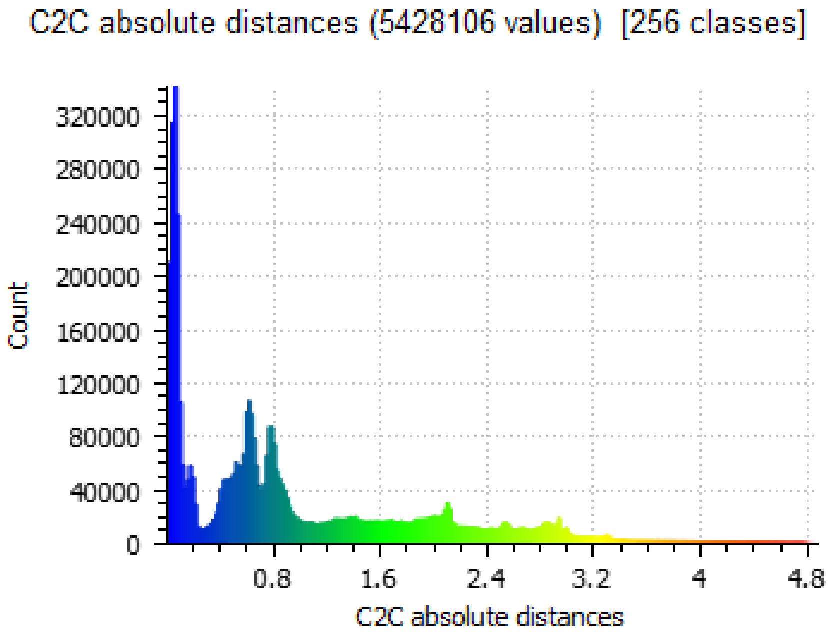


Point cloud from PLS ZEB REVO



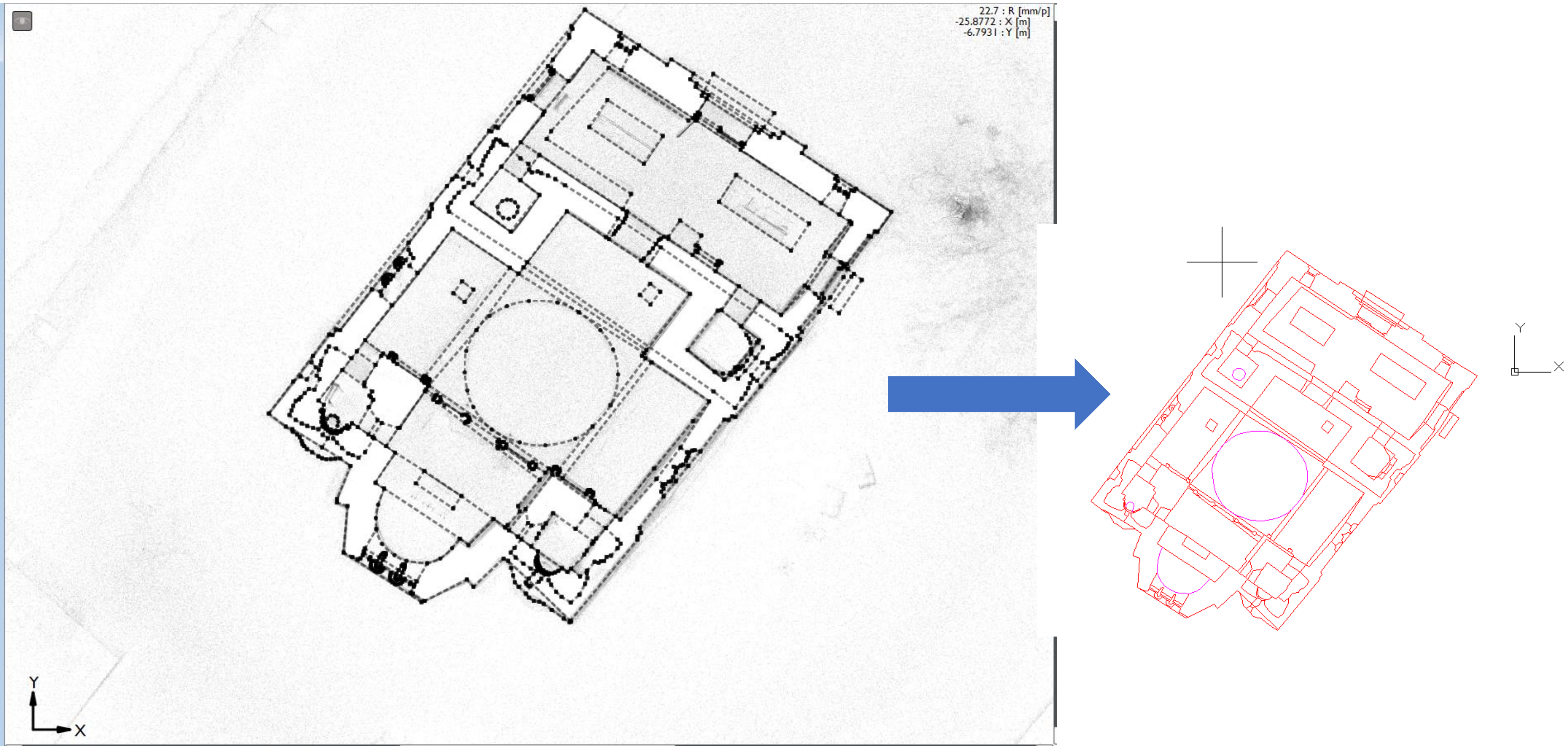


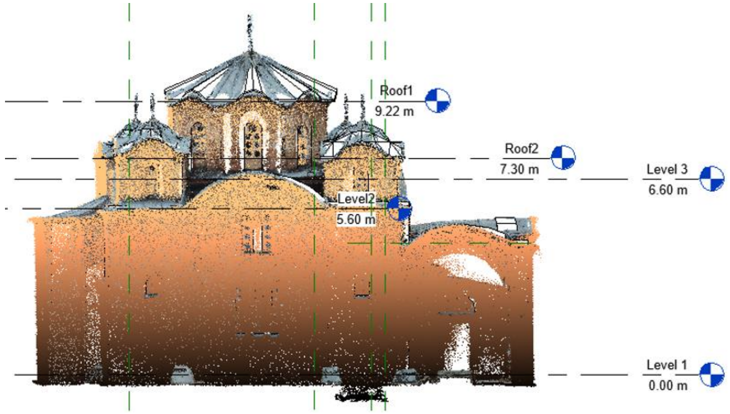




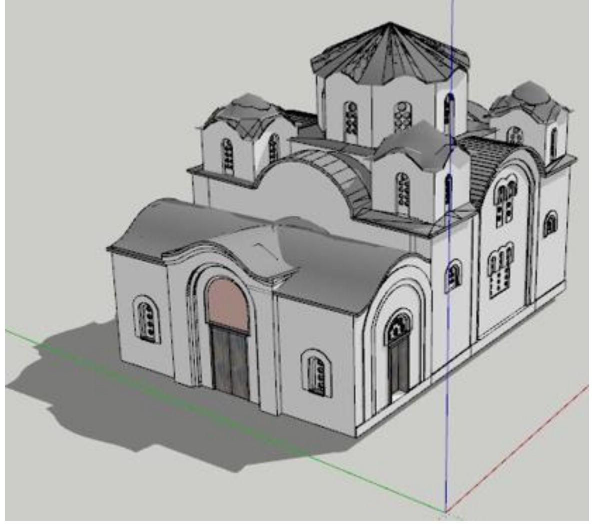
Differences between point cloud from combined terrestrial and aerial photogrammetry

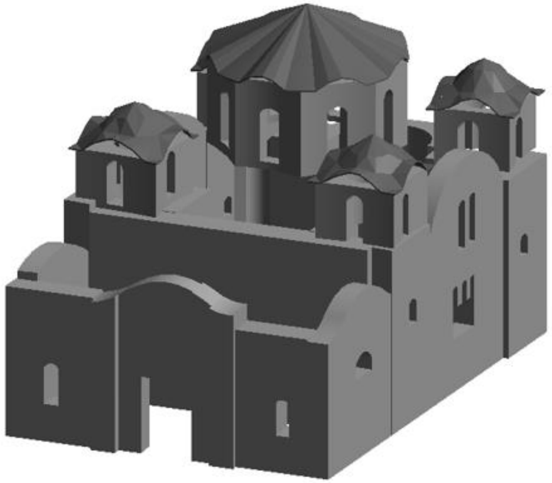
Device	Accuracy [mm] on 10 m	Range [m]	Acquiring points/sec	Data size [MB]	Time [minutes]
Nikon D3200	5-20	10	~30 photos/minute	~10/photo	~30 photos/minute
DJI Mavic Pro	5-30	30	~20 photos/minute	~4/photo	~20 photos/minute
ZEB-REVO	10-30	30	43000	100/min	slow walking
BLK360	4	30	360000	600/scan	6/scan

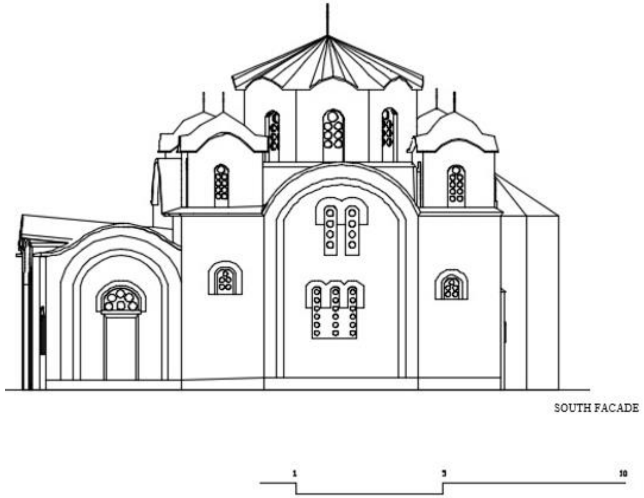

22.7 : R [mm/p]
-25.8772 : X [m]
-6.7931 : Y [m]
Y
X
Y
X



Defining of levels for creating of simplified model


Model from SketchUp


Model from Revit



Generated views from simplified models (SketchUp)

Generated VR model with texture (UnrealEngine)


VR model rendered in Lumion

Comparison of both 3D models: BIM geometrical basic model (grey), photogrammetrical model (blue)


Perspective 30°
Snap: Axis, 2D
Faces: 5,270,156 vertices: 2,648,118
Z
X
Y

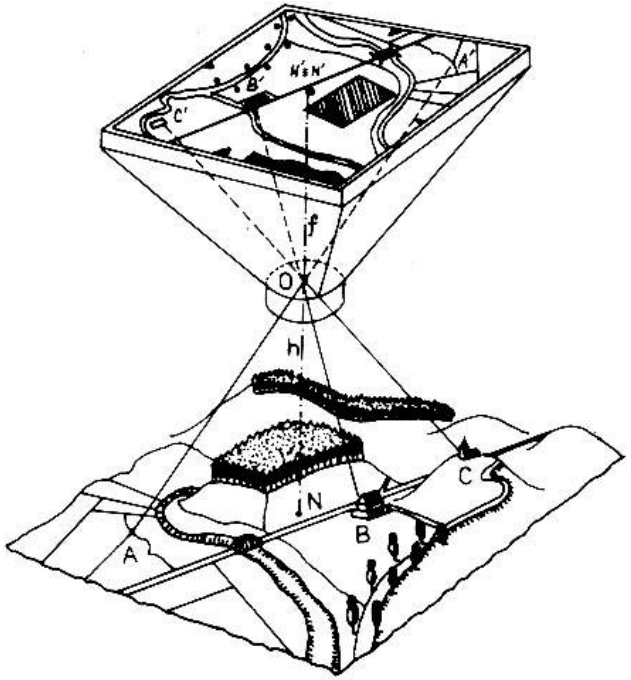
Basics of photogrammetry

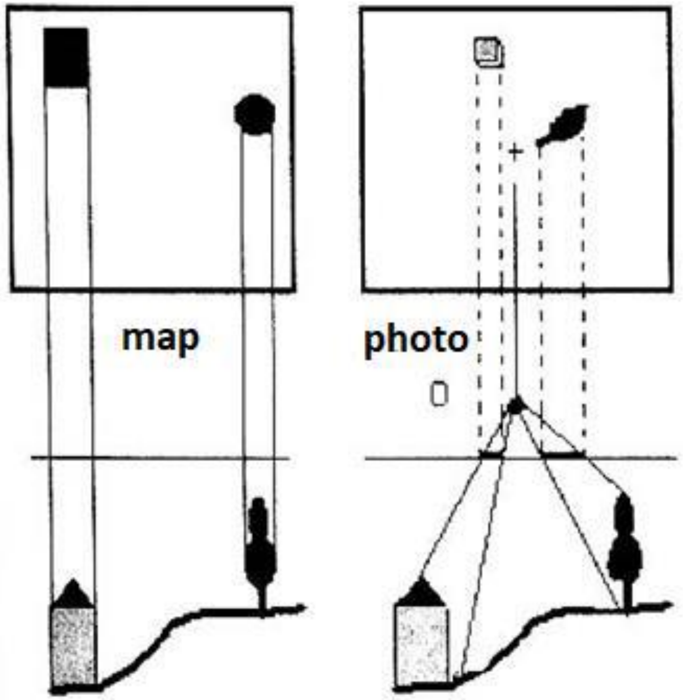
Basics of photogrammetry

Photographic image = central projection of the displayed object

Input data:

- **image source of information necessary**
- **additional data geodetic coordinates of the ground control points , elements of internal and external orientation**

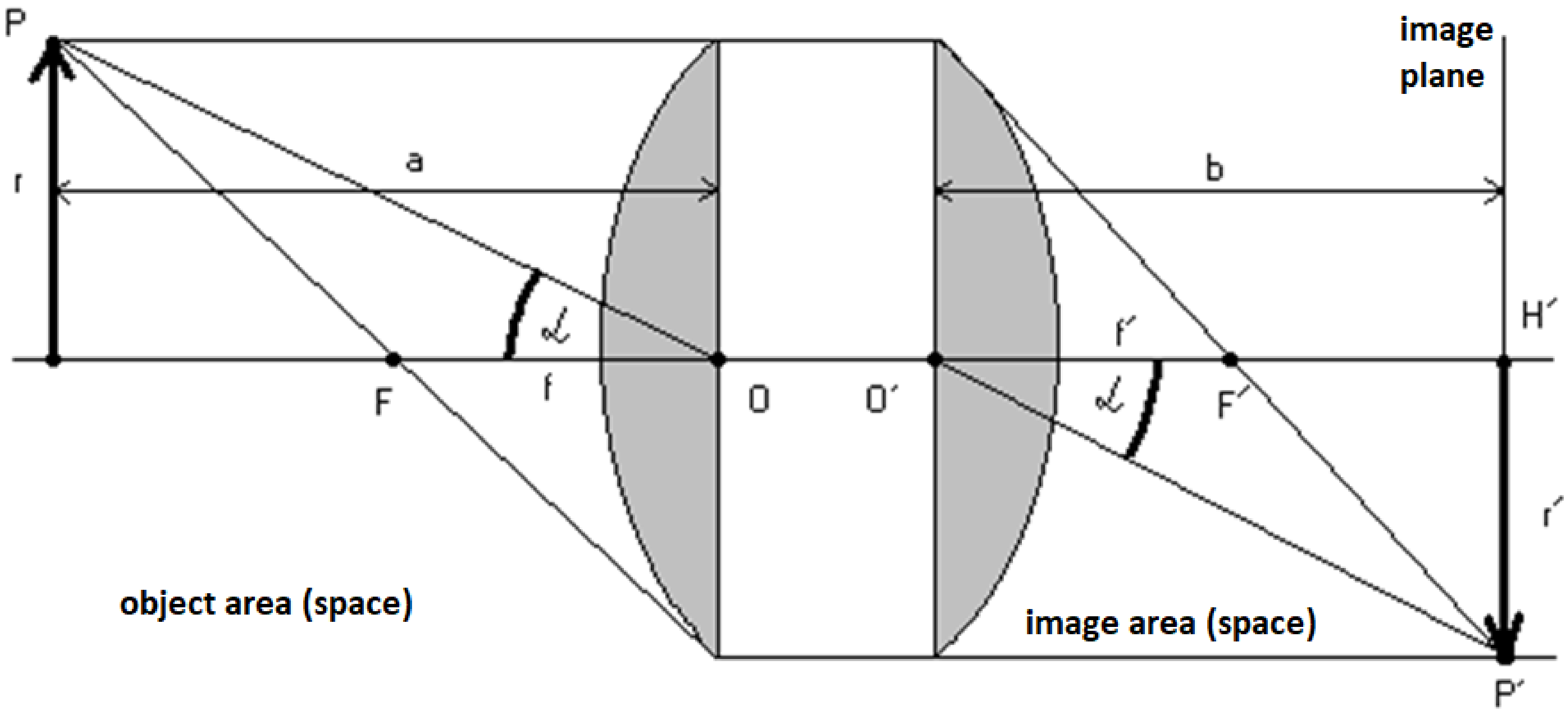




Theory - optics

A real lens aperture

- *reduces the number of rays that form an image*
- *O Input pupila image of the aperture in the subject space*
- *O´ output pupila image of the aperture in the image space*
- *f (camera lens) constant distance O ´ H ´*



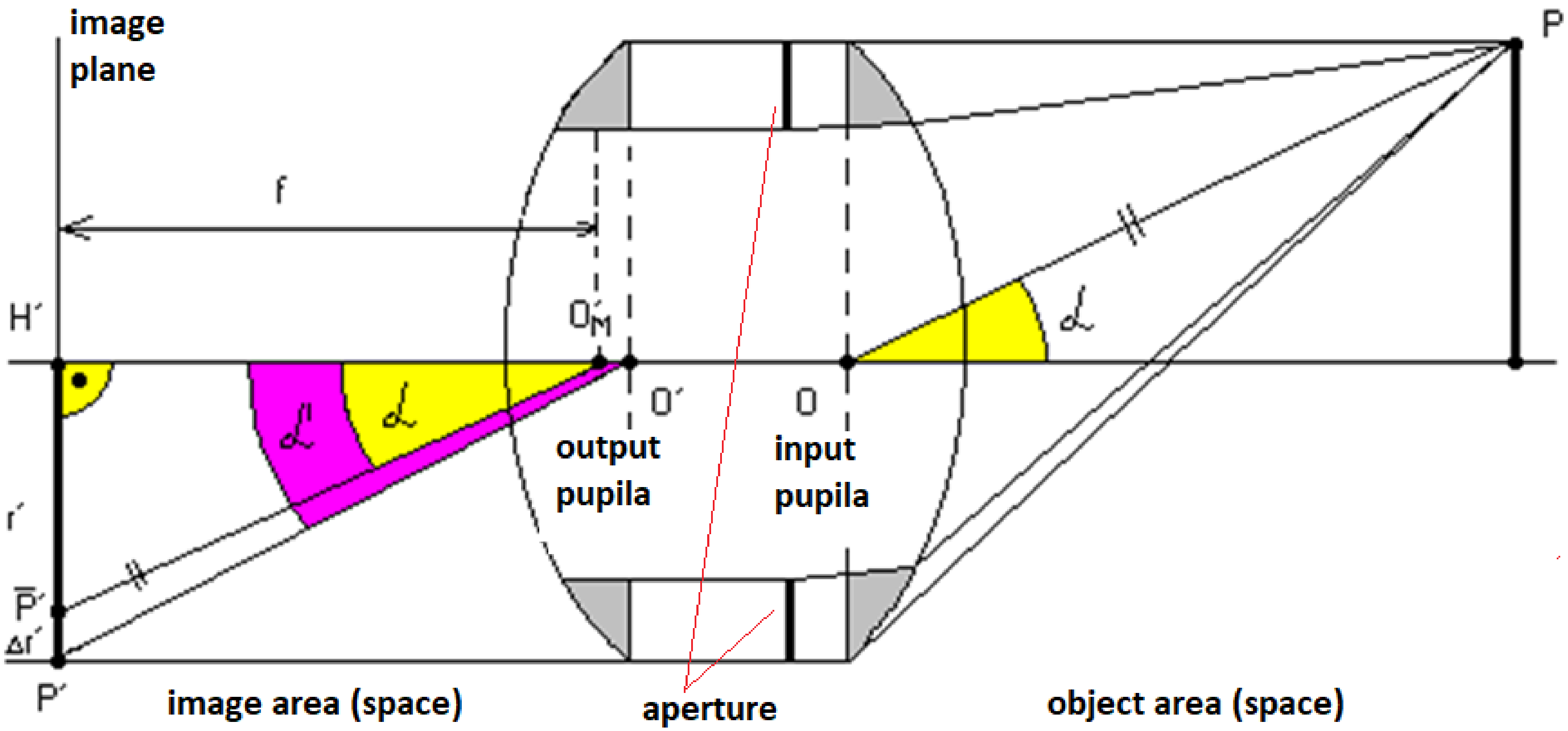
Theory - optics

$$\alpha \neq \alpha'$$

Real lens view

$r' = f \,.\, tg\, \alpha + \Delta r'$

$\Delta r'$ - effect of lens distortion



K.Kraus, 1994, Photogrammetrie, Band I.,Dümmler/Bonn, ISBN 3-427-78645-5

Summary of effects on the geometry of the lens view

Aberrations

Optical defects can be sub divided into

a) monochrome

b) coloured

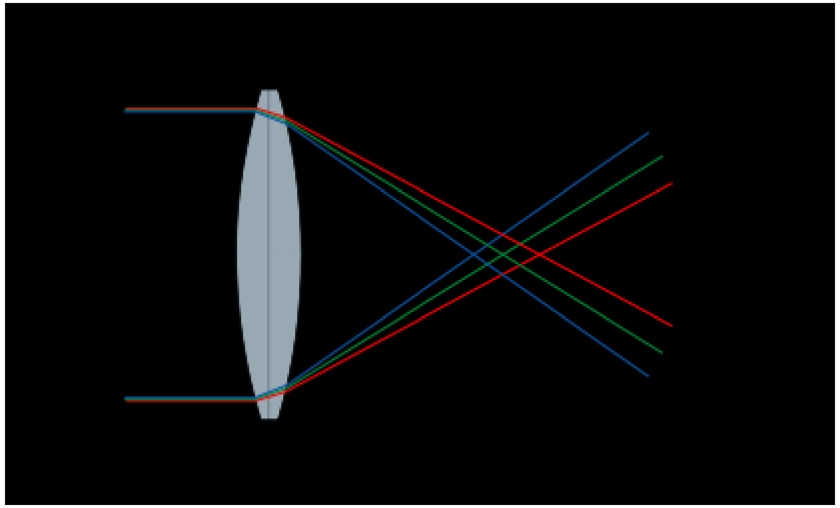
Furthermore,

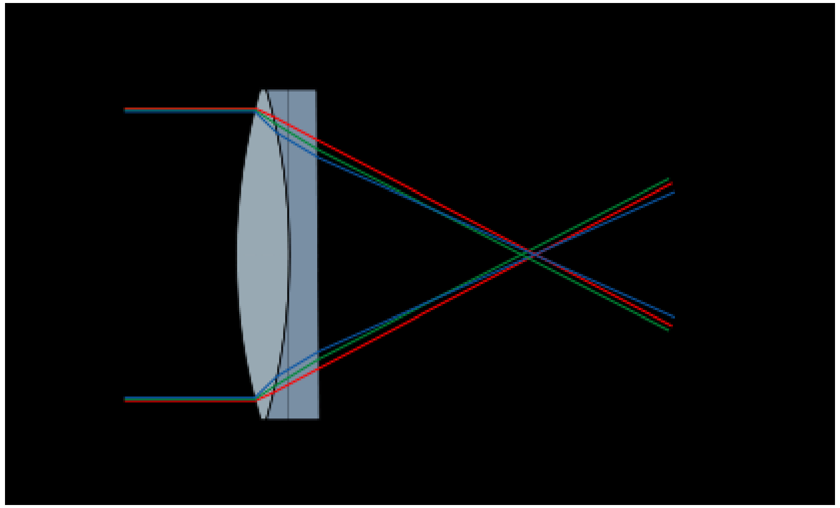
- defects arising from

c) point imaging (spherical defect, astigmatism and coma)

d) imaging of the subject (field blurring and image distortion)

Lens defects





Lens view chromatic colour defect (aberration)
and its suppression

Coordinate systems

Generally, three types of coordinate systems are used in the photogrammetry

a) main coordinate systems (system of geodetic coordinates)

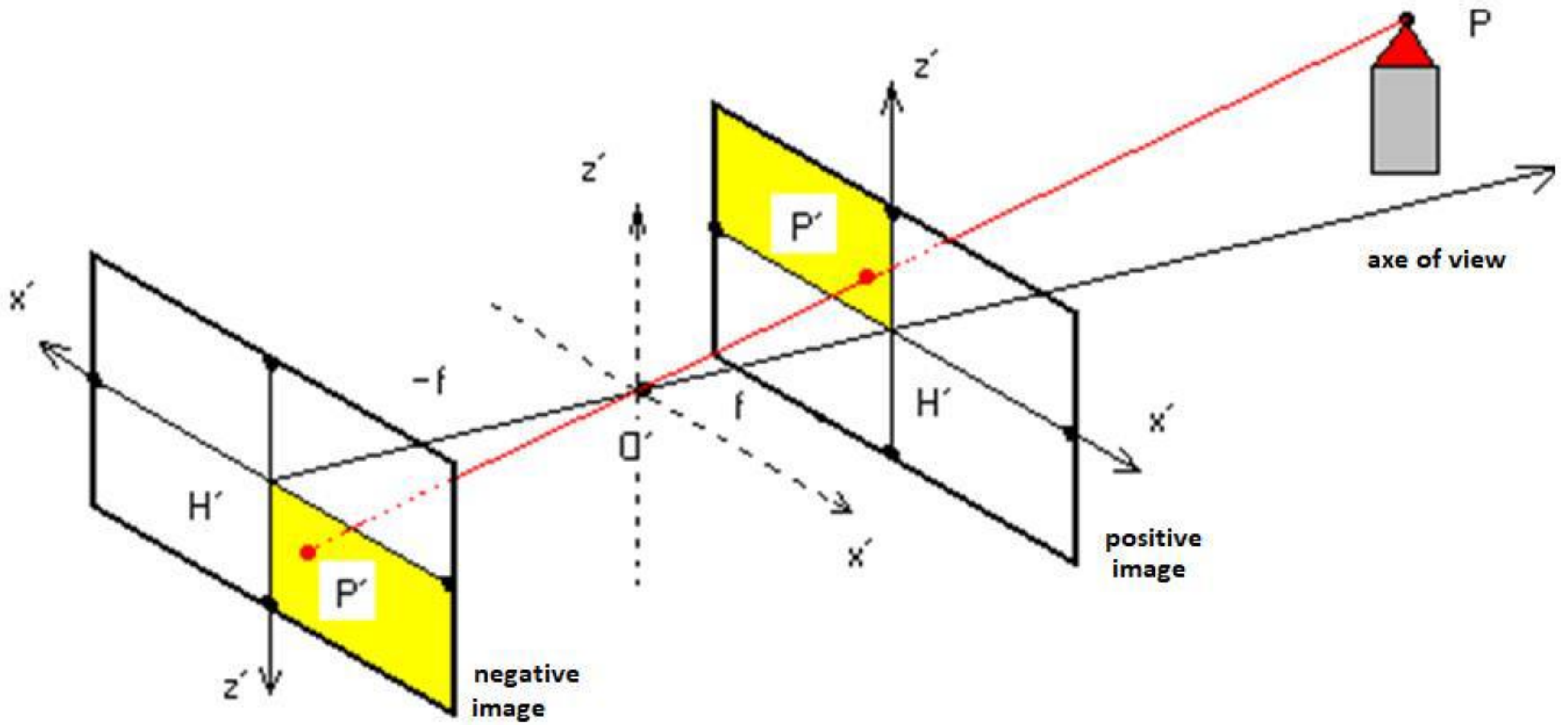
b) image coordinate system

c) model coordinate system

auxiliary coordinate systems

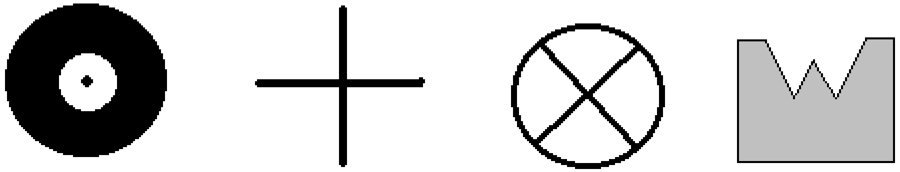
- fictitious image coordinate system (3 image coordinates)
- the image coordinate system of an exactly vertical image

