Time-stamped and free photons – 3D optical remote sensing

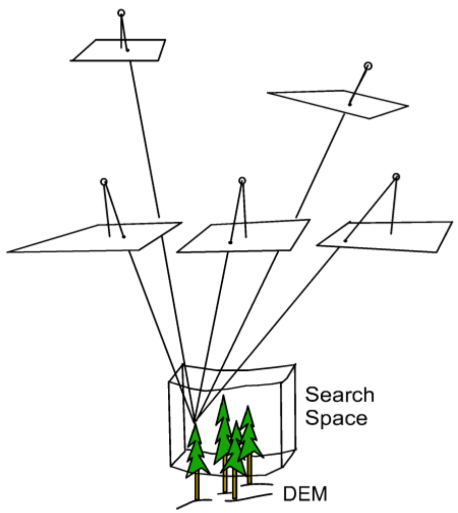
I: 3D geometry and sensor models – from the world to pixel/photon detector

II: 3D geometry, from pixels to the world

III: Radiometry of passive imaging

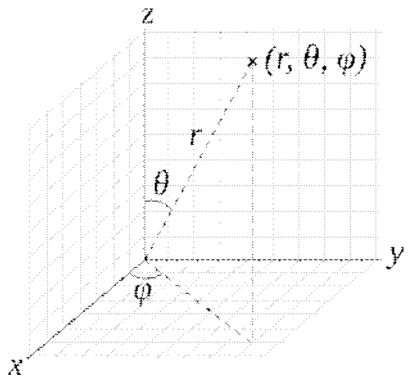
IV: Functioning of a LiDAR sensor – 3D geometry and radiometry

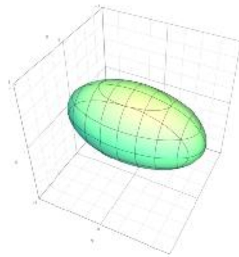
RS101, 2016
Ilkka Korpela
Academy Research Fellow, UH, Dept Forest Sciences



I: 3D geometry and sensor models – From the world to pixel/photon detector

Objectives include gaining basic understanding (awareness) in

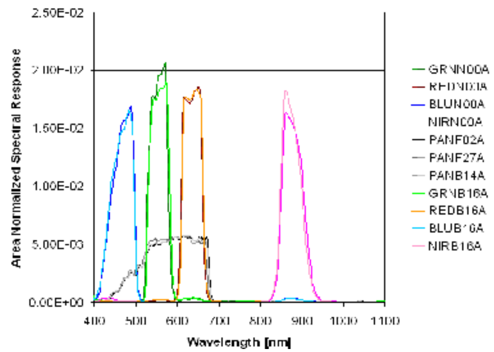




* How 3D measurements are made with light using

- passive &
- active light sources

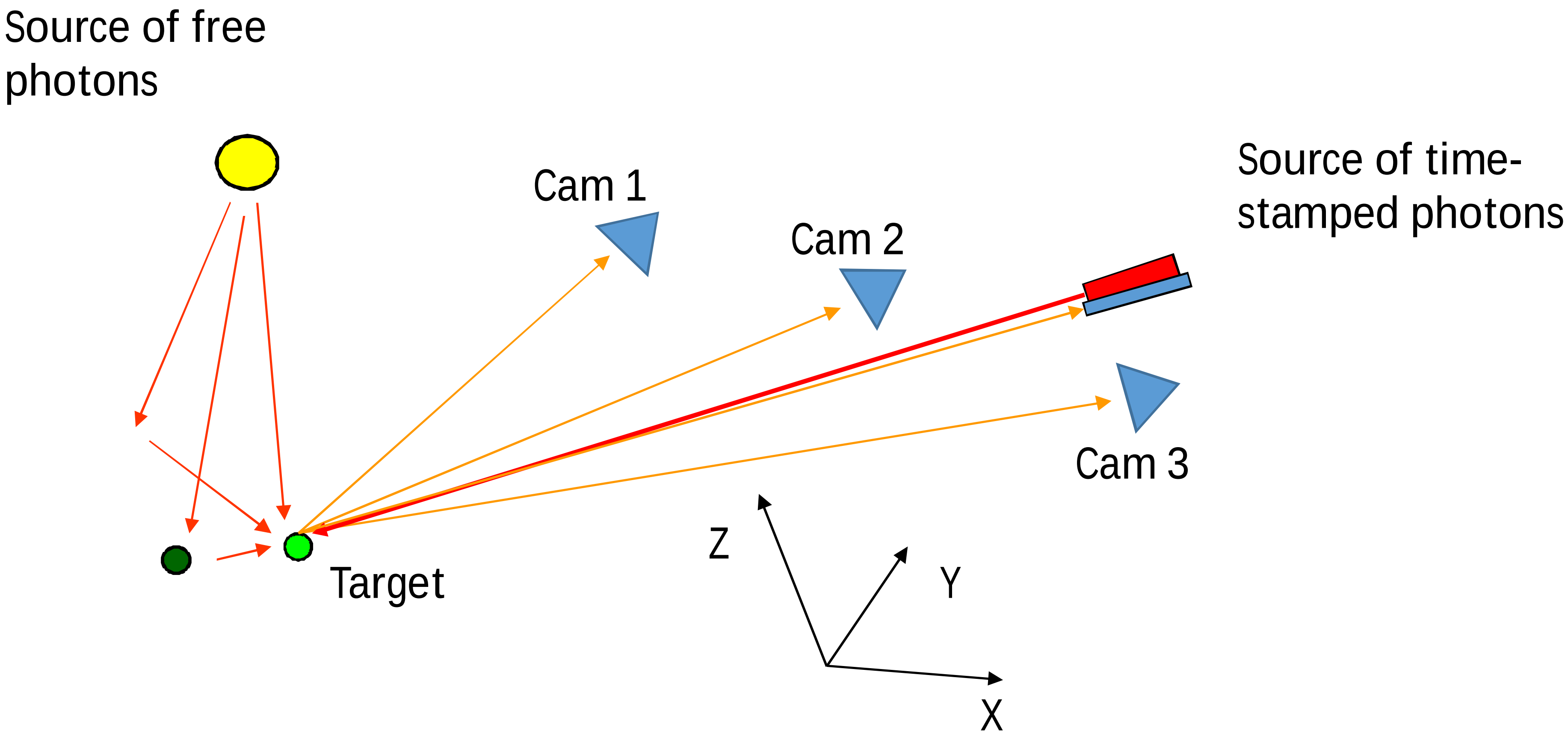
* How the 3D measurements are influenced by sensor, imaging and scene properties and how to derive error estimates