Elements of interior orientation

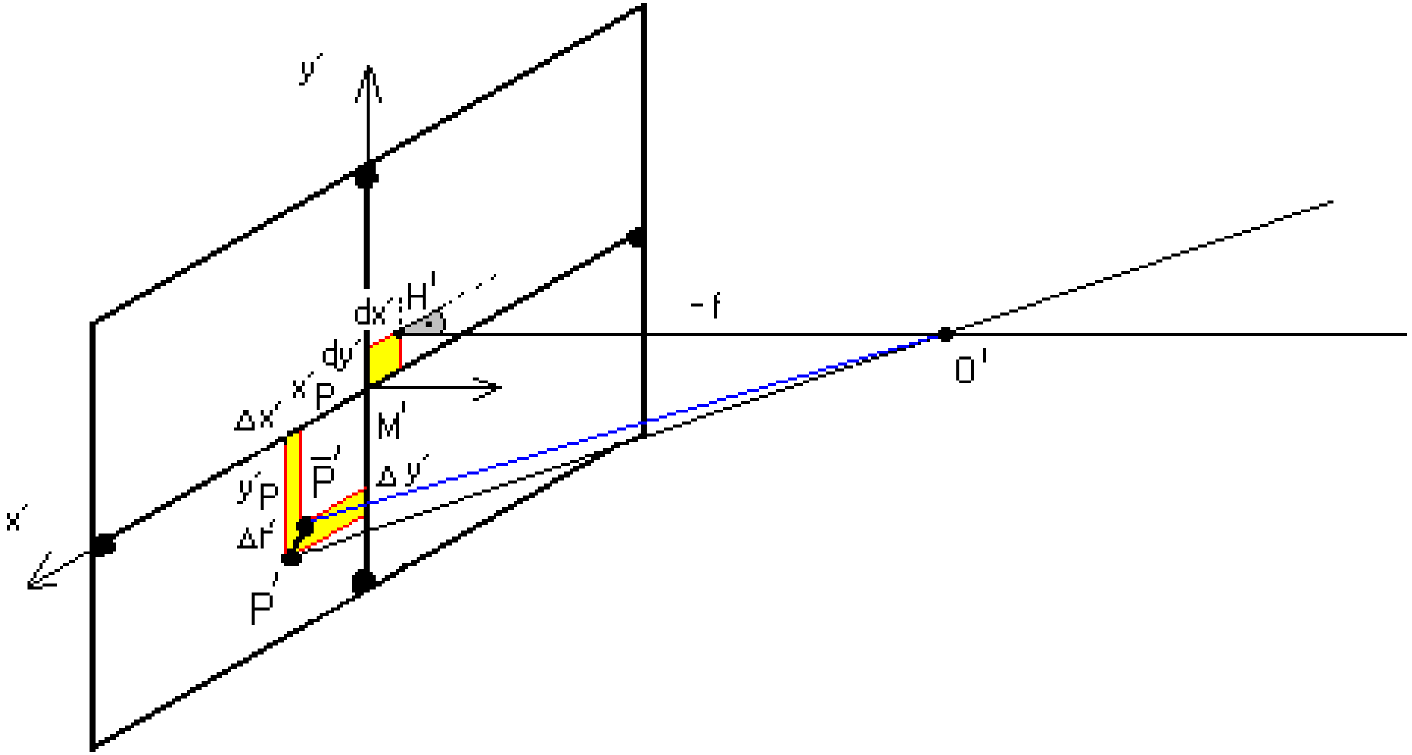


Camera constant , negative and positive, terrestrial configuration
Elements of interior orientation : x0 ´,y0 ´, f
(and known parametres of distortion)

Elements of internal orientation



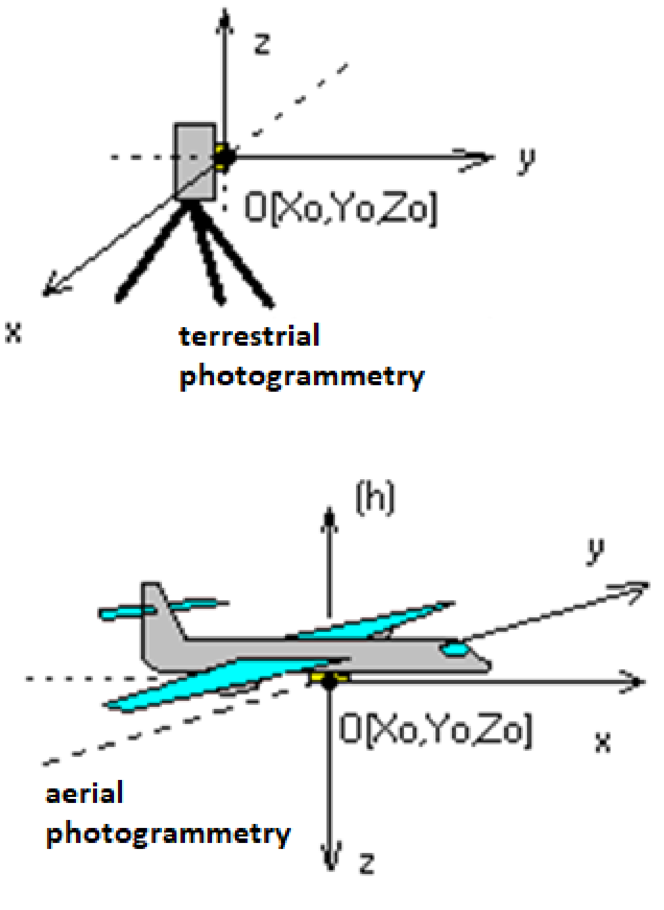
Different types of fiducial marks (on historical images or in historical cameras only)



Definition of the elements of the internal orientation in the general configuration (image coordinates x ´,y ´); The axis of view is the perpendicular to the image plane passing through the object projection centre.

Coordinate systems and conversions

Elements of internal and external orientation



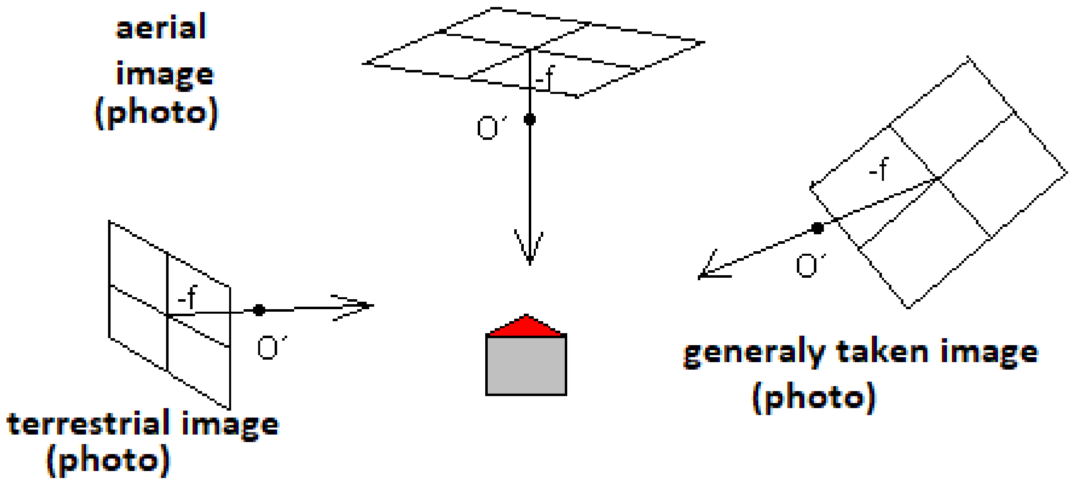
Internal and external orientation elements for terrestrial and aerial photogrammetry

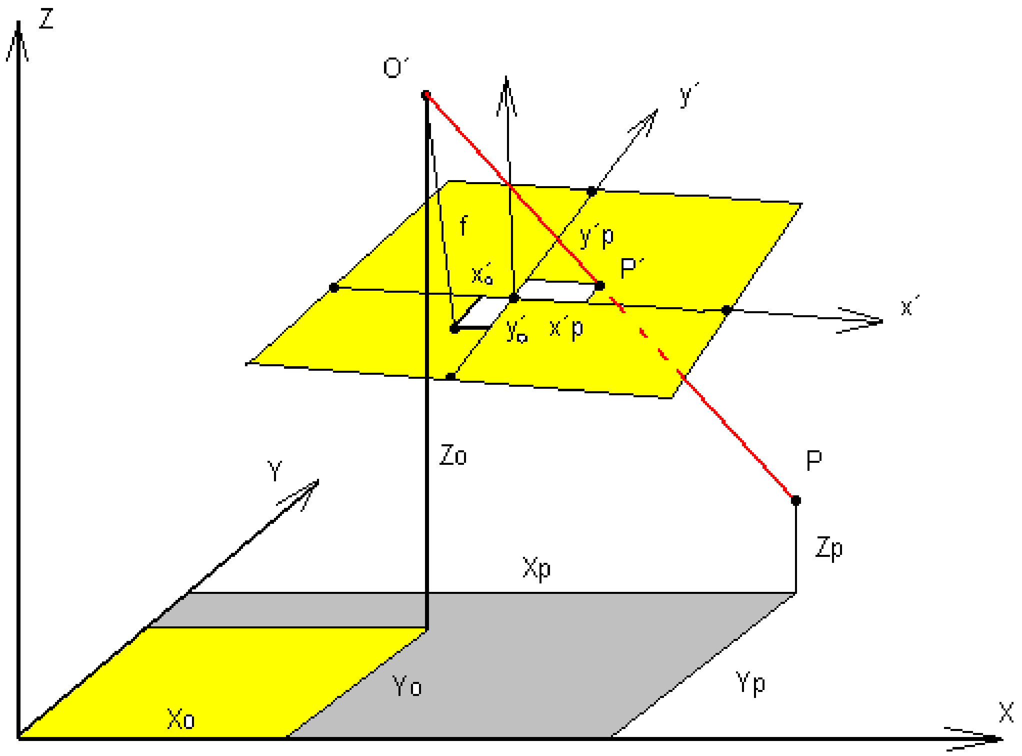
Coordinate systems

Image coordinate system label : x′ , y′ , (z′ = -f)
Model coordinate system label:: x , y , z
Geodetical system: X , Y , Z

Auxiliary systems
Fictional image coordinate system : x'_F , y'_F , z'_F
Vertical image coordinate system : x'_S , y'_S , z'_S

Classic terrestrial , aerial
and generally taken image





Coordinate systems in
aerial photogrammetry

Converting image information to geodetic systems

1) Restoration of internal orientation elements

2) External orientation

External orientations can be solved classically in two steps as:

1. **-relative orientation** (mutual orientation between the two stereo images, formation of an arbitrary spatially oriented stereo model)
2. **-absolute orientation** (rotation and displacement of the model into the geodetic reference system)

3. - in one step **using the Bundle** *Adjustment* **method** (*Bündelausgleichung*)

Rotation matrix

Resulting rotation matrix *R*

$$\mathbf{R}_{\omega\varphi} = \mathbf{R}_{\omega} \cdot \mathbf{R}_{\varphi} \qquad \mathbf{R}_{\omega\varphi\kappa} = \mathbf{R}_{\omega\varphi} \cdot \mathbf{R}_{\kappa}$$

$$\mathbf{R}_{\omega\varphi\kappa} = \begin{pmatrix} \cos\varphi\cos\kappa & -\cos\varphi\sin\kappa & \sin\varphi \\ \sin\omega\sin\varphi\cos\kappa + \cos\omega\sin\kappa & -\sin\omega\sin\varphi\sin\kappa + \cos\omega\cos\kappa & -\sin\omega\cos\varphi \\ -\cos\omega\sin\varphi\cos\kappa + \sin\omega\sin\kappa & \cos\omega\sin\varphi\sin\kappa + \sin\omega\cos\kappa & \cos\omega\cos\varphi \end{pmatrix}$$

$$\tan\omega = -\frac{r_{23}}{r_{33}}, \sin\varphi = r_{13}, \tan\kappa = -\frac{r_{12}}{r_{11}}$$

$$\mathbf{R} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix}$$

Here it is important to note that r_{13} = sin > 0 in the 1st and 2nd quadrants and further that r_{13} = sin < 0 in the 3rd and 4th quadrants. Thus, the rotation is not uniquely determined. The quadrants of the other two rotations , are uniquely determined given the expressions from which we calculate them. ***Thus we get a total of two sets of rotations „ to a single rotation matrix R****.*

Derivation of mathematical relations

Direct relationship between image and geodetic coordinates

collinear frame-model relationship

$$\frac{x' - x'_0}{-f} = \frac{x - x_0}{z - z_0}, \quad \frac{y' - y'_0}{-f} = \frac{y - y_0}{z - z_0}$$

$$\begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix} = \mathbf{R} \cdot \begin{pmatrix} x - x_0 \\ y - y_0 \\ z - z_0 \end{pmatrix}, \qquad \mathbf{R} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix}$$

the model coordinate system can be converted to a geodetic system by rotations around three axes

$$\begin{pmatrix} x - x_0 \\ y - y_0 \\ z - z_0 \end{pmatrix} = \mathbf{R}^T \cdot \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix}$$

<u>the direct relationship between image and geodetic coordinates, which is the basis of all contemporary photogrammetry</u>:

$$x' = x'_0 - f \frac{r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$

$$y' = y'_0 - f \frac{r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$

Photogrammetric series

Finally, these expressions need to be supplemented by the effect of translation

$$\Delta x' = -y' d\kappa' - \left(f + \frac{x'^2}{f} \right) d\varphi' + \frac{x' y'}{f} d\omega' + db'_x + \frac{x'}{f} db'_z$$

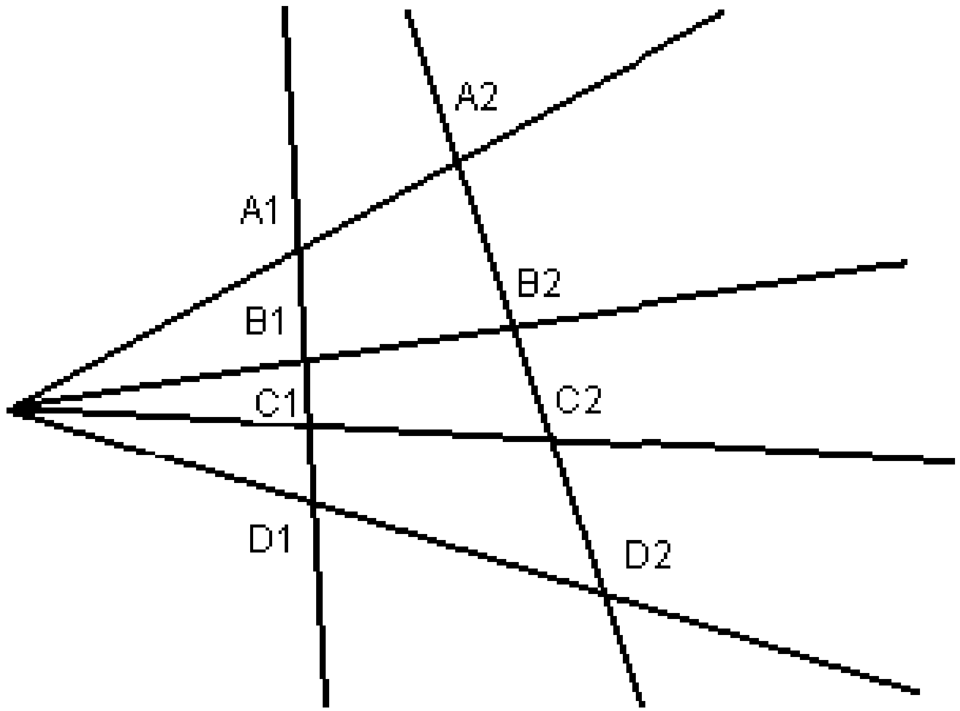
$$\Delta y' = x' d\kappa' - \frac{x' y'}{f} d\varphi' + \left(f + \frac{y'^2}{f} \right) d\omega' + db'_y + \frac{y'}{f} db'_z$$

The term is called "**complete photogrammetric series**", or historically Gruber series, and is used in simplified theoretical derivations. The meaning and use of series was quite fundamental, especially in the era of analogue photogrammetry.

Methods of photogrammetry

Single-shot photogrammetry

- relationship between two planes



Papp's theorem:

The point or ray quadrature binary ratio is preserved in the map and image planes.

$$\frac{\frac{A_1C_1}{B_1C_1}}{\frac{A_1D_1}{B_1D_1}} = \frac{\frac{A_2C_2}{B_1C_2}}{\frac{A_2D_2}{B_2D_2}}$$

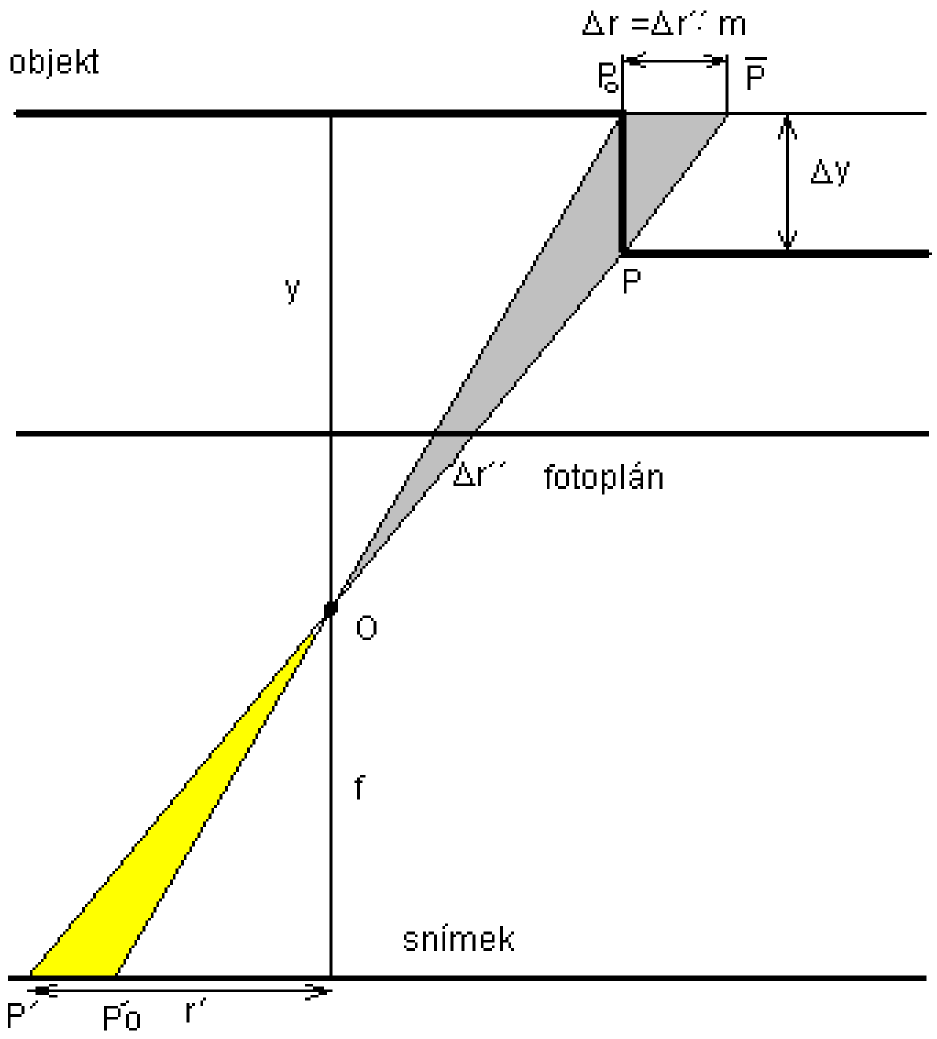
Mathematical expression
in fact, the **collinear transformation**

$$X = \frac{a_1 x' + a_2 y' + a_3}{c_1 x' + c_2 y' + 1}$$

$$Y = \frac{b_1 x' + b_2 y' + b_3}{c_1 x' + c_2 y' + 1}$$

Effect of depth zoning

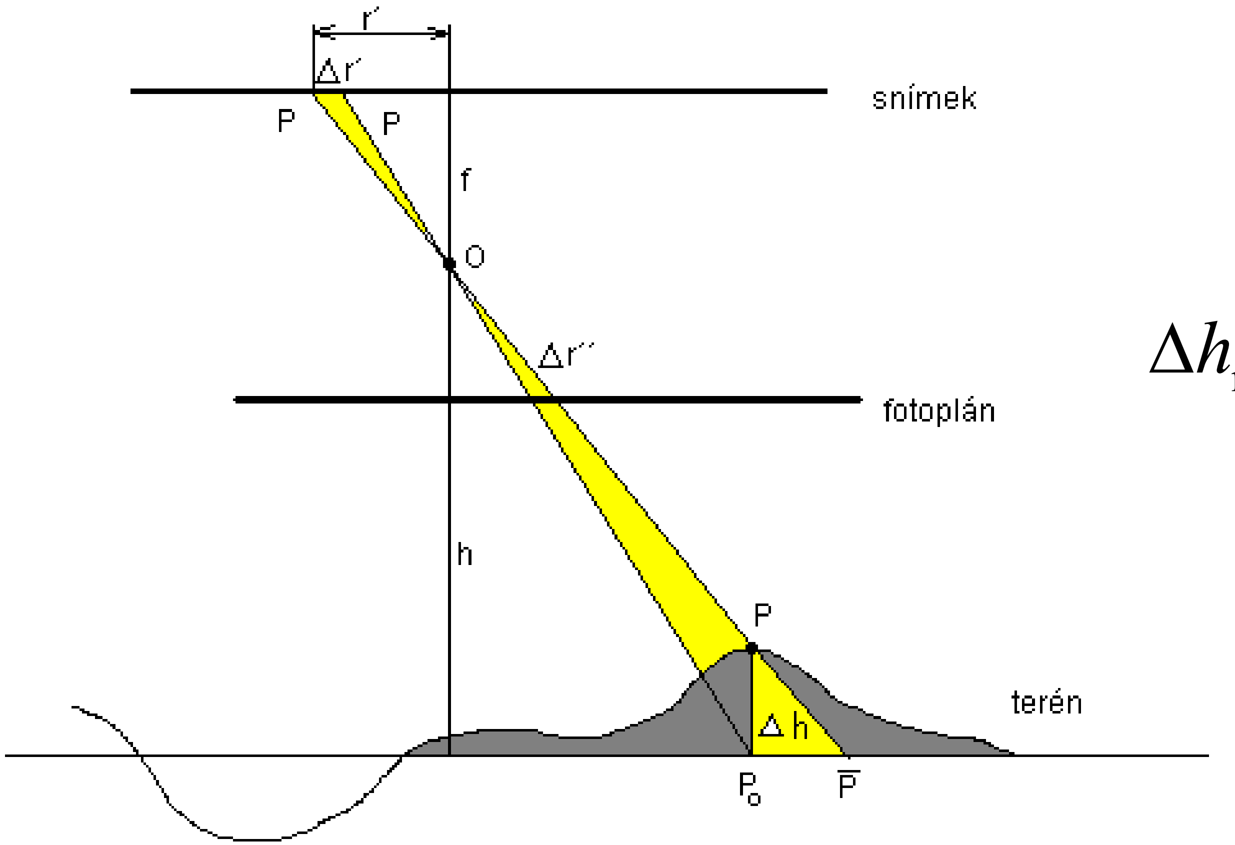
$$\Delta r = \Delta r'' \cdot m_F , \qquad \frac{\Delta r}{\Delta y} = \frac{r'}{f} , \qquad \Delta r'' = \frac{\Delta y \cdot r'}{f \cdot m_F}$$



$$\Delta y_{\max} = \frac{f \cdot m_F \cdot \Delta r''_{\max}}{r'}$$

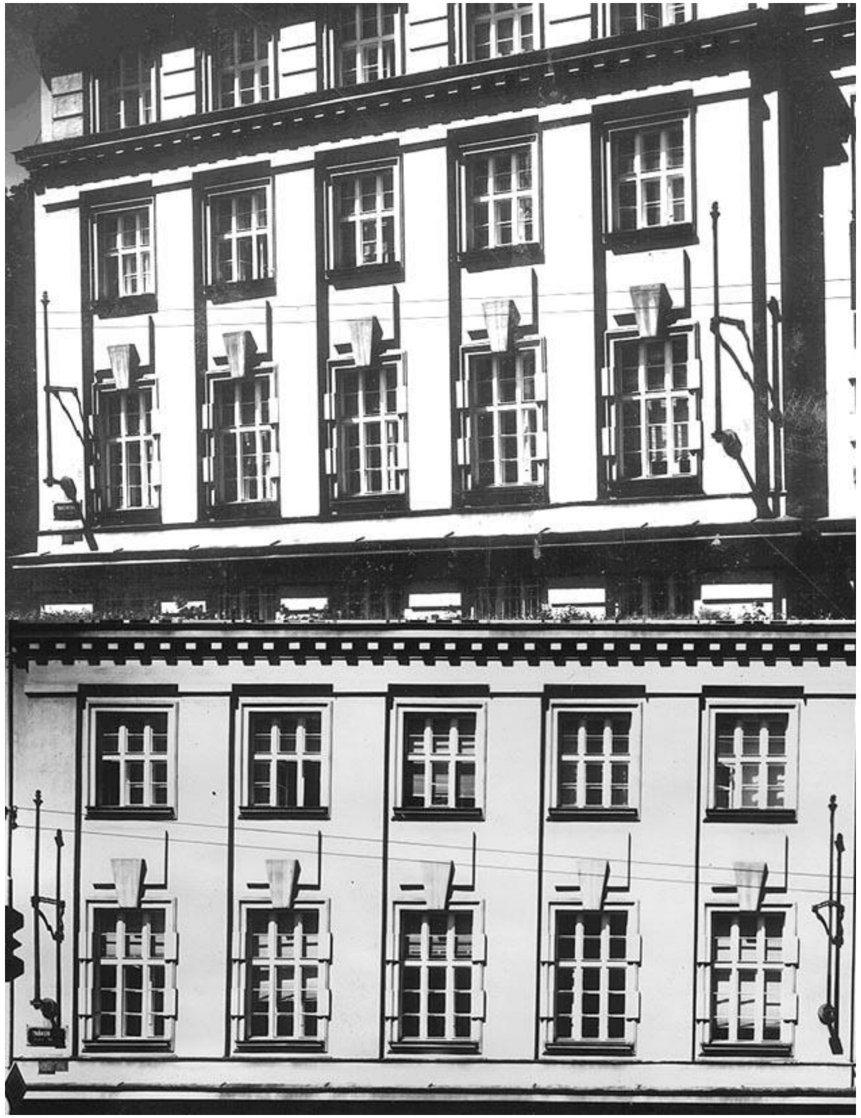
Effect of height zoning

$$\Delta r'' = \frac{\Delta h \cdot r'}{f \cdot m_F}$$



$$\Delta h_{max} = \frac{f \cdot m_F \cdot \Delta r''_{max}}{r'}$$

Digital redrawing



Original image and photo plan, taken by the measuring camera (left),
an image taken with an ordinary camera and its digitally redrawn form - an image vault,
due to uncorrected radial distortion is clearly visible (right)

Solution

$$X = \frac{a_1 x' + a_2 y' + a_3}{c_1 x' + c_2 y' + 1}$$

$$Y = \frac{b_1 x' + b_2 y' + b_3}{c_1 x' + c_2 y' + 1}$$

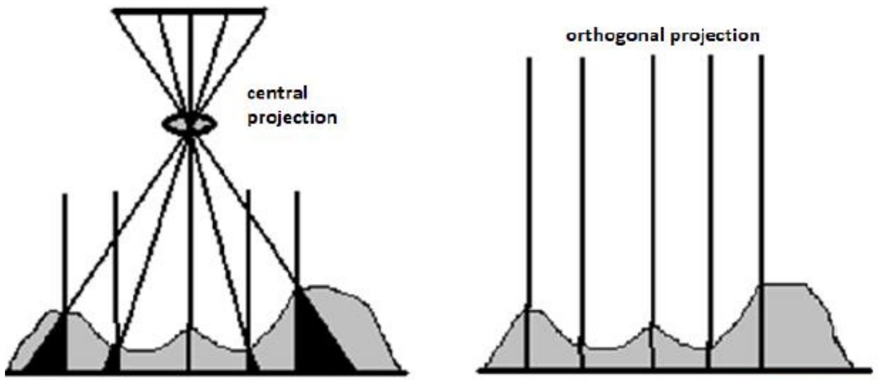
$$X = a_1 x' + a_2 y' + a_3 \qquad - c_1 x' X - c_2 y' X$$

$$Y = \qquad b_1 x' + b_2 y' + b_3 - c_1 x' Y - c_2 y' Y$$

$$\begin{pmatrix} x_1' & y_1' & 1 & 0 & 0 & 0 & -x_1'X_1 & -y_1'X_1 \\ 0 & 0 & 0 & x_1' & y_1' & 1 & -x_1'Y_1 & -y_1'Y_1 \\ x_2' & y_2' & 1 & 0 & 0 & 0 & -x_2'X_2 & -y_2'X_2 \\ 0 & 0 & 0 & x_2' & y_2' & 1 & -x_2'Y_2 & -y_2'Y_2 \\ x_3' & y_3' & 1 & 0 & 0 & 0 & -x_3'X_3 & -y_3'X_3 \\ 0 & 0 & 0 & x_3' & y_3' & 1 & -x_3'Y_3 & -y_3'Y_3 \\ x_4' & y_4' & 1 & 0 & 0 & 0 & -x_4'X_4 & -y_4'X_4 \\ 0 & 0 & 0 & x_4' & y_4' & 1 & -x_4'Y_4 & -y_4'Y_4 \end{pmatrix} \cdot \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ b_1 \\ b_2 \\ b_3 \\ c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} X_1 \\ Y_1 \\ X_2 \\ Y_2 \\ X_3 \\ Y_3 \\ X_4 \\ Y_4 \end{pmatrix}$$

$$\mathbf{A} \cdot \mathbf{a} = \mathbf{X}$$

$$\mathbf{a} = \mathbf{A}^{-1} \cdot \mathbf{X}$$

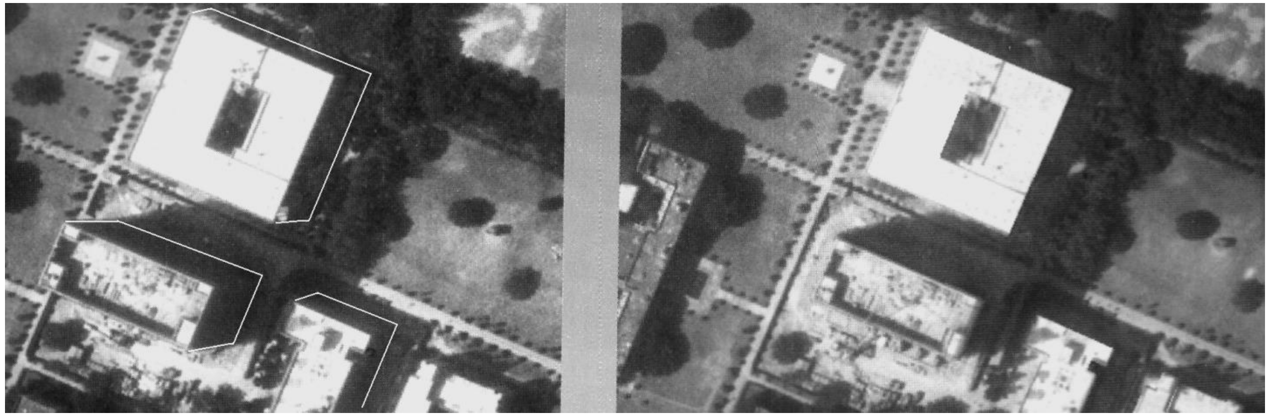


Digital orthophoto

Converting the central projection to orthogonal - to orthophoto - allows you to work with the image information as a map and insert it as a data layer in GIS.

Digital orthophoto

Digital orthophoto is a photogrammetric product - image conversion with central projection to orthogonal projection

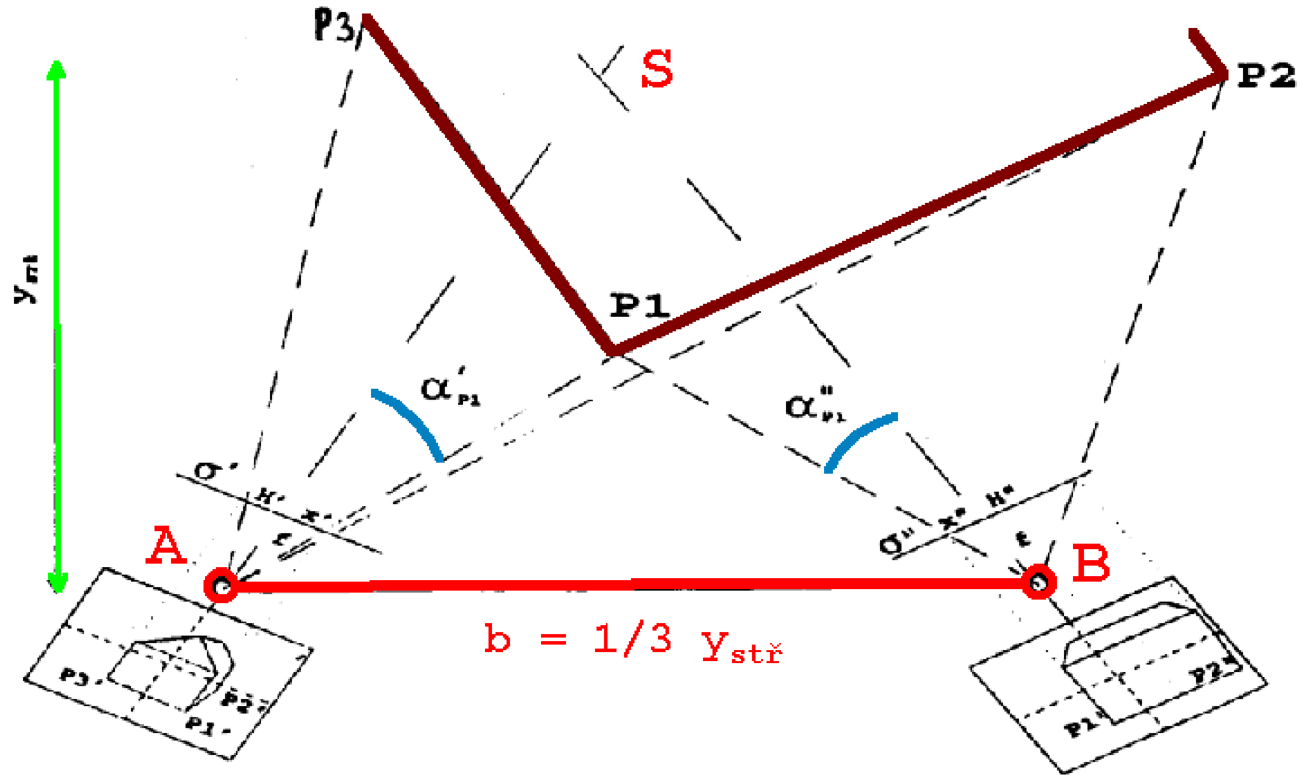


For creation:
Required image with known elements of internal and external orientation and DMT

Ortophoto and true ortophoto

The problem of mosaicking
- seamless orthophoto

Multi-frame photogrammetry - cross-sectional



The oldest photogrammetric method
- based on intersection of rays
- today only in digital form

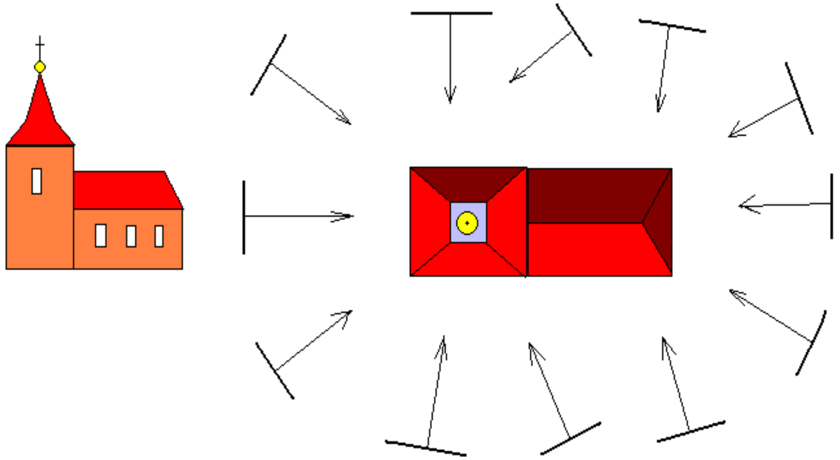
Today's solution

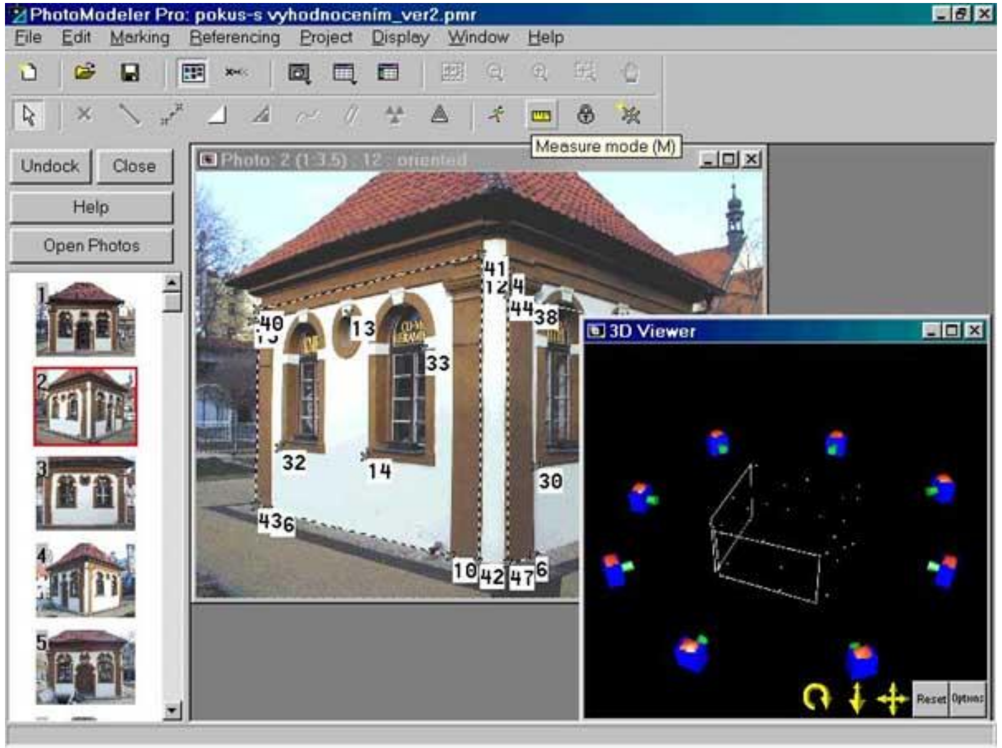
$$X = X_0 + (Z - Z_0)\frac{r_{11}(x' - x'_0) + r_{12}(y' - y'_0) - r_{13} f}{r_{31}(x' - x'_0) + r_{32}(y' - y'_0) - r_{33} f}$$

$$Y = Y_0 + (Z - Z_0)\frac{r_{21}(x' - x'_0) + r_{22}(y' - y'_0) - r_{23} f}{r_{31}(x' - x'_0) + r_{32}(y' - y'_0) - r_{33} f}$$

$$\begin{pmatrix} x' - x'_0 + \Delta x' \\ y' - y'_0 + \Delta y' \\ -f \end{pmatrix} = m \cdot \boldsymbol{R}^T \cdot \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix}$$

Cross-sectional photogrammetry





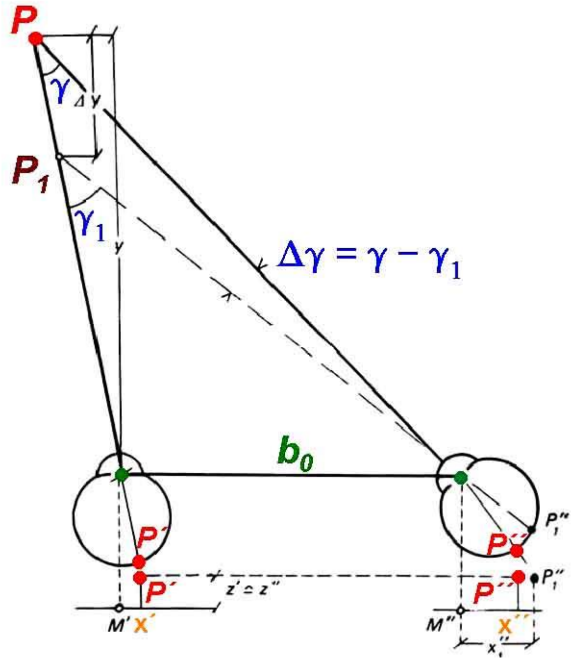
Stereophotogrammetry

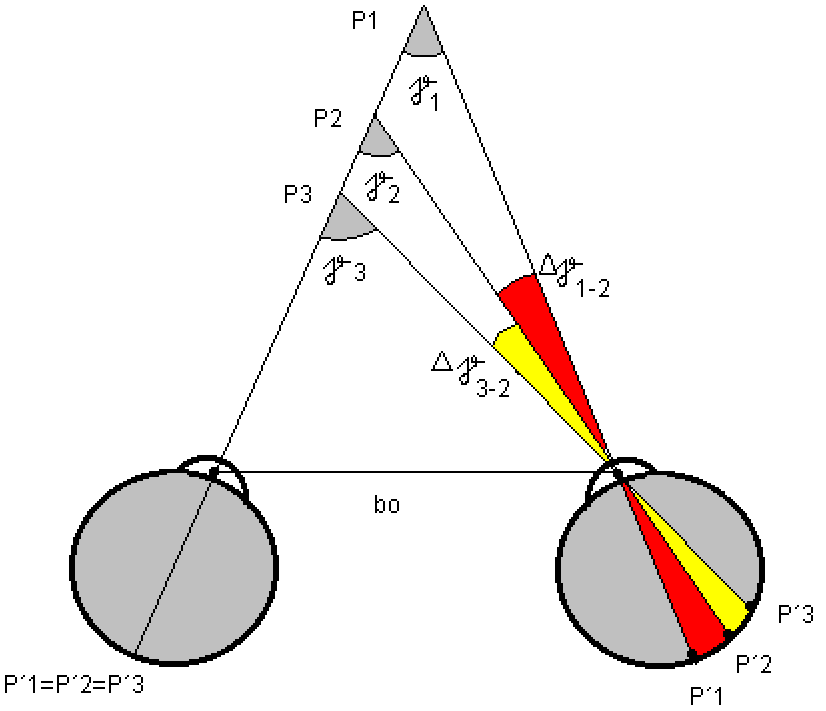
Stereophotogrammetric method introduced at the beginning of the 20th century (Pulfrich)

Evaluation based on stereoscopic perception also for non-signalized points

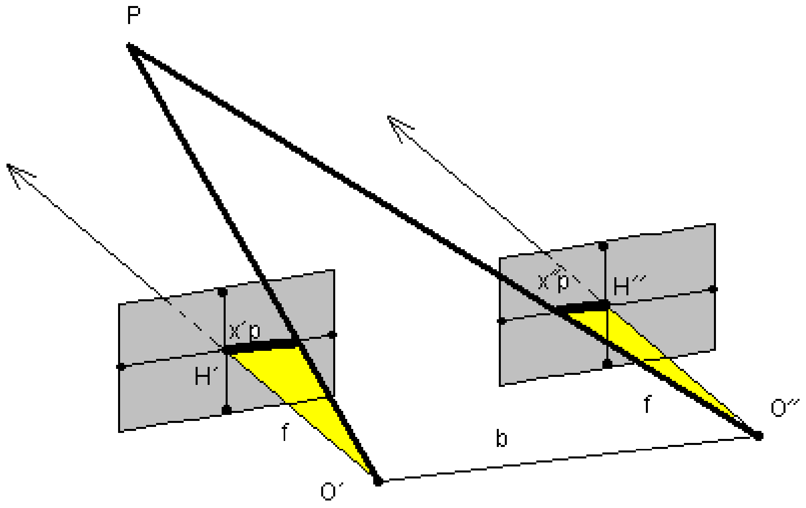
Photogrammetric stereoscopic observation and evaluation

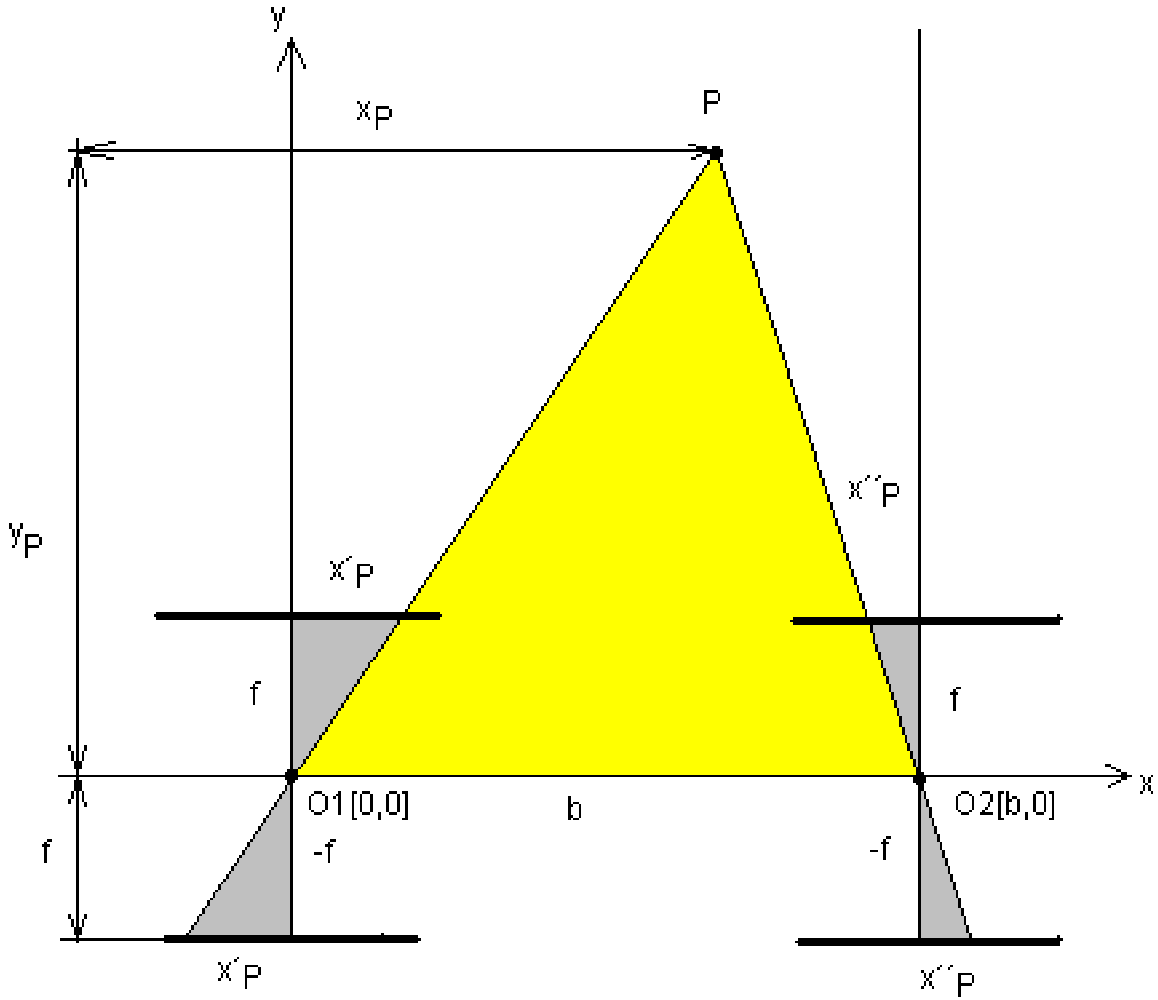
- artificial stereoscopic perception based on the natural perception of healthy eyes





Solution





Terrestrial stereophotogrammetry - normal case

In terrestrial applications, standardization of the external orientation elements can be ensured

R=E

$$x = \frac{b \cdot x'}{p} \quad y = \frac{b \cdot f}{p} \quad z = \frac{b \cdot z'}{p}$$

b (AB) base

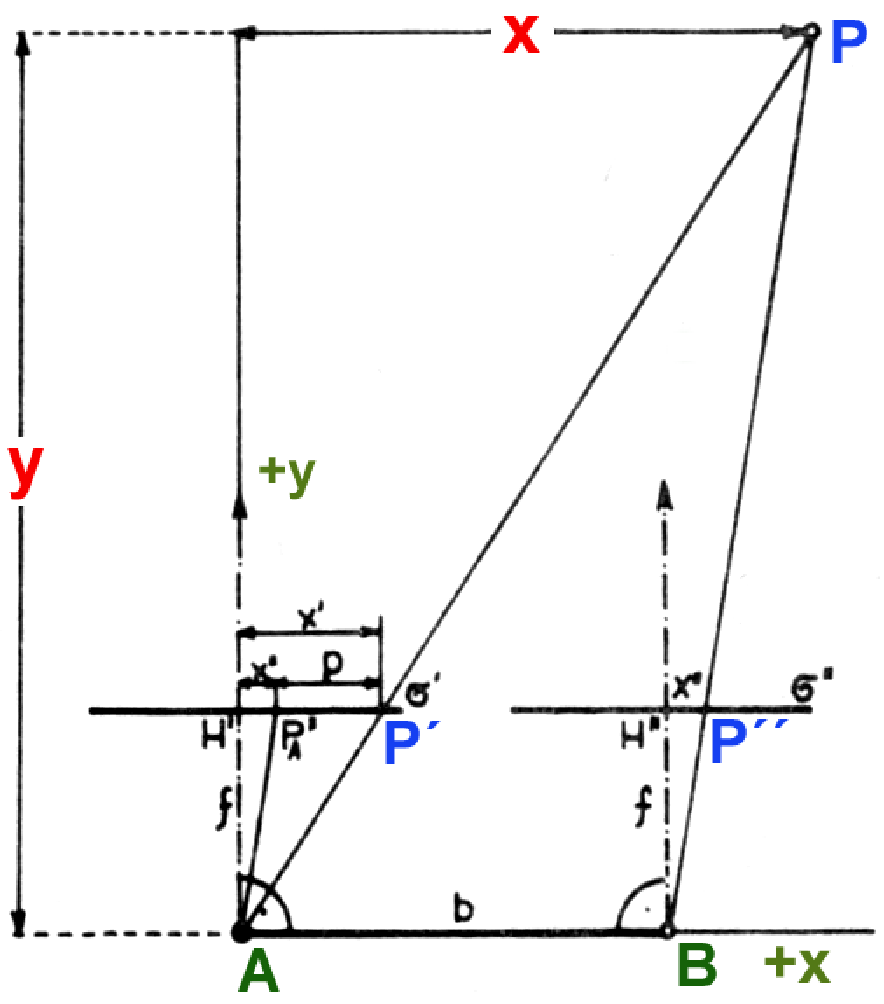
x y (z) model system

´, ´´ image planes

x´, x´´,z´, z´´ image coordinates

p parallax

f chamber constant



Accuracy of photogrammetry

$$\frac{y}{f} = \frac{b}{p}$$

$$x = \frac{b \cdot x'}{p} \qquad y = \frac{b \cdot f}{p} \qquad z = \frac{b \cdot z'}{p}$$

$$x = y\frac{x'}{f} \qquad z = y\frac{z'}{f}$$

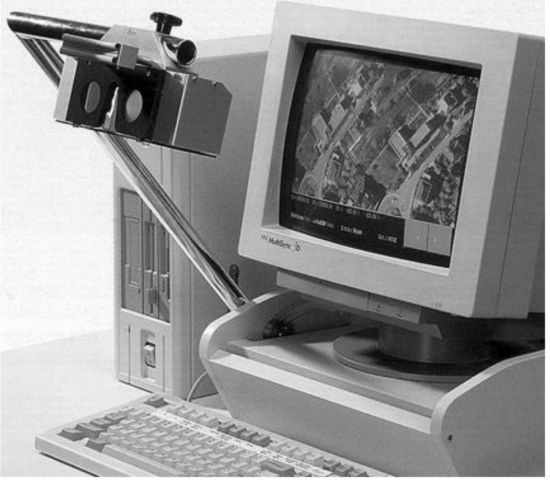
$$y = \frac{b \cdot f}{p}, \qquad dy = \frac{f}{p}db + \frac{b}{p}df - \frac{bf}{p^2}dp$$

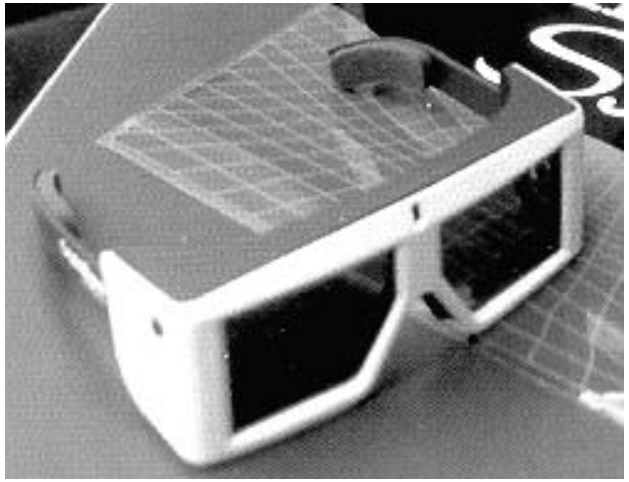
$$dy = -\frac{b \cdot f}{p^2}dp, \quad p^2 = \left(\frac{b \cdot f}{y}\right)^2$$

$$dy = -\frac{y \cdot y}{b \cdot f}dp$$

$$m_y = \pm\frac{y \cdot y}{b \cdot f}m_P$$

Device for stereoscopic perception





new solutions

new solutions

The emergence of the digital image

A digital image is an image in digital form (expressed in numbers). It is created either primarily by digital capture devices or by scanning analogue images. A digital image consists of individual pixels,

(from English *picture elements*) taking certain values which are not arbitrary (determined by technical possibilities of the computer and coding).

$$P[i,j] = \mathrm{f}(i,j)$$

f(i,j)	f(i,j+1)	f(i, j+2)	f(i, j+3)	f(i, j+4)
f(i+1,j)	f(i+1,j+1)	f(i+1,j+2)	f(i+1,j+3)	f(i+1,j+4)
f(i+2,j)	f(i+2,j+1)	f(i+2,j+2)	f(i+2,j+3)	f(i+2,j+4)
.....				
.....				f(m,n)

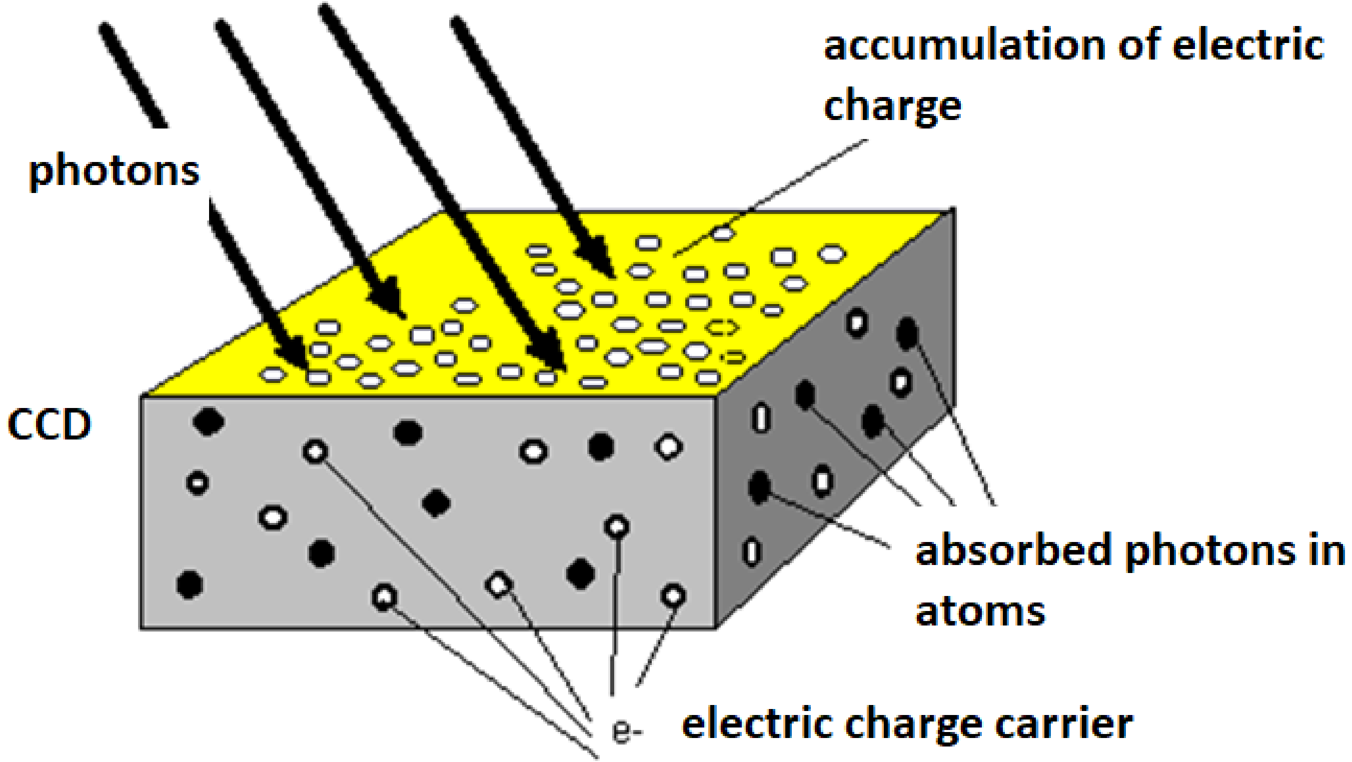
$$M = m \cdot n \cdot e \ [\mathrm{byte}]$$

The origin of the image

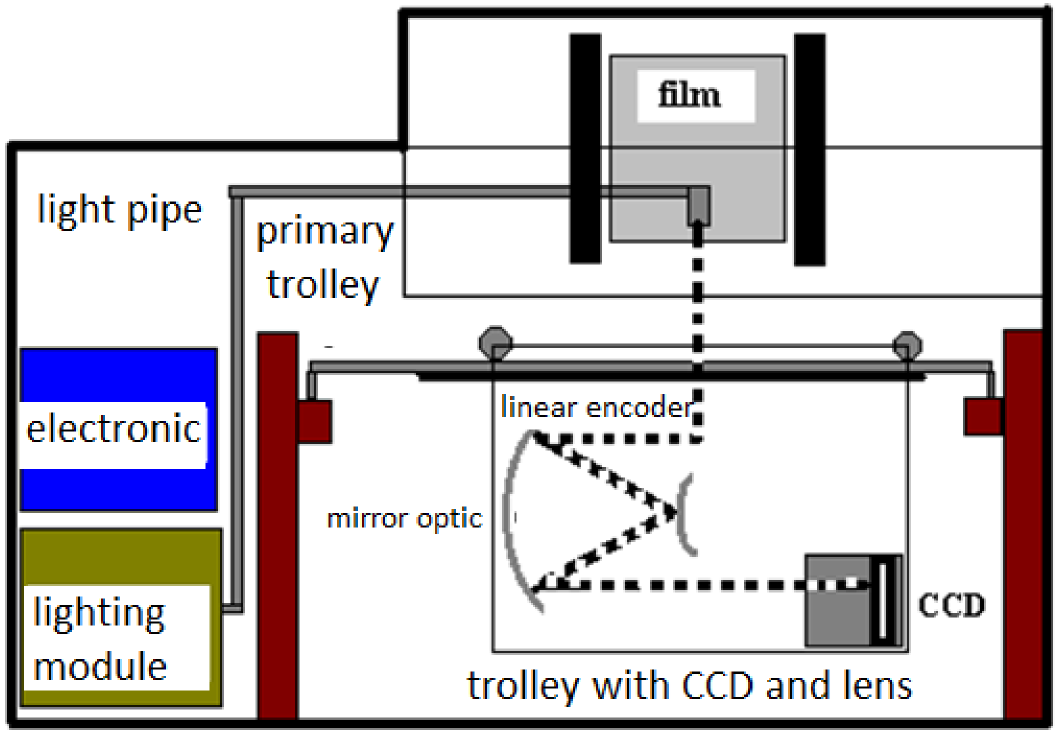
The most common type of detector is the CCD element. The name is derived from the name of the element in English "*Charge Coupled Device*".

CMOS (*Complementary Metal Oxide Semiconductor*) is a transistor-based electronic component. Compared to a CCD, it is simpler to manufacture, smaller, up to 80% cheaper, and consumes less power than a CCD (only 1%!).

Photocell - the principle of its function is generally the same with CCD detectors, differing mainly in size

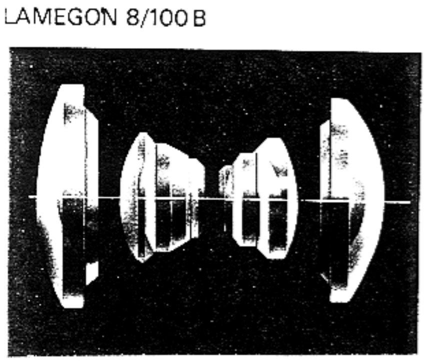


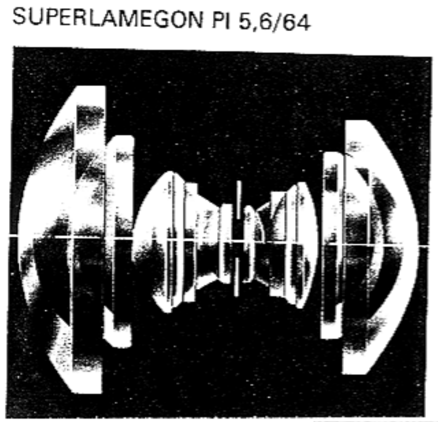
Secondary digital image formation: by scanning

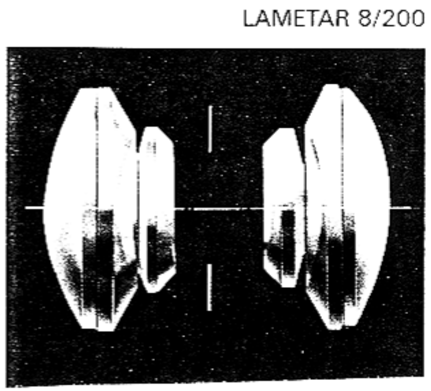


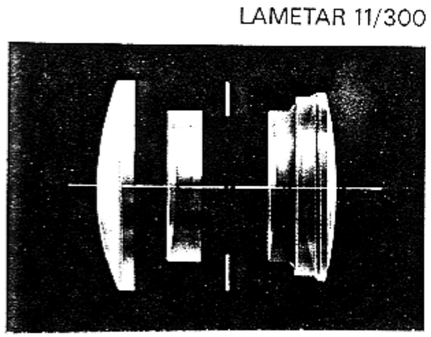
Scanner PhotoScan2001

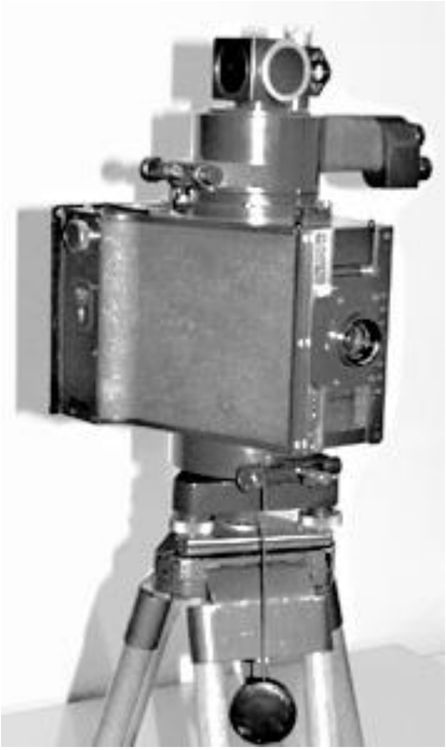
Photogrammetric terrestrial cameras











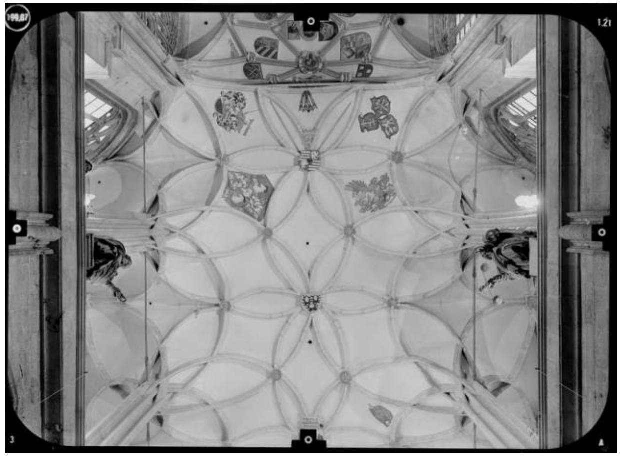
Photheo 13x18, UMK 201318 and Wild P31 chamber

Photogrammetric cameras

Leica RC 30 camera
Zeiss RMK-TOP camera and TAS gyrostabilised platform,
LMK camera (Zeiss Jena)

Classical photogrammetric records

frame marks



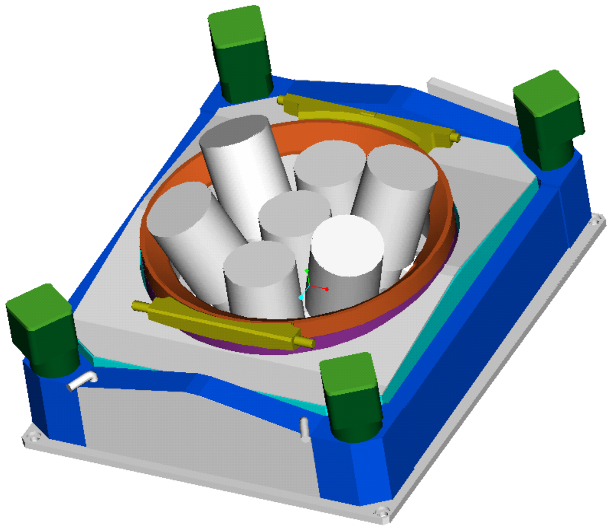
2003, GSD 50 cm

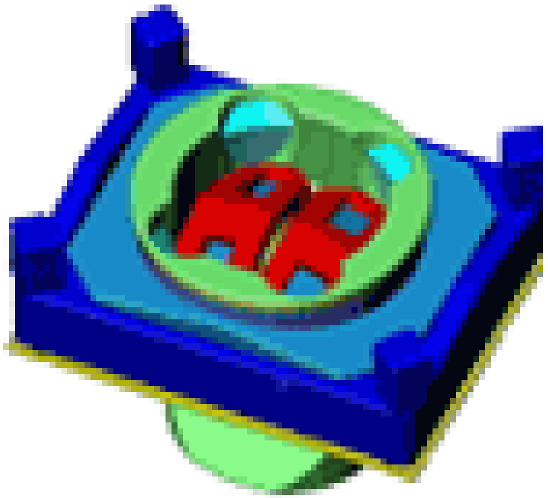
2015, GSD 15cm

L-410FG

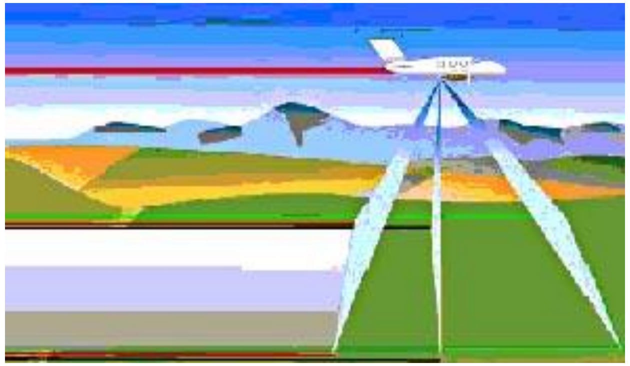
2021 GSD 2cm

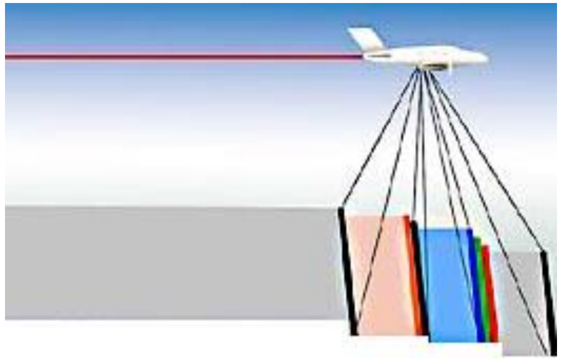
Digital air cameras





View of the DMC camera (top), original schematic of the gyrostabilized sensor part (left), current schematic (right)





Sensor head ADS40 , ADS40, surface scanning principle

satellite photogrammetry

Ikonos 1, 1999 (1m PAN, 4m MSS);
today's civilian satellites 0.35-0.5m PAN

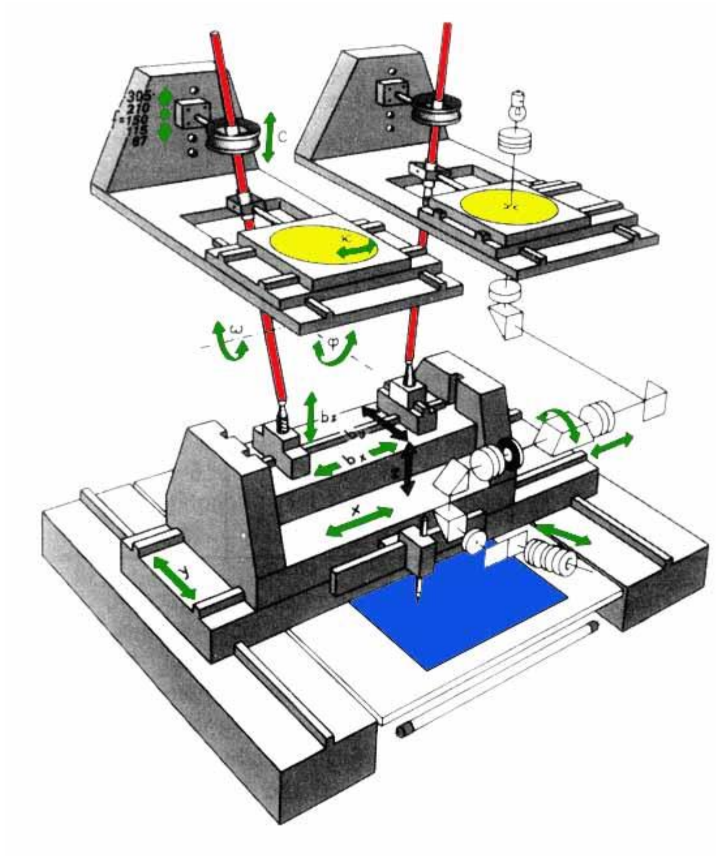
Photogrammetric technologies for image content evaluation

Analog technology
(obsolete, not used)

Numerical (analytical) technology
- using analogue machines and partial counting steps (classical)

Analytical technology
-cannot be solved without a computer
- present

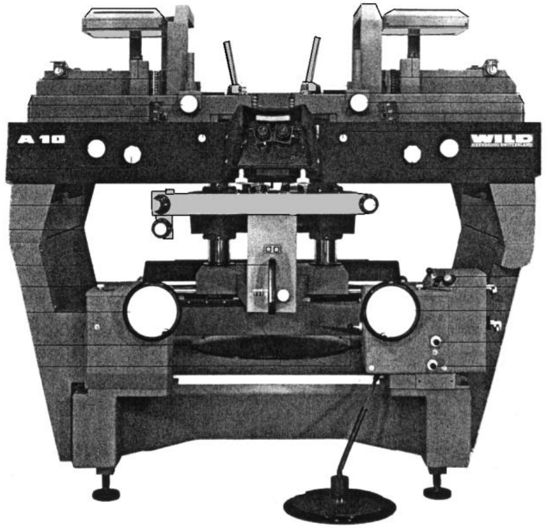
Spatial evaluation using streptophotogrammetric devices

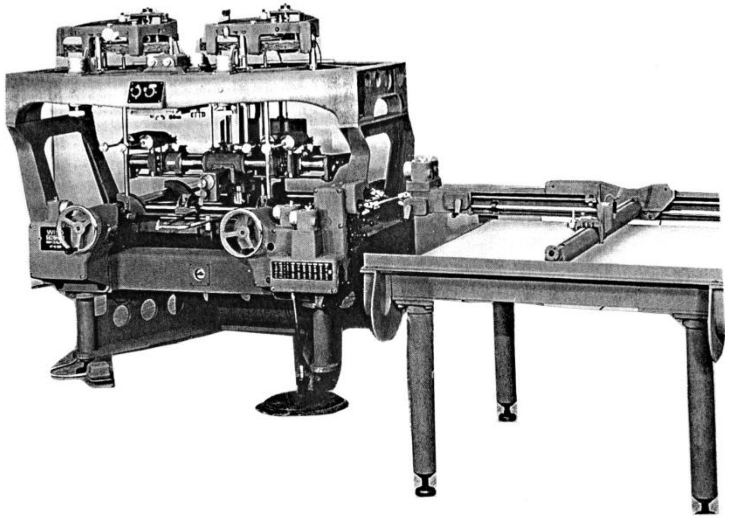


Analog plotters

-produced until 1986 (Wild) and 1990 (Zeis Jena)
- a complex and precise mechanical device, allowing the restoration of the elements of the external orientation
- a realistic stereoscopic model is created by tilting and shifting the images
- latest models with computer support
- model coordinates are controlled
- currently obsolete

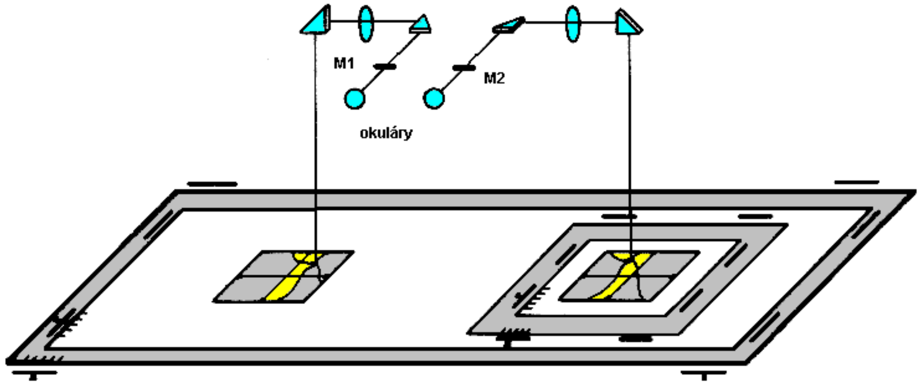
Analog plotters

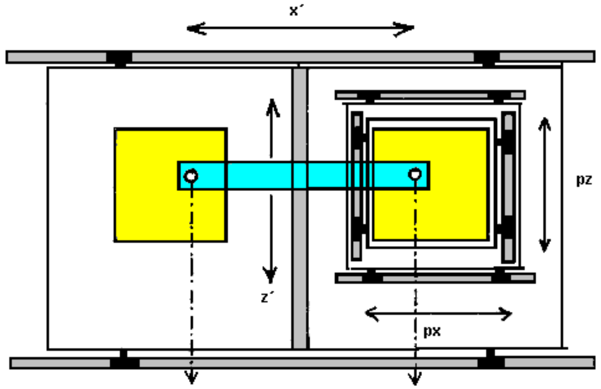


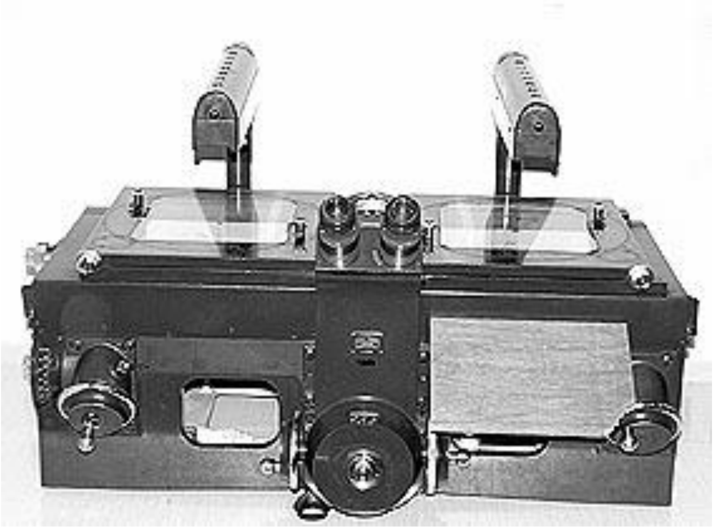


Stereometrograph, Topocart (Zeiss Jena) A-10 and A-7 (Wild)

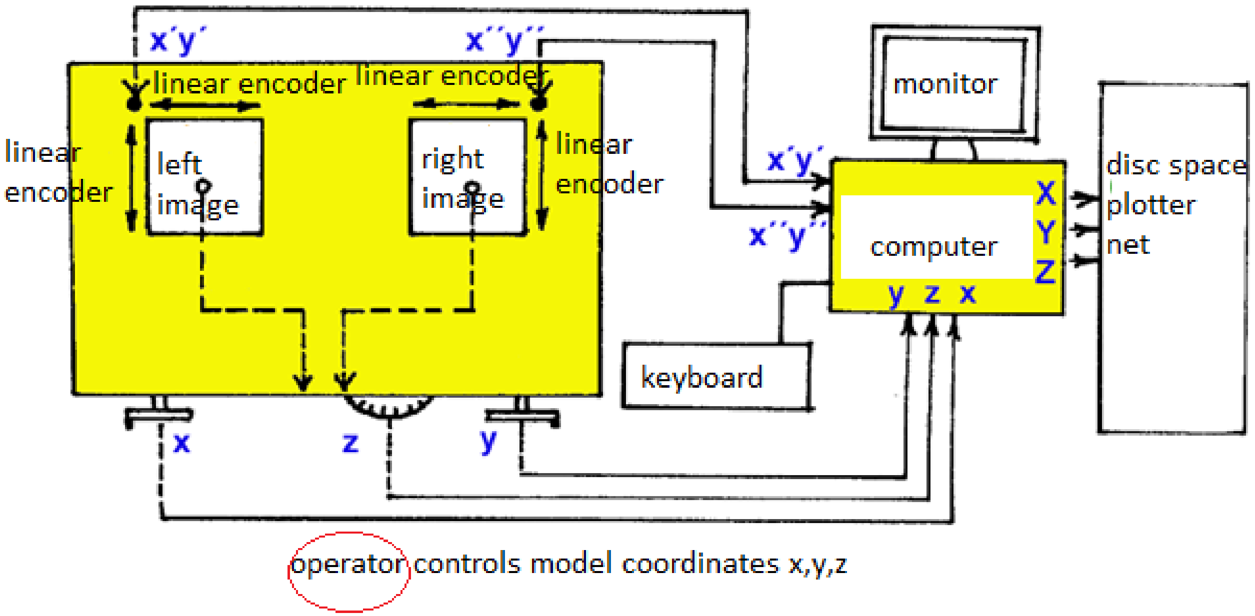
analogue comparators







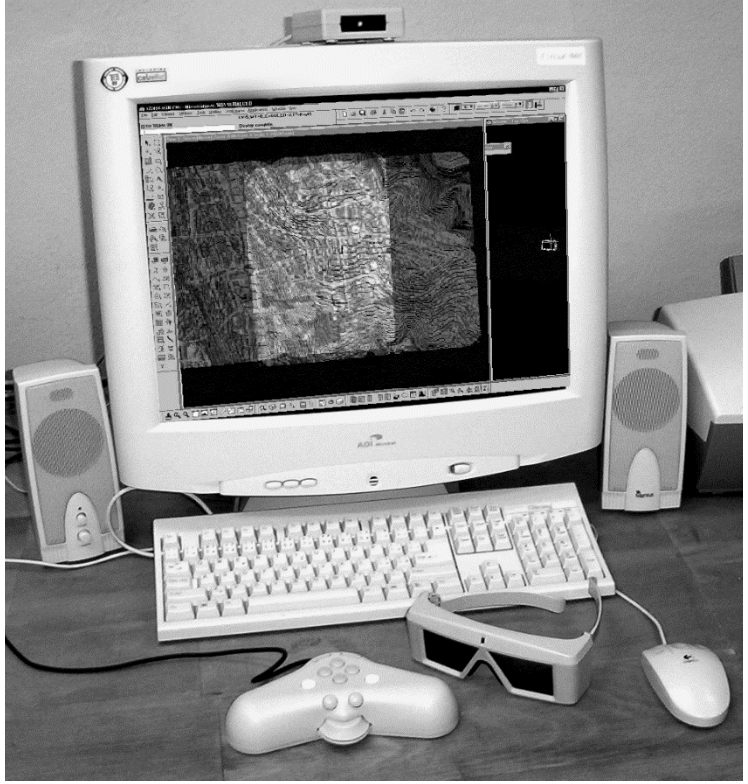
Analytical plotters



- measured on real images, computer required
- no real model is created
- the most accurate fm method
- model coordinates are controlled, converted to frame coordinates on the computer
- mobile image carriers are set to the calculated image coordinates

BC-1 (Wild, 1985) SD 2000 (Leica, 1995)

Digital stations



Imagestation Unix Imagestation SSK
Helava (Leica) VSD

aerial photogrammetry

Image orientation:

•*internal orientation (elements of internal orientation)*

•*External orientation (coordinates of the centre of the entrance pupil X_0 , Y_0 , Z_0 , then inclinations „)*

For stereo-evaluation of photogrammetric images, the exterior orientation is defined as:

- direct transformation relation based on complex solution - beam alignment
- older step-by-step procedure called:

a) ***relative orientation*** *(relative orientation between the two stereo images, forming an arbitrary spatially oriented virtual stereo model)*
b) ***absolute orientation*** *(scaling, rotation and shifting of the model to the geodetic reference system)*

aerial photogrammetry

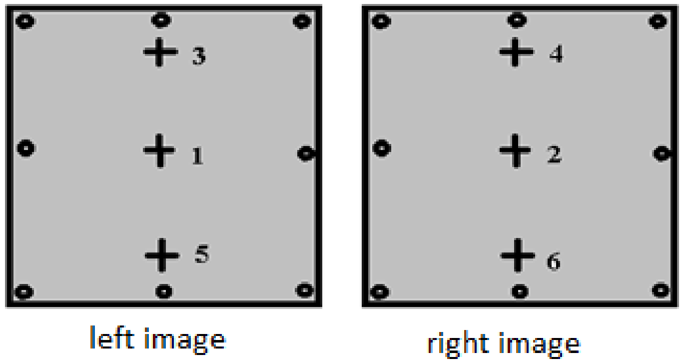
Relative orientation of the independent pair

The rotation *d, d , d, d, =d -d* is chosen as the determinate unknowns. assumption *yy*

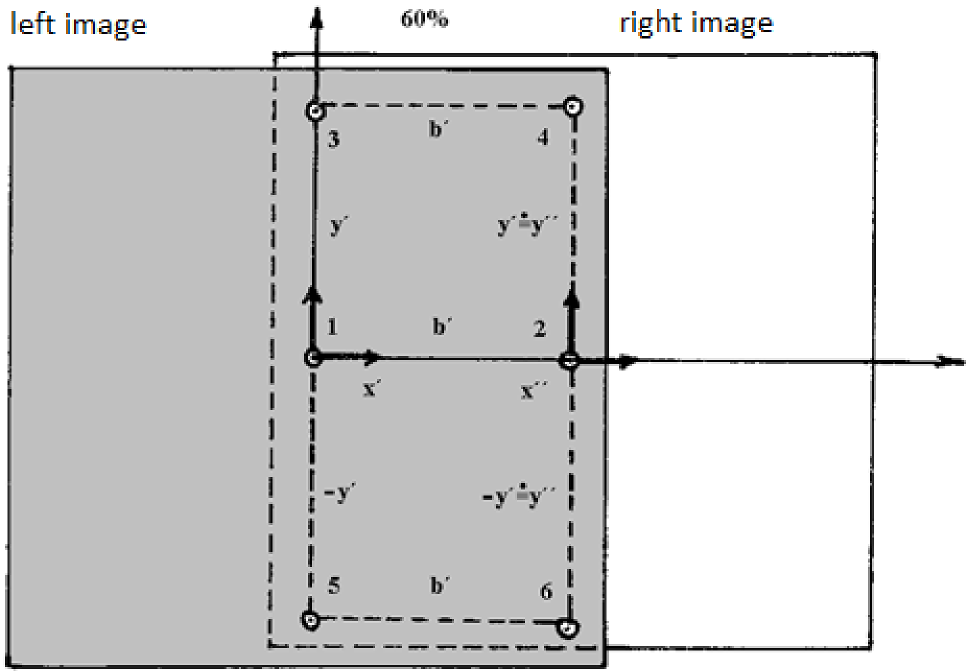
$$0 = q + x'd\kappa' - x'd\kappa'' - \frac{x'y'}{f}d\varphi' + \frac{x'y'}{f}d\varphi'' + \left(f + \frac{y'^2}{f}\right)\Delta\omega$$

$$\left(f + \frac{y'^2}{f}\right)d\omega' - \left(f + \frac{y''^2}{f}\right)d\omega'' \cong \left(f + \frac{y'^2}{f}\right)(d\omega' - d\omega'') = \left(f + \frac{y'^2}{f}\right)\Delta\omega$$

orinthal point	left picture x	left frame y	right picture x	right image y
1	0	0	-b	0
2	+b	0	0	0
3	0	+y	-b	+y
4	+b	+y	0	+y
5	0	-y	-b	-y
6	+b	-y	0	-y



aerial photogrammetry



$$0 = q_1 + b' d\kappa'' + f\Delta\omega$$

$$0 = q_2 + b' d\kappa' + f\Delta\omega$$

$$0 = q_3 + b' d\kappa'' - \frac{b' y'}{f} d\varphi'' + \left(f + \frac{y'^2}{f} \right) \Delta\omega$$

$$0 = q_4 + b' d\kappa' - \frac{b' y'}{f} d\varphi' + \left(f + \frac{y'^2}{f} \right) \Delta\omega$$

$$0 = q_5 + b' d\kappa'' + \frac{b' y'}{f} d\varphi'' + \left(f + \frac{y'^2}{f} \right) \Delta\omega$$

$$0 = q_6 + b' d\kappa' + \frac{b' y'}{f} d\varphi' + \left(f + \frac{y'^2}{f} \right) \Delta\omega$$

aerial photogrammetry

Relative orientation when attaching an image

The rotations d, d, db_y , db_z are chosen as the determinate unknowns.

$$0 = q - x''d\kappa'' + \frac{x''y''}{f}d\varphi'' - \left(f + \frac{y''^{2}}{f}\right)d\omega'' - db_y'' - \frac{y''}{f}db_z''$$

$$0 = q_1 + b'd\kappa'' - fd\omega'' - db_y''$$

$$0 = q_2 - fd\omega'' - db_y''$$

$$0 = q_3 + b'd\kappa'' - \frac{b'y''}{f}d\varphi'' - fd\omega'' - \frac{y''^{2}}{f}d\omega'' - db_y'' - \frac{y''}{f}db_z''$$

$$0 = q_4 - fd\omega'' - \frac{y''^{2}}{f}d\omega'' - db_y'' - \frac{y''}{f}db_z''$$

$$0 = q_5 + b'd\kappa'' + \frac{b'y''}{f}d\varphi'' - fd\omega'' - \frac{y''^{2}}{f}d\omega'' - db_y'' + \frac{y''}{f}db_z''$$

$$0 = q_6 - fd\omega'' - \frac{y''^{2}}{f}d\omega'' - db_y'' + \frac{y''}{f}db_z''$$

aerial photogrammetry

Absolute orientation

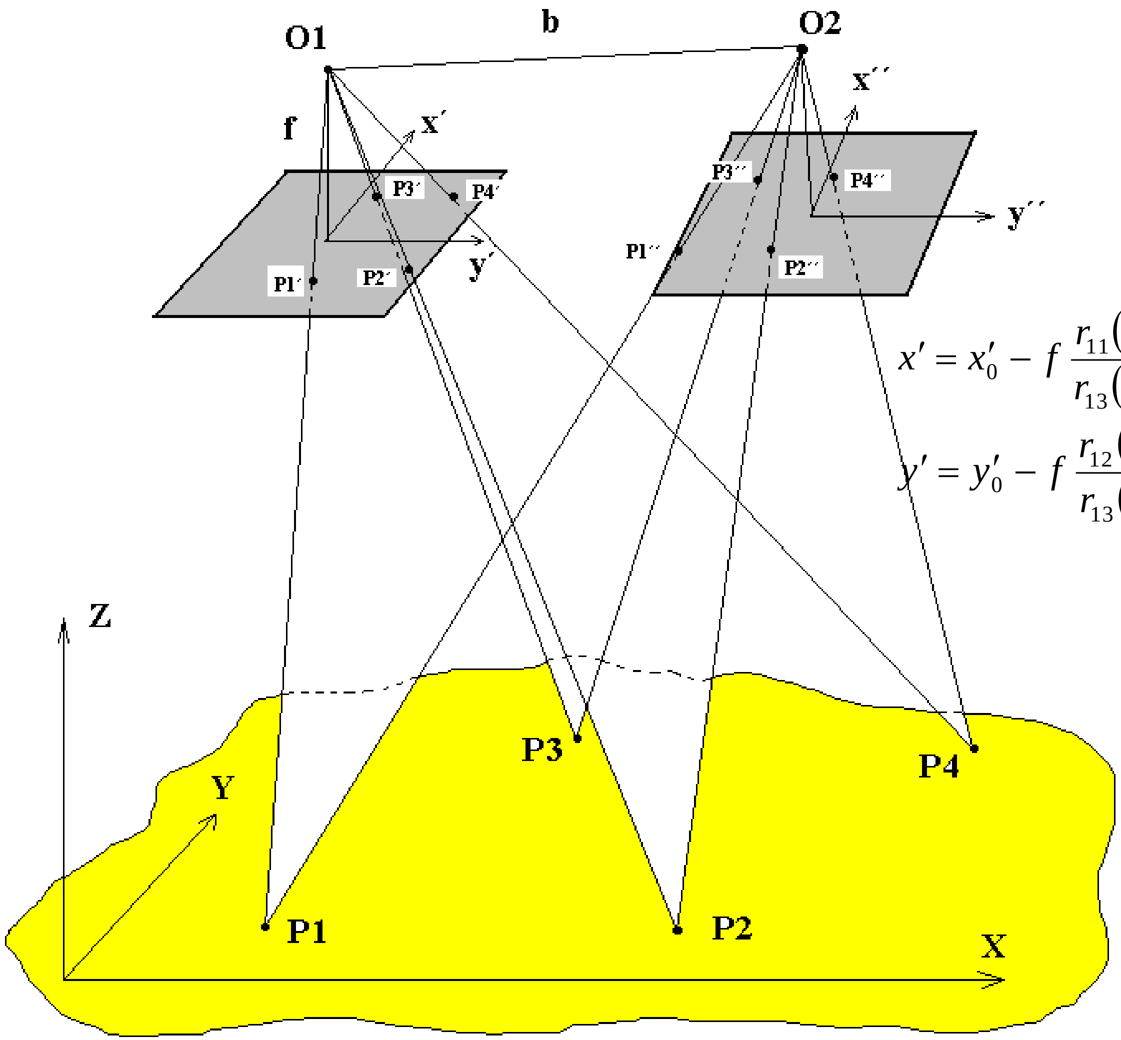
$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_0 \\ Y_0 \\ Z_0 \end{pmatrix} + m.\mathbf{R}.\begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

where X,Y,Z are geodetic coordinates, X_0 , Y_0 , Z_0 are the geodetic coordinates of the origin of the model coordinate system x,y,z , m is the scale of the model and $\boldsymbol{R}$ is the spatial rotation matrix of the model coordinate system in the geodetic coordinate system, containing the three angles ,,. The relation (14.12) is a spatial similarity transformation with unknowns X_0 , Y_0 , $Z_{0,}$ m, , .

$$M = \begin{pmatrix} m_x & 0 & 0 \\ 0 & m_y & 0 \\ 0 & 0 & m_z \end{pmatrix}$$

Analytical methods

***Comprehensive** solution*



$$x' = x'_0 - f\frac{r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)} = x'_0 - f\frac{\mathbf{R_1}\cdot\mathbf{X}}{\mathbf{R_3}\cdot\mathbf{X}}$$

$$y' = y'_0 - f\frac{r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)} = y'_0 - f\frac{\mathbf{R_2}\cdot\mathbf{X}}{\mathbf{R_3}\cdot\mathbf{X}}$$

Analytical methods

Comprehensive solution

$$x'_{i1} = F_x\left(f, x'_0 = d'x, X_{01}, Y_{01}, Z_{01}, \omega_1, \varphi_1, \kappa_1, X_i, Y_i, Z_i\right)$$
$$y'_{i1} = F_y\left(f, y'_0 = d'y, X_{01}, Y_{01}, Z_{01}, \omega_1, \varphi_1, \kappa_1, X_i, Y_i, Z_i\right)$$
$$x''_{i2} = F_x\left(f, x''_0 = d'x, X_{02}, Y_{02}, Z_{02}, \omega_2, \varphi_2, \kappa_2, X_i, Y_i, Z_i\right)$$
$$y''_{i2} = F_y\left(f, y''_0 = d'y, X_{02}, Y_{02}, Z_{02}, \omega_2, \varphi_2, \kappa_2, X_i, Y_i, Z_i\right)$$

$$f(x_1, \ldots, x_n) = f(x_1^0, \ldots, x_n^0) + \left(\frac{\partial f}{\partial x_1}\right)^0 dx_1 + \ldots + \left(\frac{\partial f}{\partial x_n}\right)^0 dx_n$$

$$\begin{aligned} v_{xij} = & \left(\frac{\partial x'}{\partial X_{0j}}\right)^0 dX_{0j} + \left(\frac{\partial x'}{\partial Y_{0j}}\right)^0 dY_{0j} + \left(\frac{\partial x'}{\partial Z_{0j}}\right)^0 dZ_{0j} + \\ & + \left(\frac{\partial x'}{\partial \omega_j}\right)^0 d\omega_j + \left(\frac{\partial x'}{\partial \varphi_j}\right)^0 d\varphi_j + \left(\frac{\partial x'}{\partial \kappa_j}\right)^0 d\kappa_j + \\ & + \left(\frac{\partial x'}{\partial X_i}\right)^0 dX_i + \left(\frac{\partial x'}{\partial Y_i}\right)^0 dY_i + \left(\frac{\partial x'}{\partial Z_i}\right)^0 dZ_i - \left(x'_{ij} - x'^{\,0}_{ij}\right) \end{aligned}$$

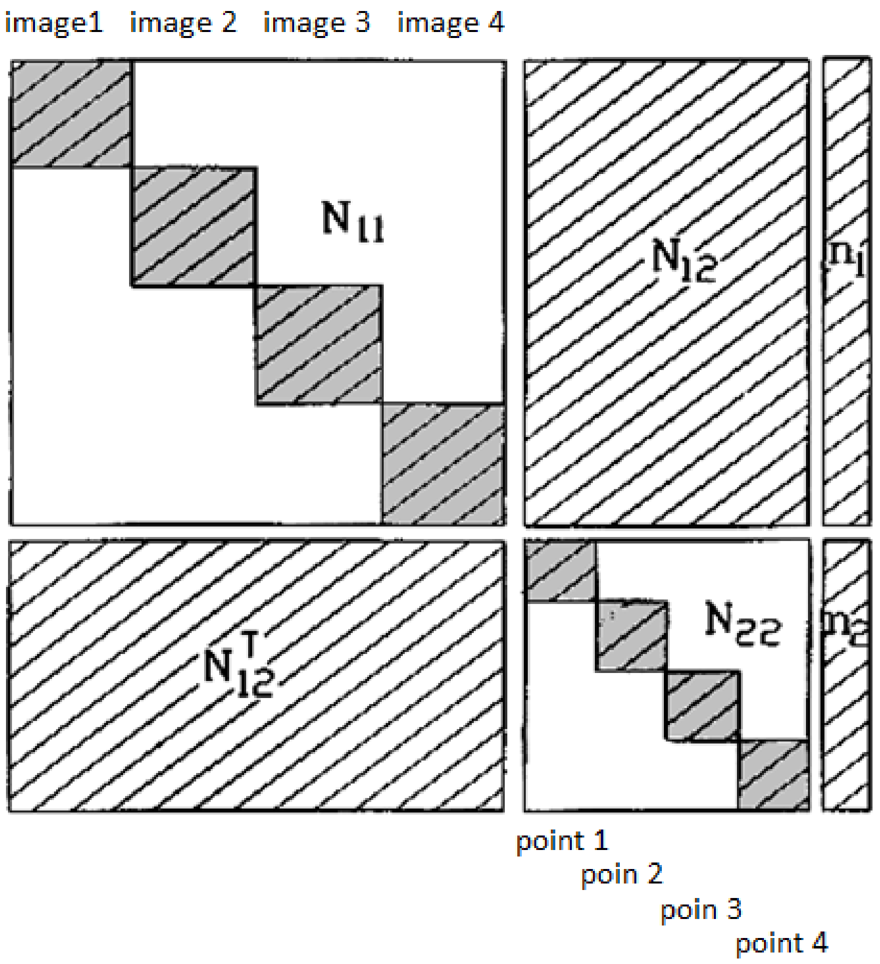
Analytical methods

Comprehensive solution

$$\mathbf{v} = \mathbf{A}_1 \cdot \mathbf{x}_1 + \mathbf{A}_2 \cdot \mathbf{x}_2 - \mathbf{l} \quad \leftrightarrow \quad (\mathbf{v} = \mathbf{A} \cdot \mathbf{x} - \mathbf{l})$$

$$\mathbf{x} = \left(\mathbf{A}^T \mathbf{A}\right)^{-1} \cdot \mathbf{A}^T \mathbf{l}$$

$$\mathbf{A}^T \mathbf{A} = \mathbf{N} \qquad \mathbf{A}^T \cdot \mathbf{l} = \mathbf{n}$$



$$\mathbf{v} = \mathbf{A} \cdot \mathbf{x} - \mathbf{l}$$

$$\Downarrow$$

$$\mathbf{N} \cdot \mathbf{x} = \mathbf{n}$$

$$\begin{pmatrix} \mathbf{N}_{11} & \mathbf{N}_{12} \\ \mathbf{N}^T{}_{12} & \mathbf{N}_{22} \end{pmatrix} \cdot \begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{pmatrix} = \begin{pmatrix} \mathbf{n}_1 \\ \mathbf{n}_2 \end{pmatrix}$$

$$\left(\mathbf{N}_{11} - \mathbf{N}_{12} \cdot \mathbf{N}_{22}{}^{-1} \cdot \mathbf{N}^T{}_{12}\right)\mathbf{x}_1 = \mathbf{n}_1 - \mathbf{N}_{12} \cdot \mathbf{N}_{22}{}^{-1} \cdot \mathbf{n}_2$$

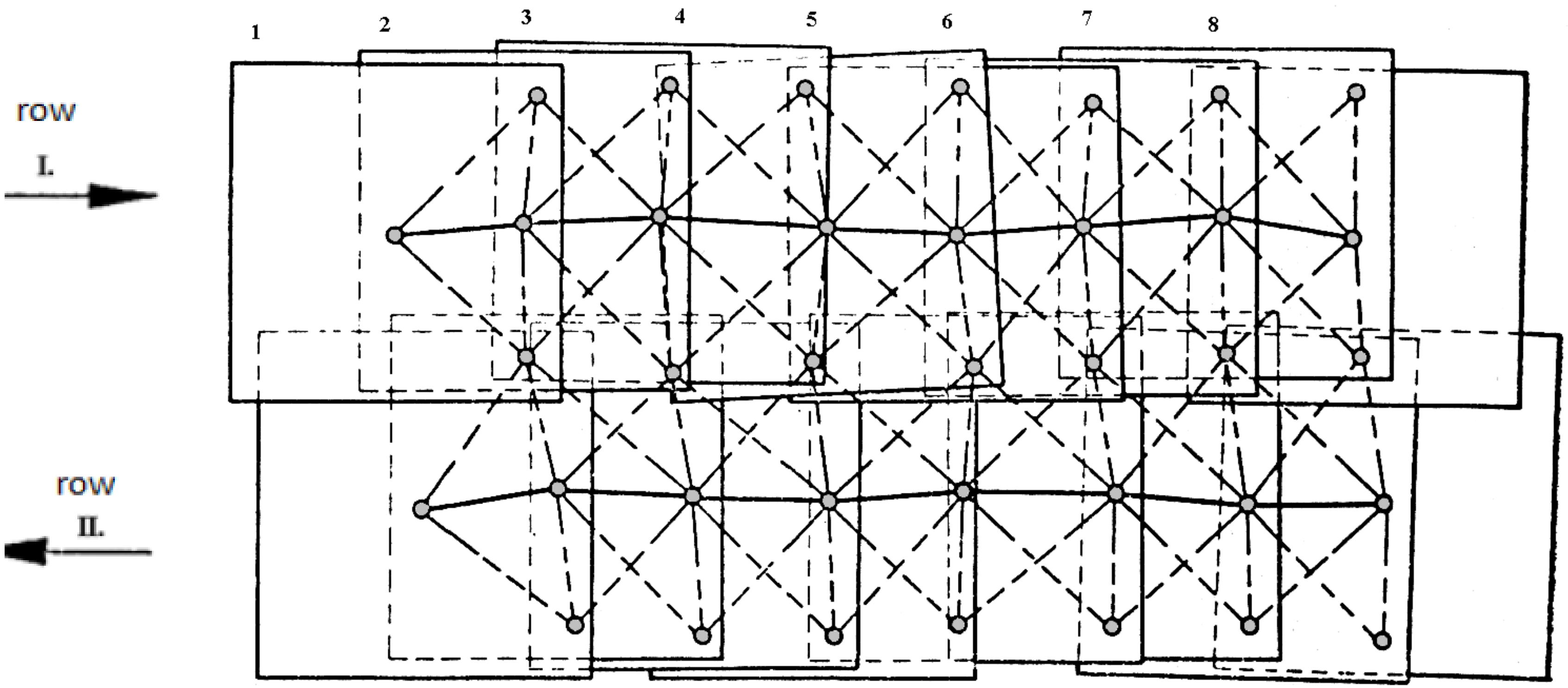
Image triangulation

The goal of today's analytical aerotriangulation is:

- ***- obtaining germination points for detailed evaluation***
- ***- Alignment of a set of images or models to ensure continuous evaluation***
- ***- accurate calculation of exterior orientation elements for all images***

- *Historically, there are radial, analoque,semi-analyticaland analytical technology of aerotriangulation*
- *•Today only automated (digital) aerotriangulation is used(**AAT**)*

Image triangulation



Full triangular radial mesh and normal image block in radial triangulation

digital photogrammetry

Theory of image correlation

$$\rho\,(A,B)=\frac{\operatorname{cov}(A,B)}{\rho(A)\cdot\rho(B)}$$

If we want to calculate the correlation coefficient for two equally sized digital images (or their cuts),
we will use to calculate the pixel value $p(A)_{i,j}$ for image **A** and $p(B)_{i,j}$ for image **B**. We obtain the expression:

$$r(A,B)=\frac{C(A,B)}{\sqrt{C(A)\cdot C(B)}}$$

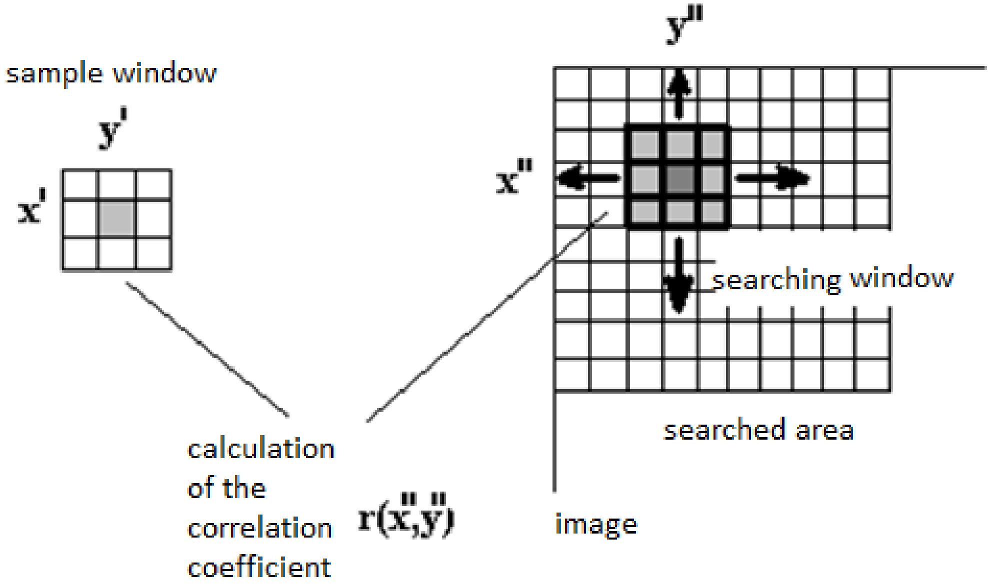
where the individual expressions are (*n* is the number of pixels in the side of the square window)

$$C(A,B)=\frac{1}{n^2-1}\sum_{i=1}^{n}\sum_{j=1}^{n}\left(p(A)_{i,j}-\overline{p}(A)\right)\cdot\left(p(B)_{i,j}-\overline{p}(B)\right)$$

$$C(A)=\frac{1}{n^2-1}\sum_{i=1}^{n}\sum_{j=1}^{n}\left(p(A)_{i,j}-\overline{p}(A)\right)^2,\quad \overline{p}(A)=\frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}\left(p(A)_{i,j}\right)$$

$$C(B)=\frac{1}{n^2-1}\sum_{i=1}^{n}\sum_{j=1}^{n}\left(p(B)_{i,j}-\overline{p}(B)\right)^2,\quad \overline{p}(B)=\frac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}\left(p(B)_{i,j}\right)$$

digital photogrammetry



We are looking for its maximum with subpixel precision. Since it reaches its maximum only in a limited region, we can replace the discrete correlation function by a continuous function and describe it by, for example, a second degree polynomial:

$$r = \bar{r} + v = a_0 + a_1 x + a_2 y + a_3 xy + a_4 x^2 + a_5 y^2$$

where x_i , y_i is the position of the search window for the calculated value of the correlation coefficient $r_{i\,;}$ if we have a matrix of 3x3 correlation coefficients, we get 9 values. We need a total of 6 to calculate the coefficients and$_i$ and

digital photogrammetry

Subpixel transformation

$$p_B(x) = p_A(x + a_1)$$

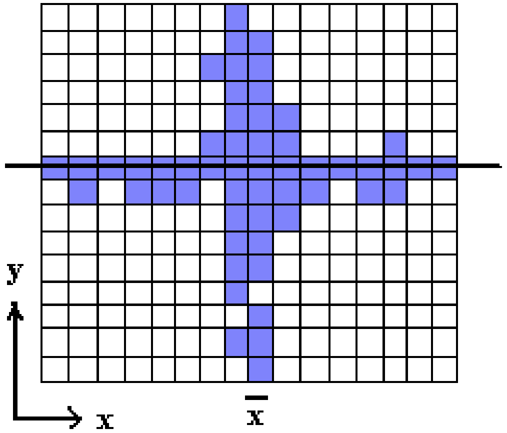
$$p_B(y) = p_A(y + a_2)$$

$$v_x + p_B(x) = p_A(x + a_1)a_3 + a_5$$

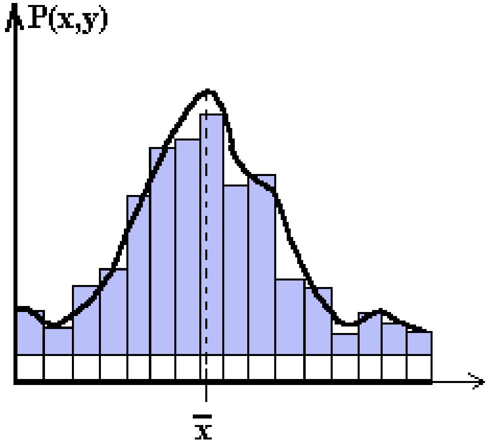
$$v_y + p_B(y) = p_A(y + a_2)a_4 + a_6$$

$$v_x + p_B(x) = p_A \cdot a_3(x) + p'_A \cdot a_3 a_1(x) + a_5$$

$$v_y + p_B(y) = p_A \cdot a_4(y) + p'_A \cdot a_4 a_2(y) + a_6$$



a detail of displayed cross
(for example fiducial mark)



its probable centre

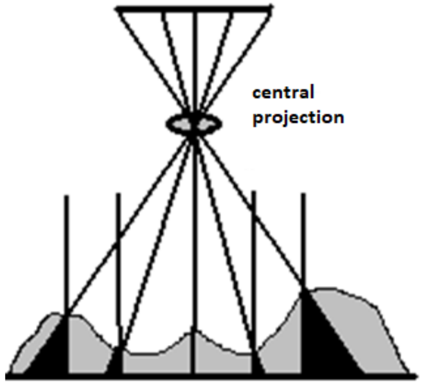
digital photogrammetry

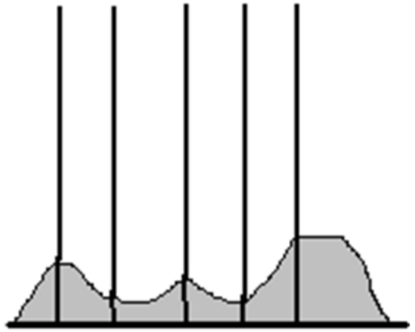
Digital orthophoto

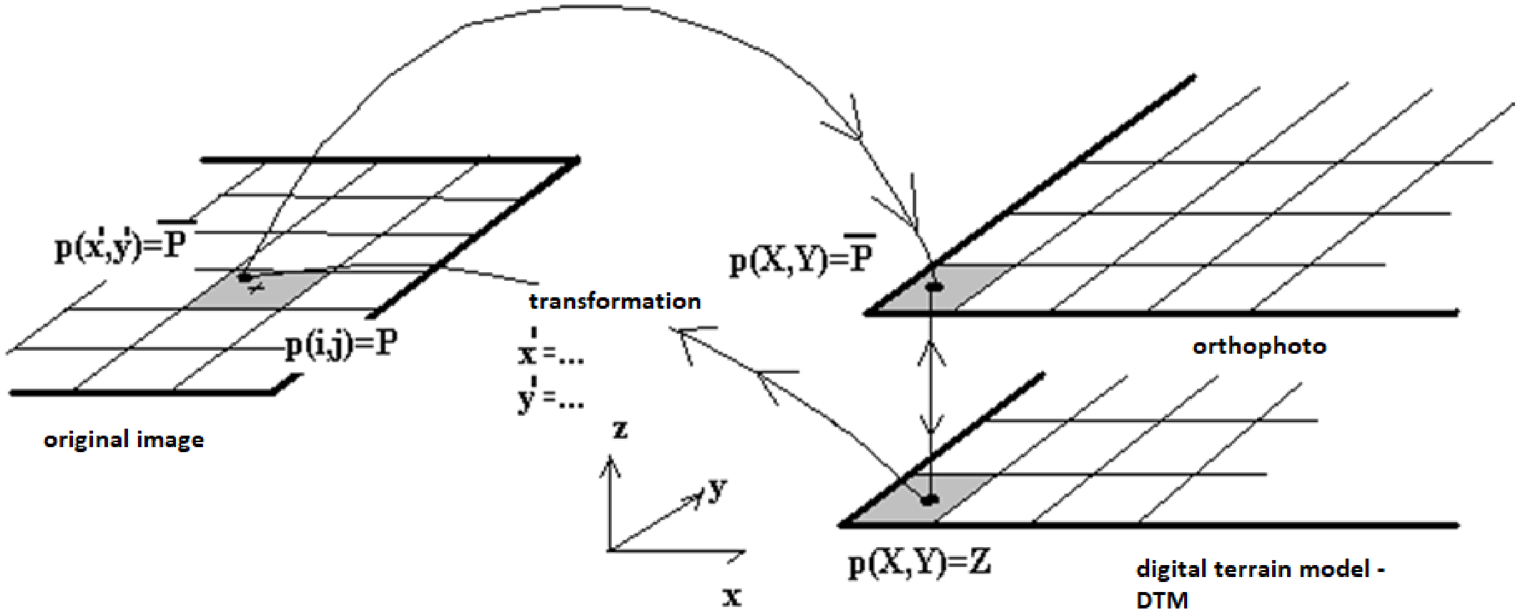
What is necessary for an orthophoto creating?
-images,
-known interior and exterior orientation,
-digital terrain model (DRM, DEM or DSM),
-software

$$x' = x_0' - f\,\frac{r_{11}(X - X_0) + r_{21}(Y - Y_0) + r_{31}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$

$$y' = y_0' - f\,\frac{r_{12}(X - X_0) + r_{22}(Y - Y_0) + r_{32}(Z - Z_0)}{r_{13}(X - X_0) + r_{23}(Y - Y_0) + r_{33}(Z - Z_0)}$$





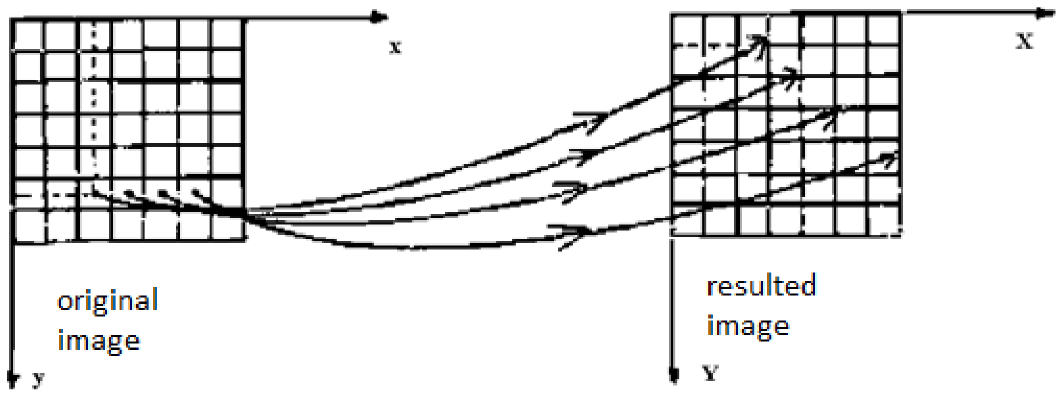


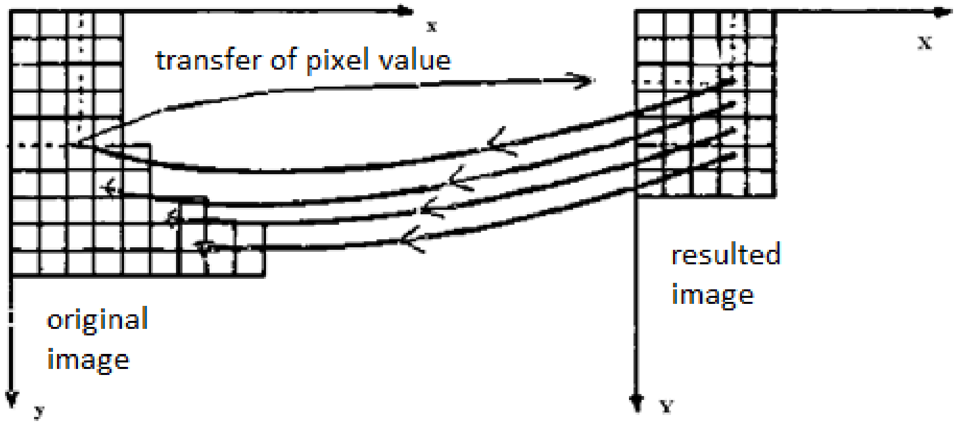
Geometric transformation

The aim of geometric transformation is either to remove image distortion caused by the instability of geometric conditions during measurement and to convert the data into a suitable projection (especially in DPZ) or to create a new image (e.g. orthophoto) based on transformation relations. Geometric correction can be performed in three different ways:

- ***data transformation based on precisely known carrier trajectory parameters***
- ***direct geometric transformation based on embedding points or vectors***

- ***direct geometric transformation based on embedding points or vectors***





- data transfer from the original image matrix to the corrected matrix

  Nearest Neighbour Method
- ***Bilinear transformation***
- ***Bicubic Convolution***

End of photogrammetry

3D scanning

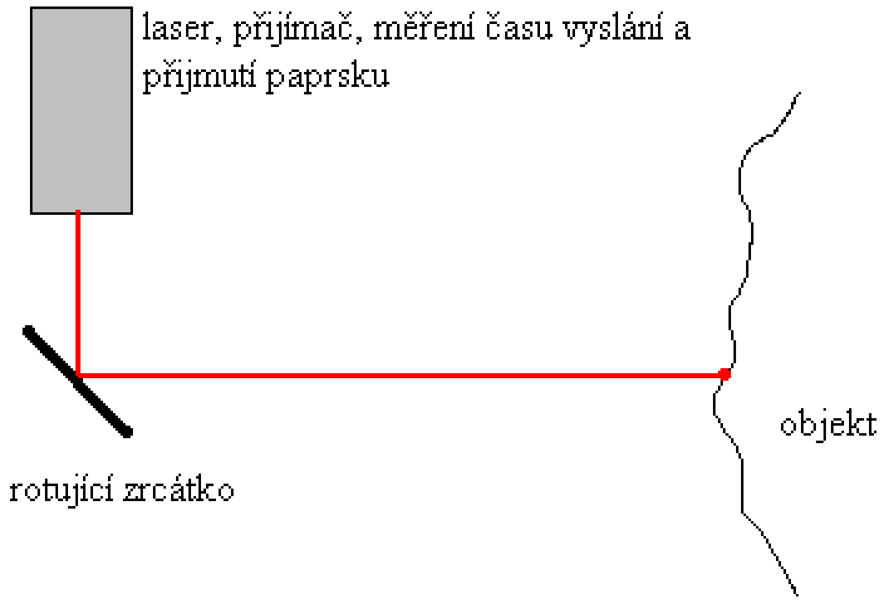
- Direct 3D detailed point coordinate technology
- 1)terrestrial scanning (laser scanners, triangulation scanners, optical correlation systems)-applications in construction or conservation, documentation of technological units
- 2)aerial scanning-applications for photogrammetry and GIS (creation of DTM, DRM, DSM)

The use of 3D scanners and their accuracy

-since about 2000, aerial applications earlier (1995)- Laser scanners (range m to hundreds of m, accuracy 4-8mm
-triangulation scanners (range cm to approx. 20 m, accuracy from fractions of mm to mm)
-optical correlation scanners or systems (range cm to approx. 20m, accuracy from fractions of mm to cm)

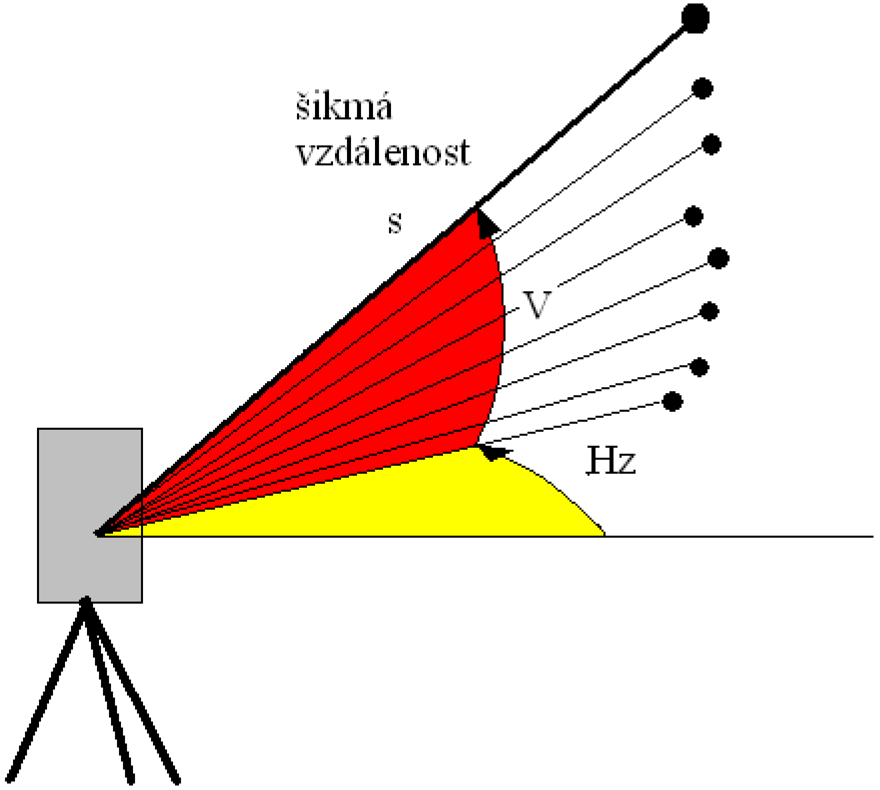
Laser scanning

principle



Laser scanners ToF (time of flight)

Terrestrial laser scanner



Laser scanning (comparing 2002 and 2020

Callidus

Optech

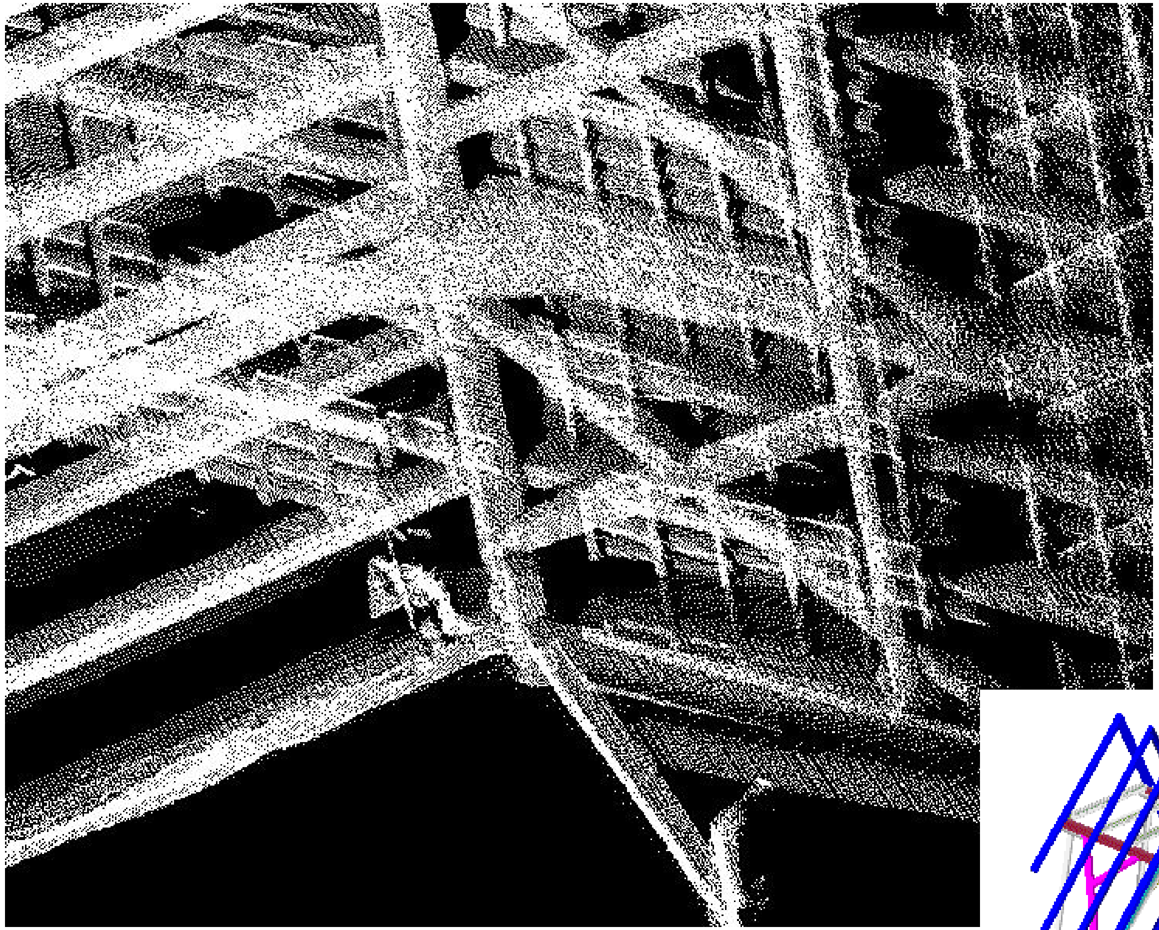
Leica

Trimble

Surphaser

Faro

Laser scanning

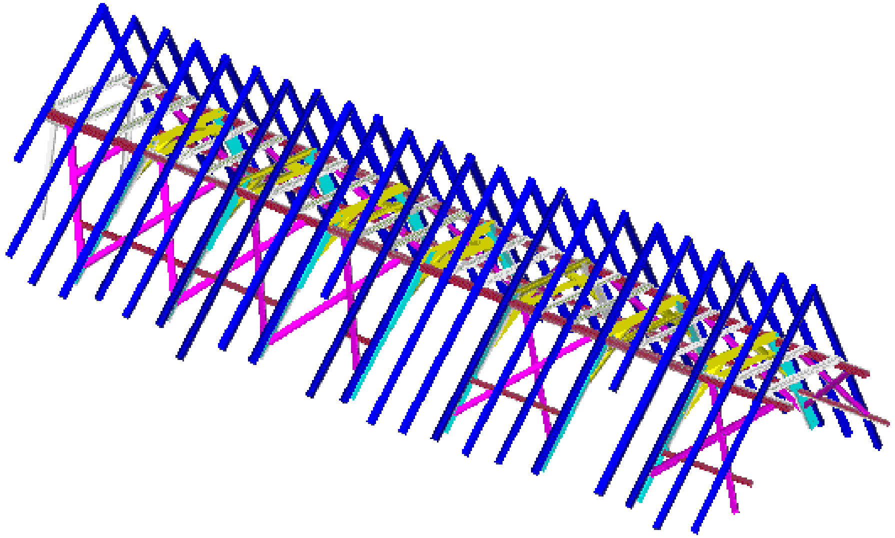


Documentation of the board

- point *cloud*

- *evaluation into the model in AUTOCAD*

- *Callidus laser scanner, 2004*

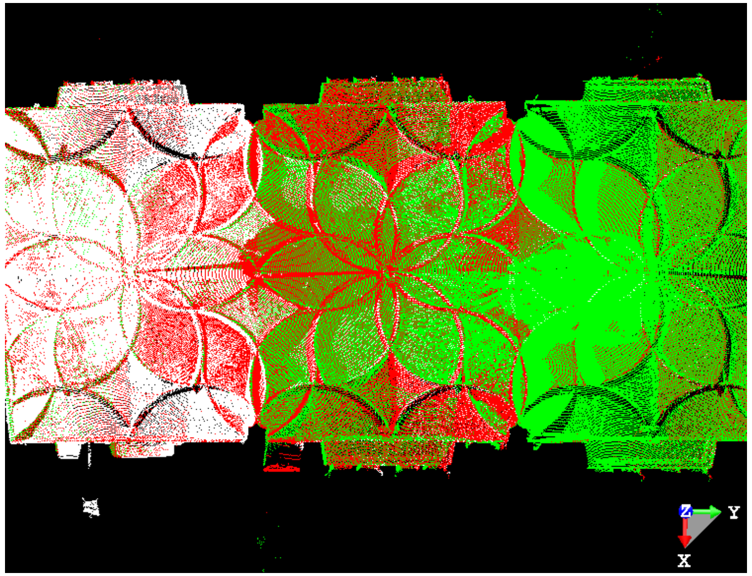


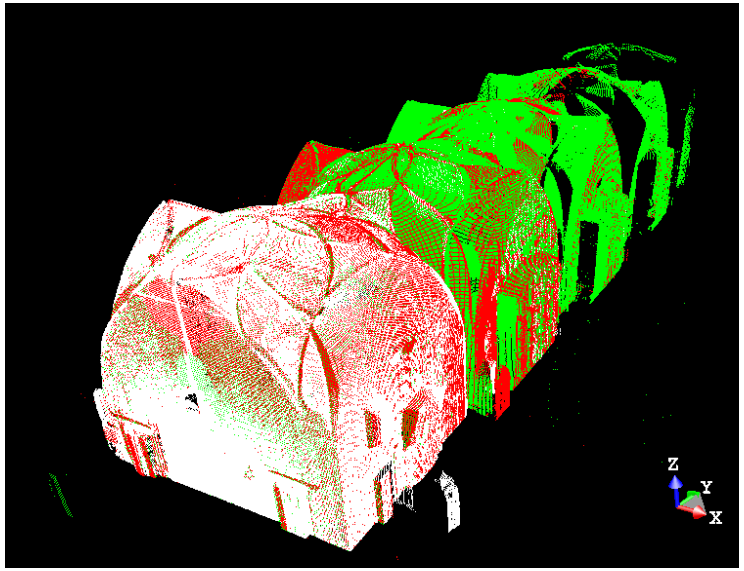
Laser scanning

Documentation of monumental objects

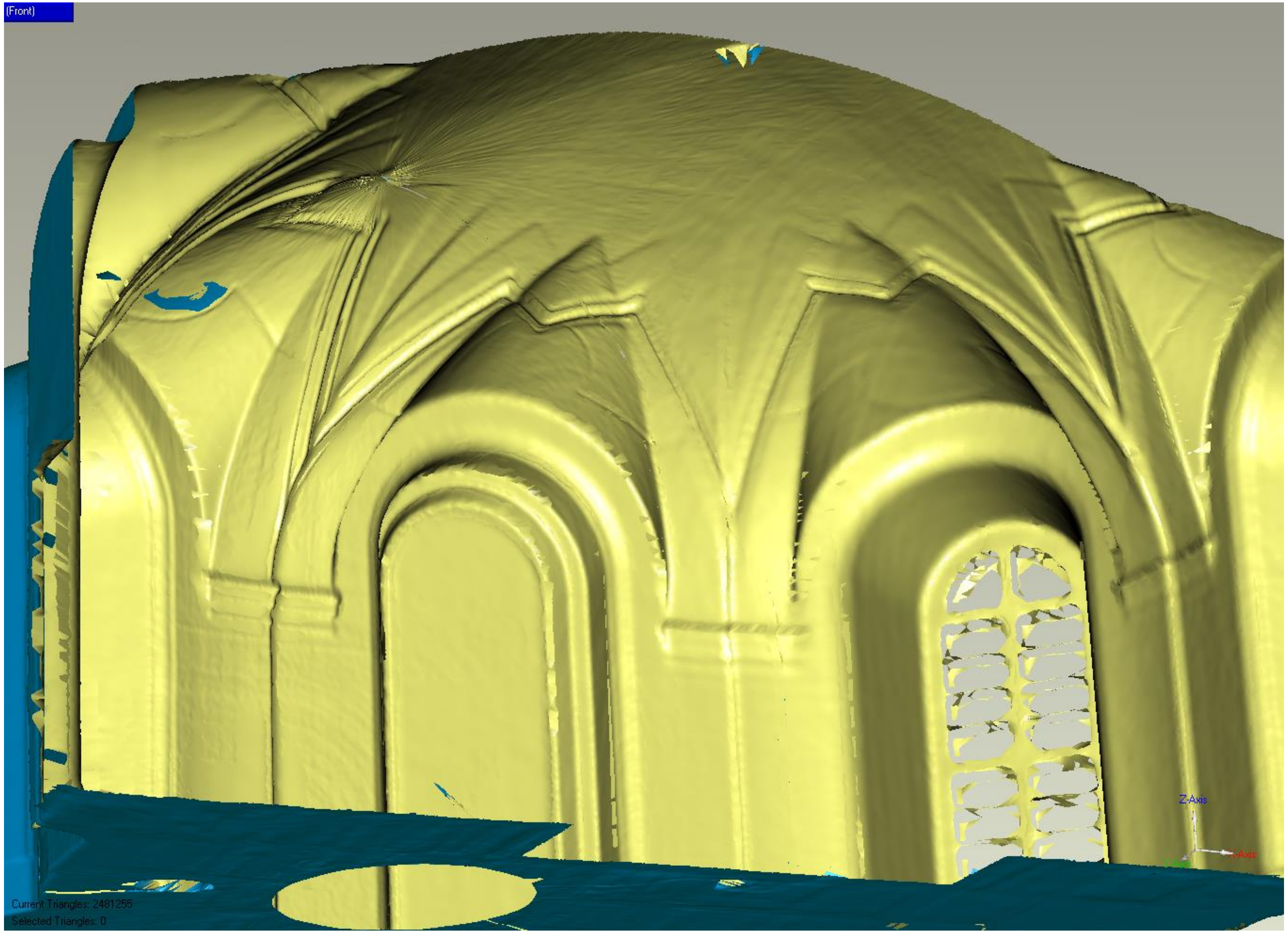
Vladislav Hall, Prague Castle

Callidus laser scanner, 2005

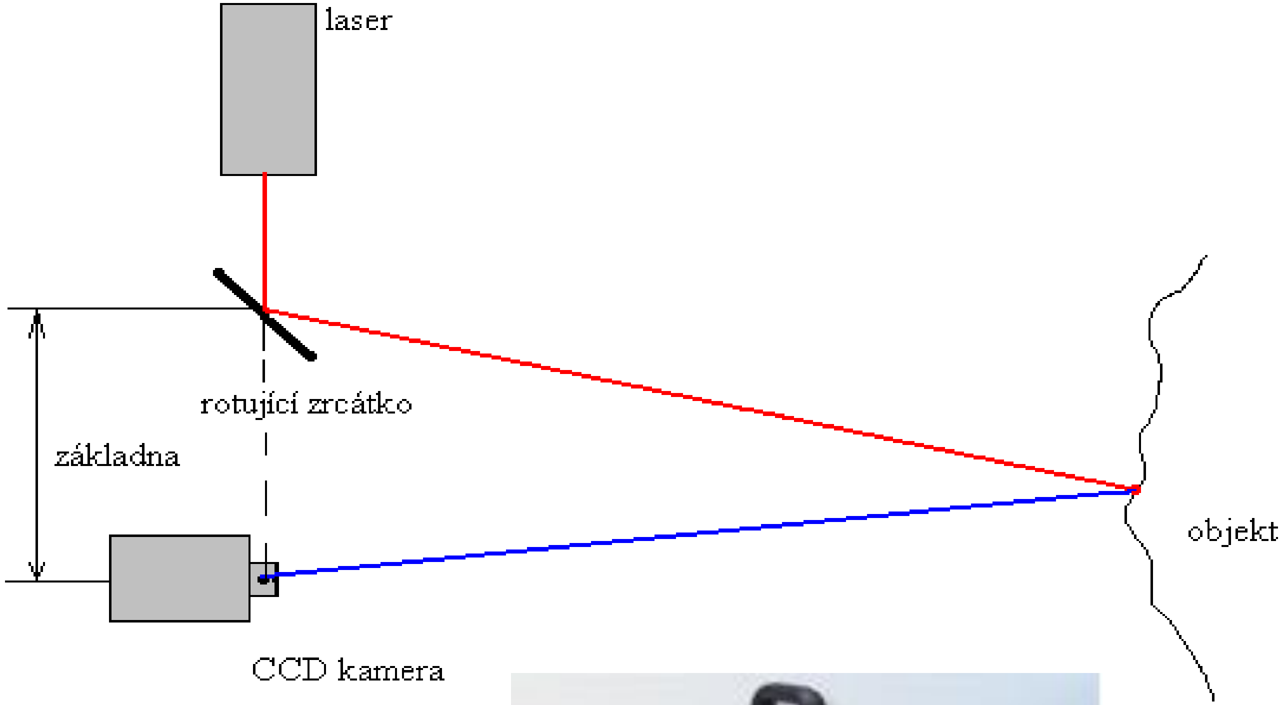


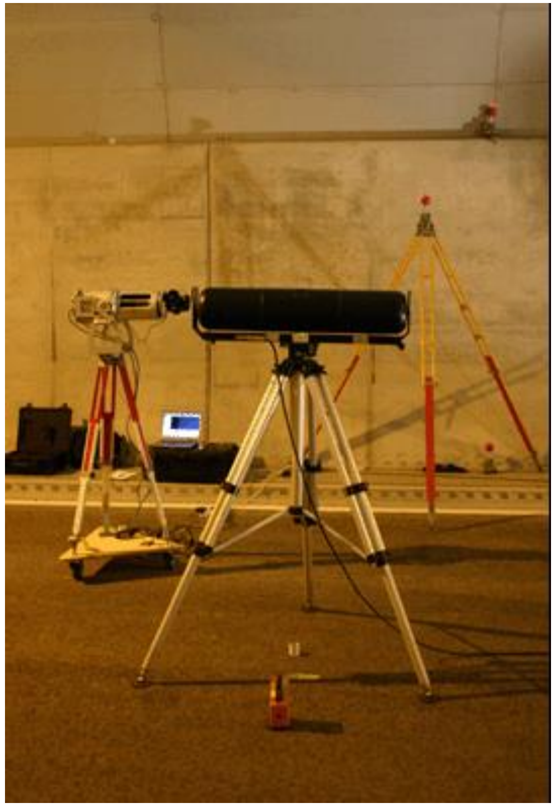


Plasy: laser scanner Callidus, 2006



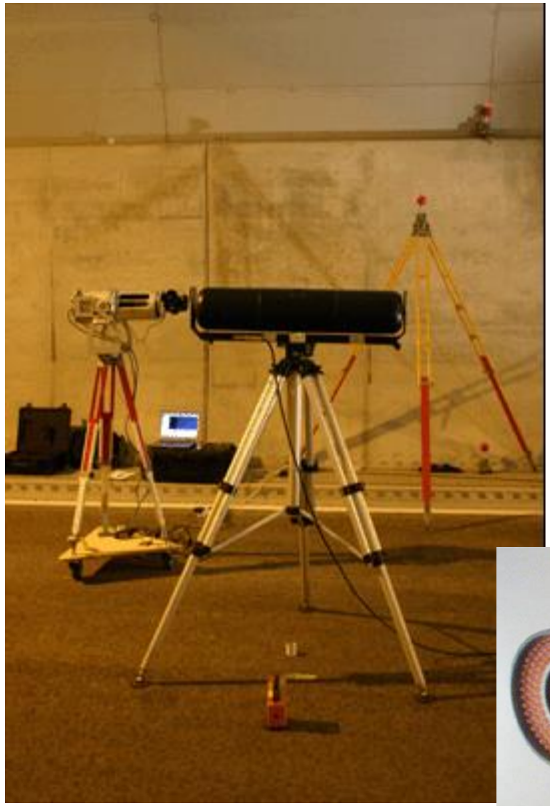
Triangulation principle





Laser scanning

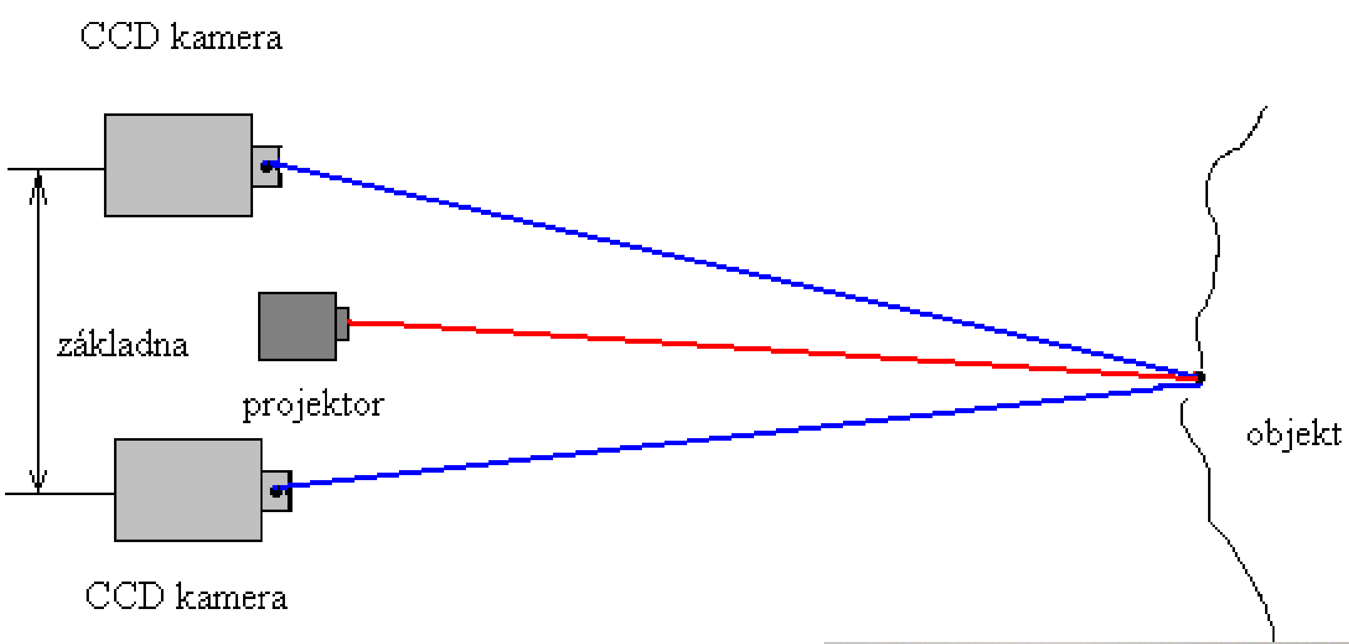
Mensi/Trimble S25



Atos

•Part of the documentation of the Mausoleum of Maximilian I, triangulation scanner Atos II, Mensi S25; scanning time 4 days, 50GB of data (i3mainz, Böhler, http://www.i3mainz.fh-mainz.de/Article240.html)

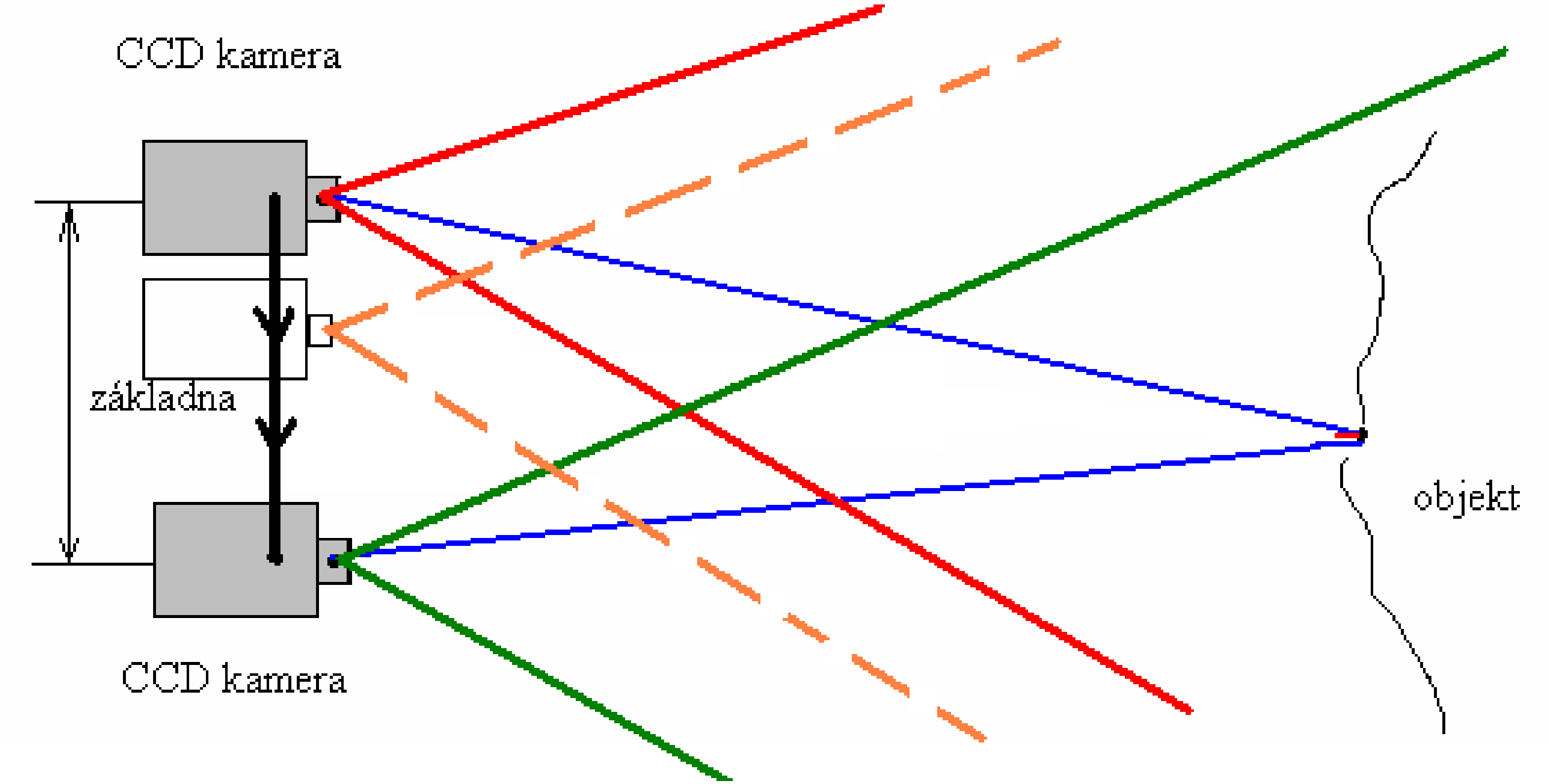
Principle of using two cameras



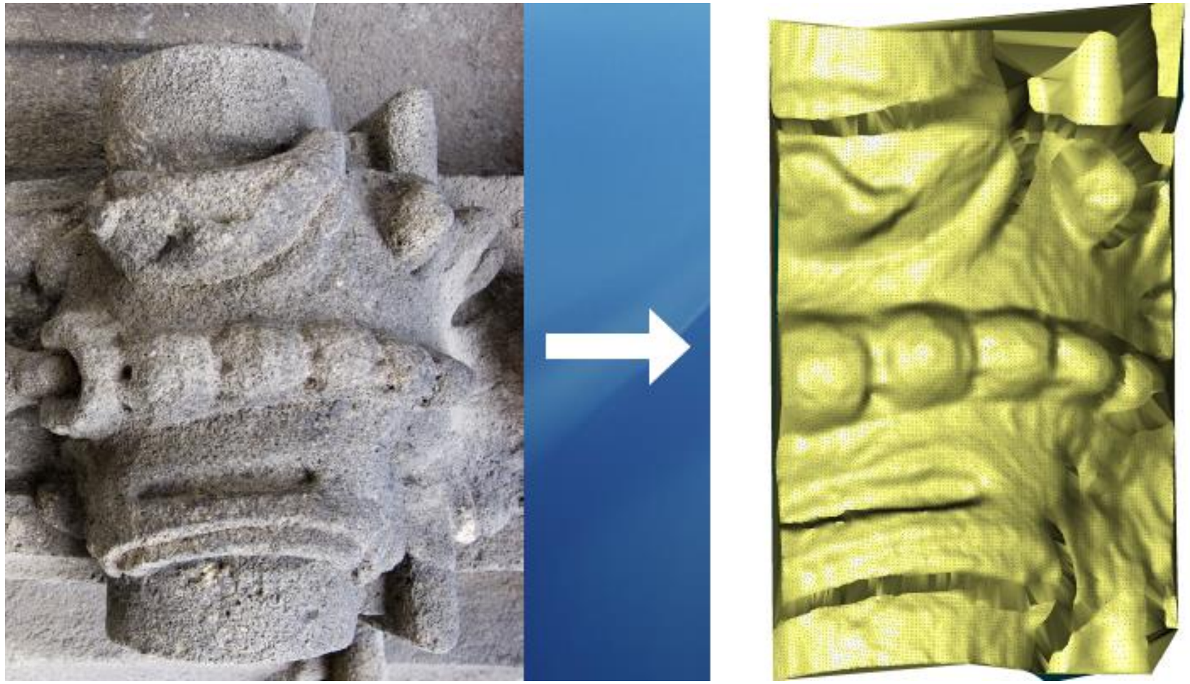
InduSCAN

Scanner Atos

Using of image correlation



scanner OKS, own student scanner, 2011

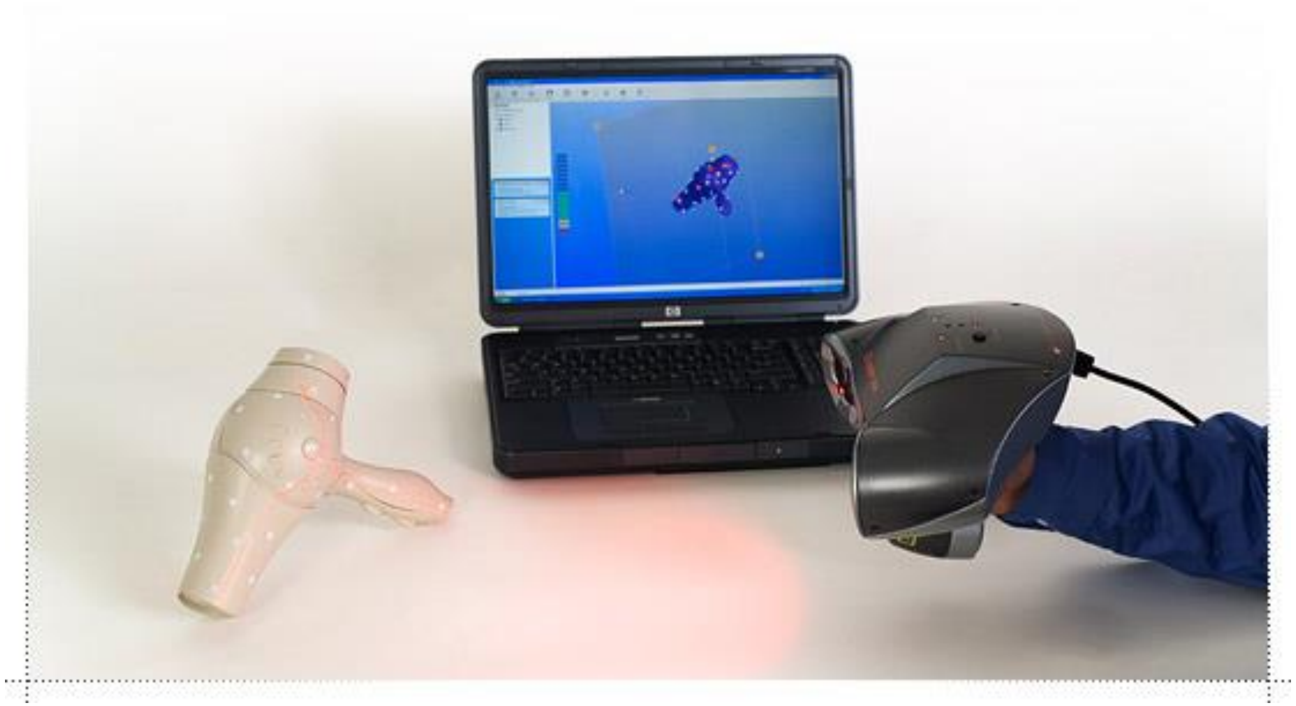


OKS

Hand-held scanners

- *Original and final model*
- *(Zscanner 700 handheld scanner),*
- *Geovap and CTU*

Zscanner 700



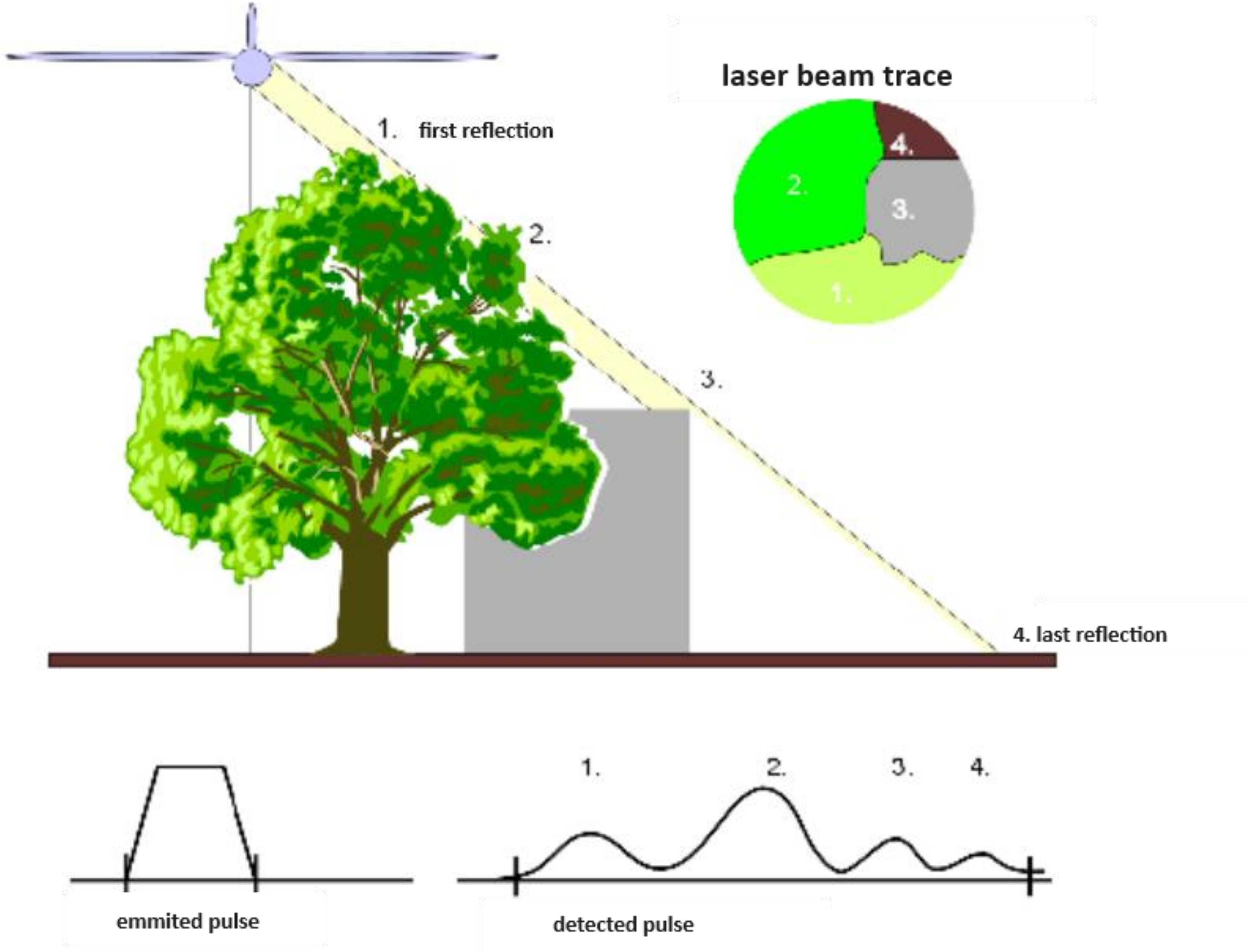
Leica T-ScanTS 50

Technician using, very- high precission

ALS
(airborne laser scanning)

ALS

The principle of laser airborne scanning



ALS Technology - hardware

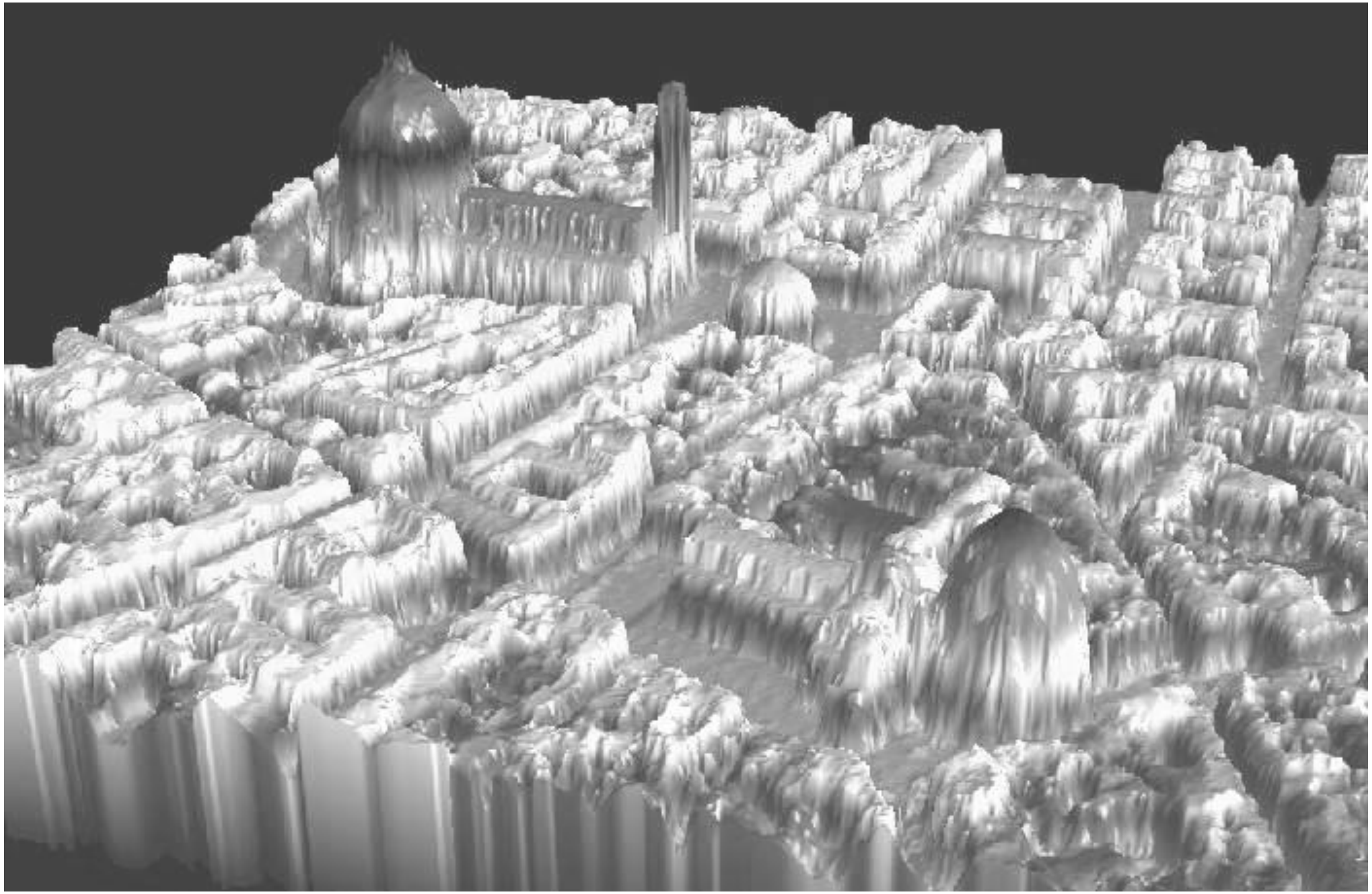
Lidar Falcon III.

Lidar Leica ALS 80

LMS Q56 a date recorder DR-560

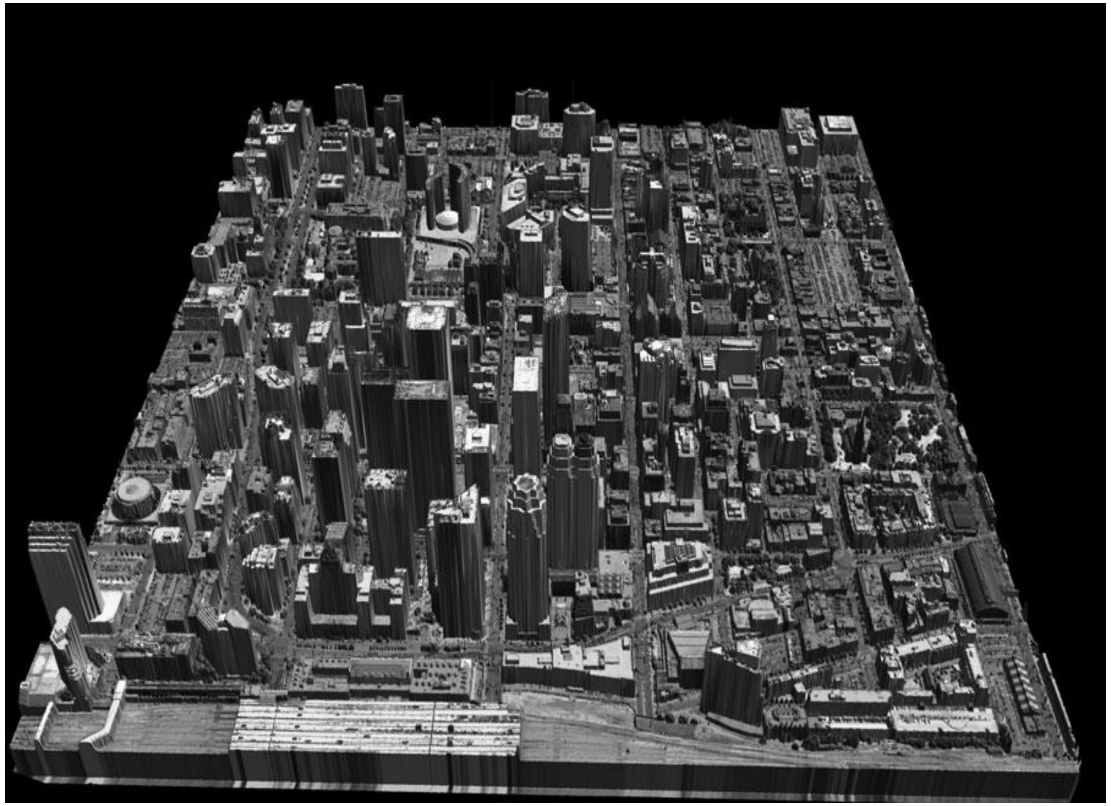
ALTM 3100 (Optech)

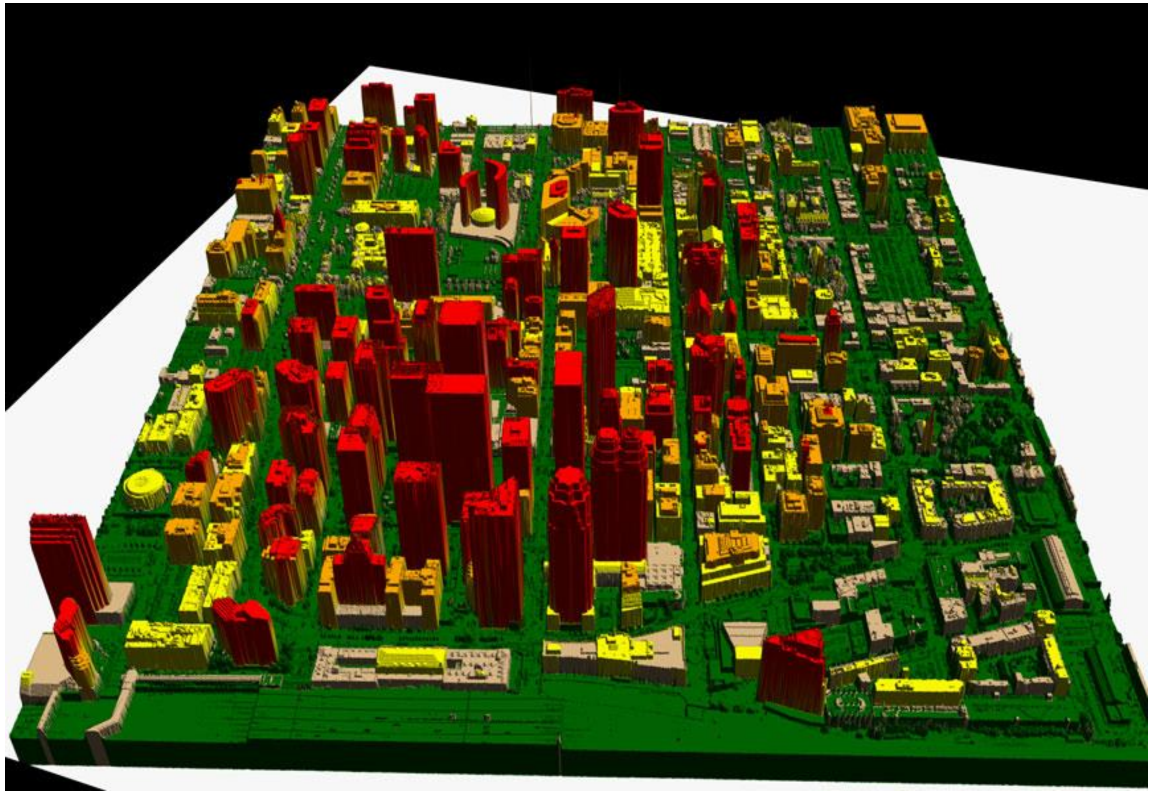
ALS



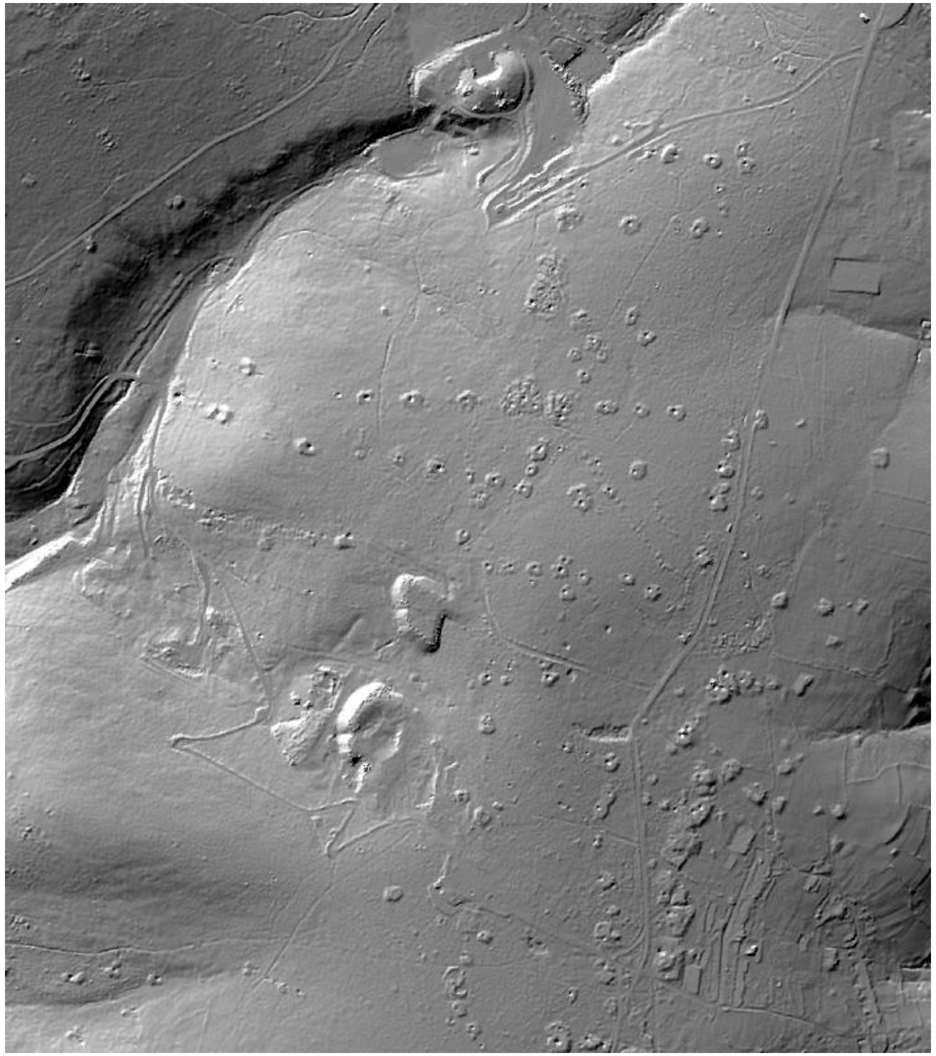
•**Older unfiltered 3D model of the city (1990s)**

Digital surface model and laser "image": ALTM sensor, flight height 850m, area 1400x1300m, measurement time 37min, processing 4h, density (raster) 60x60cm (Optech material, 2008)



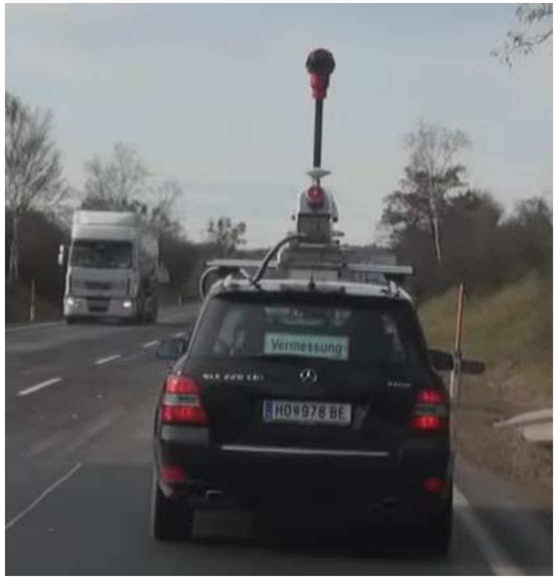


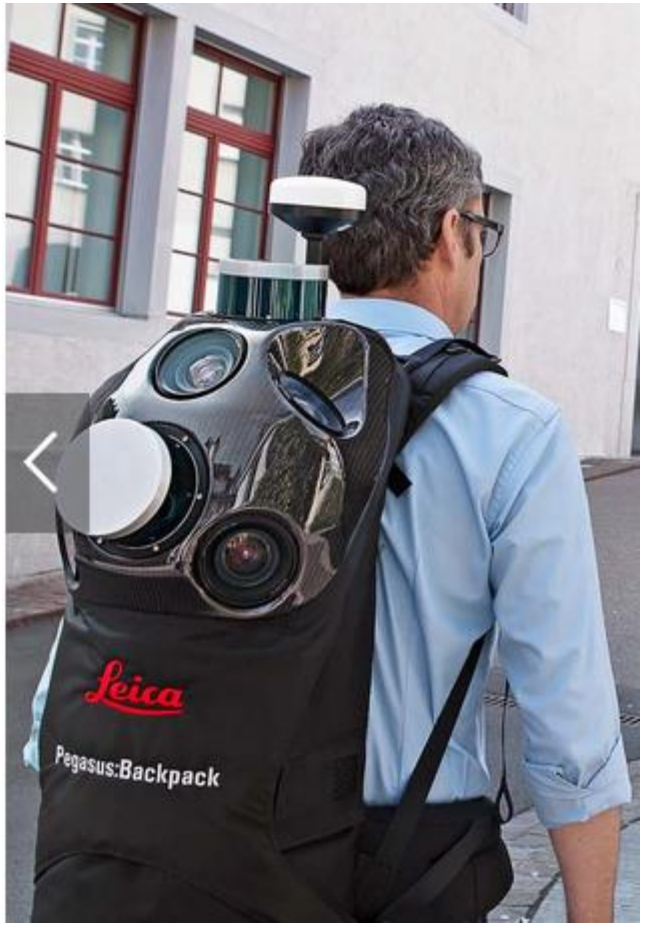
Aerial laser scanning: medieval silver mines and uranium mines
of the last century. 2013.



L410 Turbolet FG (CZ)

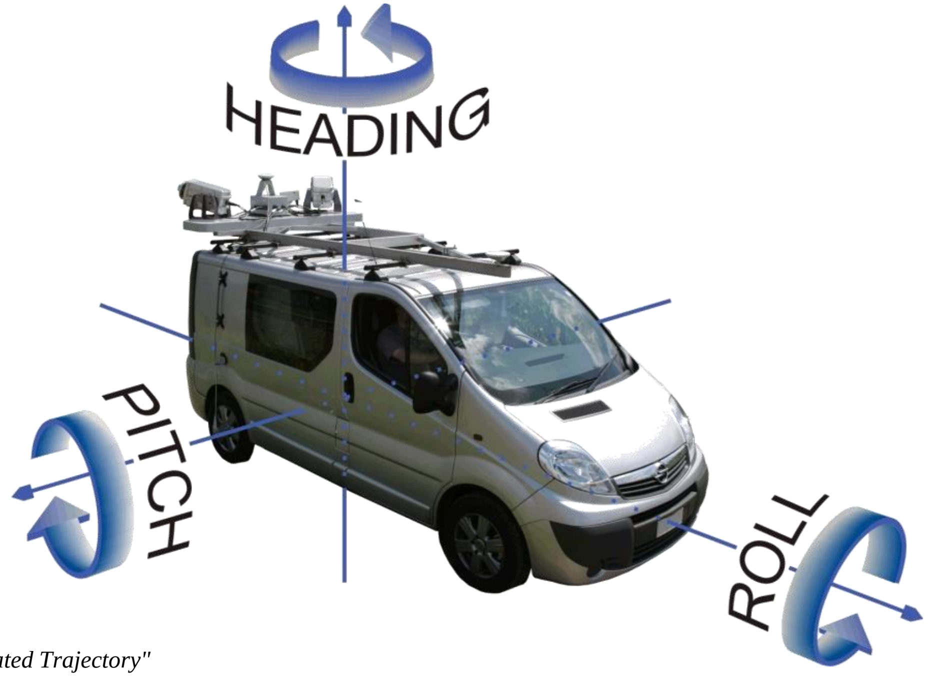
New technologies: mobile mapping devices - carried by a person, in a car or other vehicle.





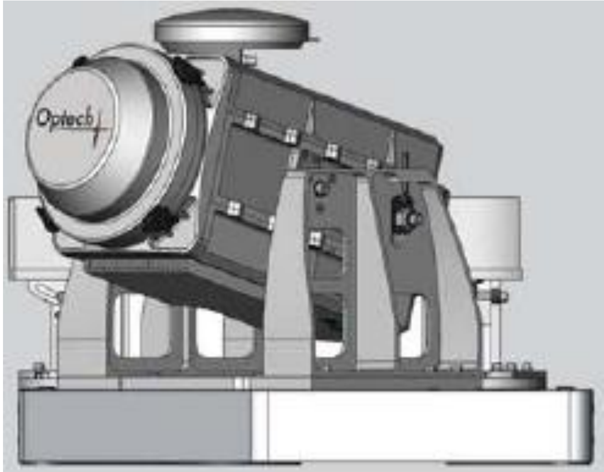
Mobile laser scanning

	with GNSS	1 min without GNSS
X,Y (m)	0.020	0.100
Z (m)	0.050	0.120
Tilts (°)	0.005	0.020
Angular Bending (°)	0.020	0.020



- *SBET "Smoothed Best Estimated Trajectory"*
- *Real-time vehicle trajectory*
- *200* ***records per second***
- ***Vehicle position (x, y, z) + roll and yaw***

- **Applanix POSLV 420**
- 2 GPS receivers
- Trimble Zephyr
- 1 DMI (Distance Measuring Indicator)
- 1 IMU (Inertial Measuring Unit)
- Northrop Grumman LN-200
- 3 gyroscopes
- 3 accelerometers



Mobile laser scanning

•*Sample data - absolute accuracy of points +/- **5** cm (Geovap Pardubice)*

•*LYNX system - laser head*

•LYNX scanner heads

•360° coverage

•Rotation speed: 9000 rpm

•Output: 200,000 pulses/sec

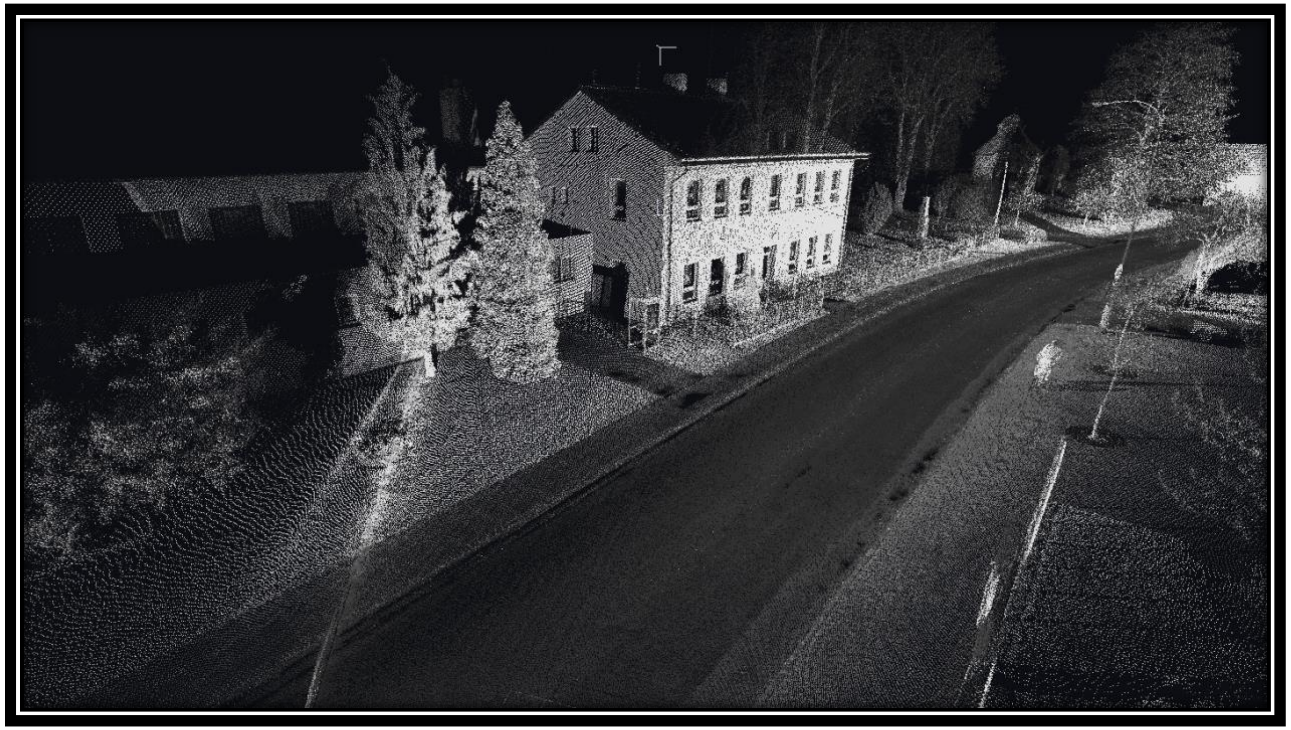
•Measuring up to 4 reflections/pulse

•Class 1 laser radiation safety

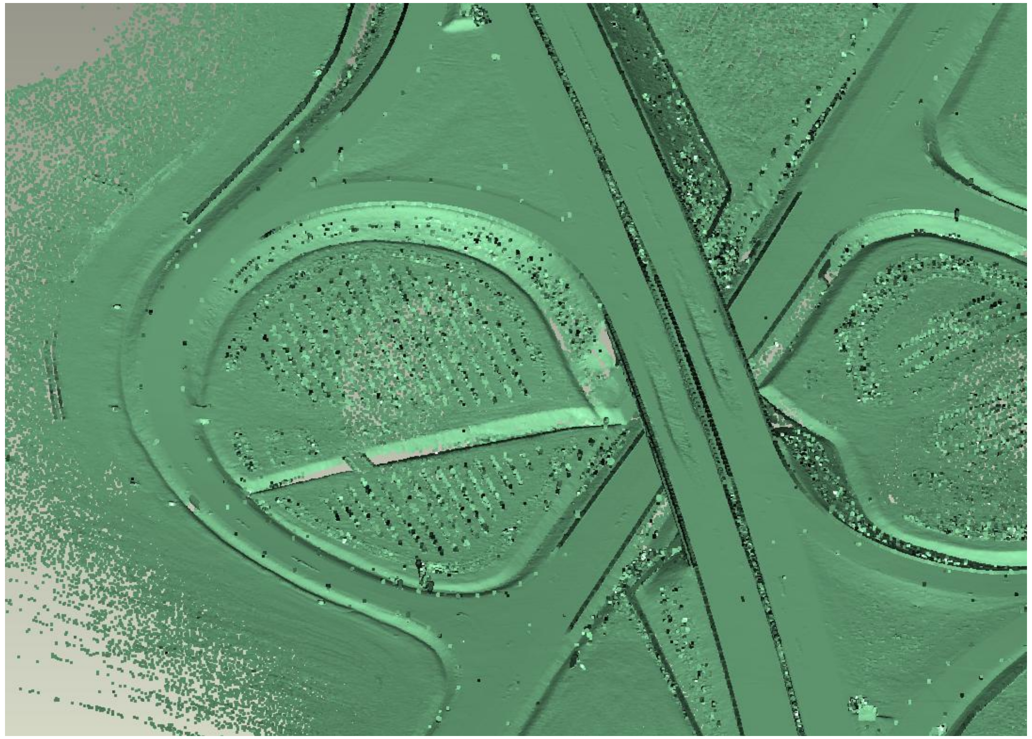
•Invisible beam

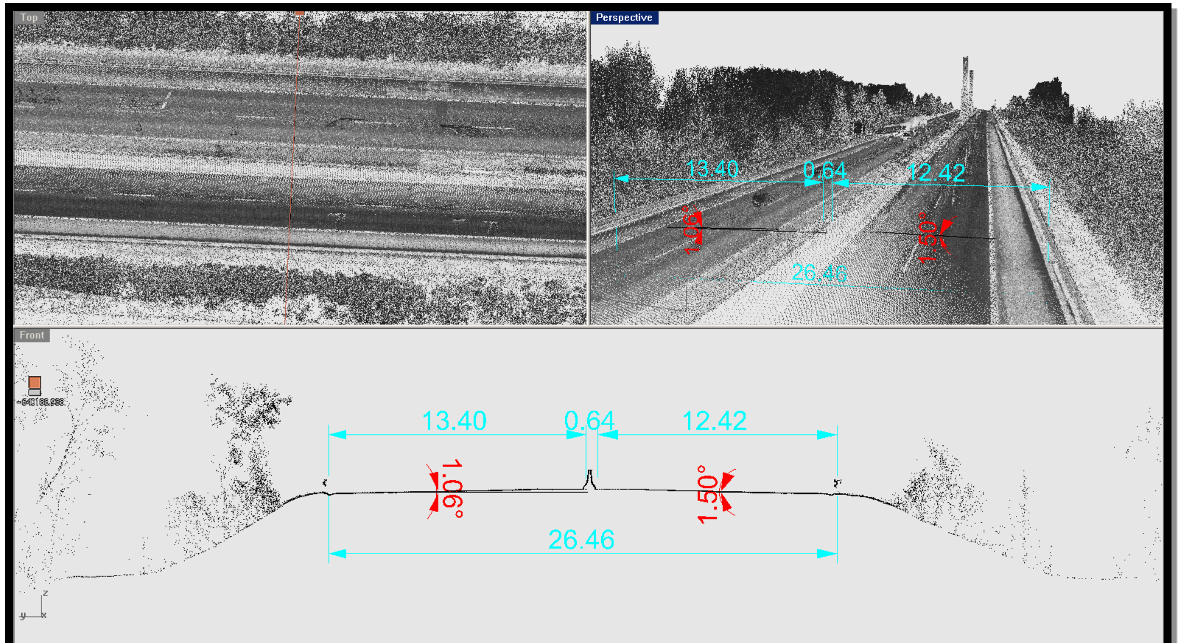
•Range up to 200 m

•>> targeting a 400 m wide swath



Mobile laser scanning





- *Easy and fast use of measured data - no need for new types of software*

.

PLS: mobile - personal - handheld - laser scanner

•*Designed mainly for data conversion to BIM, hand carried, no GNSS,*

•*SLAM technology is used for orientation in confined spaces*

Geoslam go

Daro Orbis

End of laser scanning