* The radiometry of frame and line-cameras, the main factors influencing the pixel DN-values

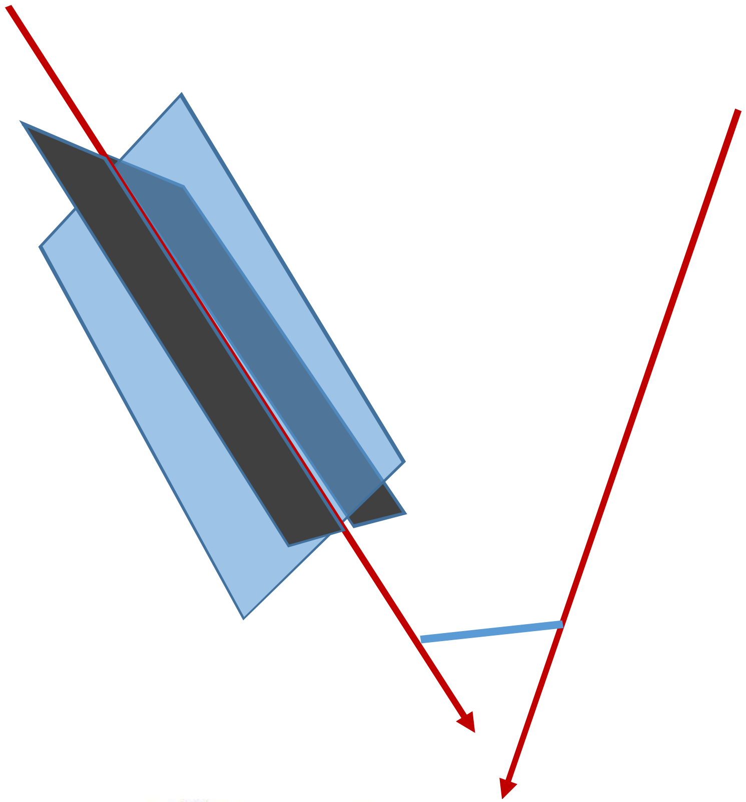
* The intertwined nature of radiometry and geometry in LiDAR sensors

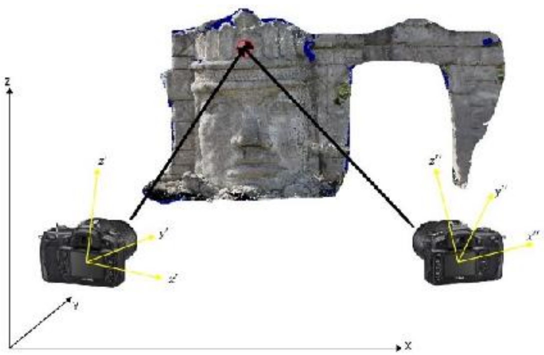
Photogrammetry is about using light to measure coordinates

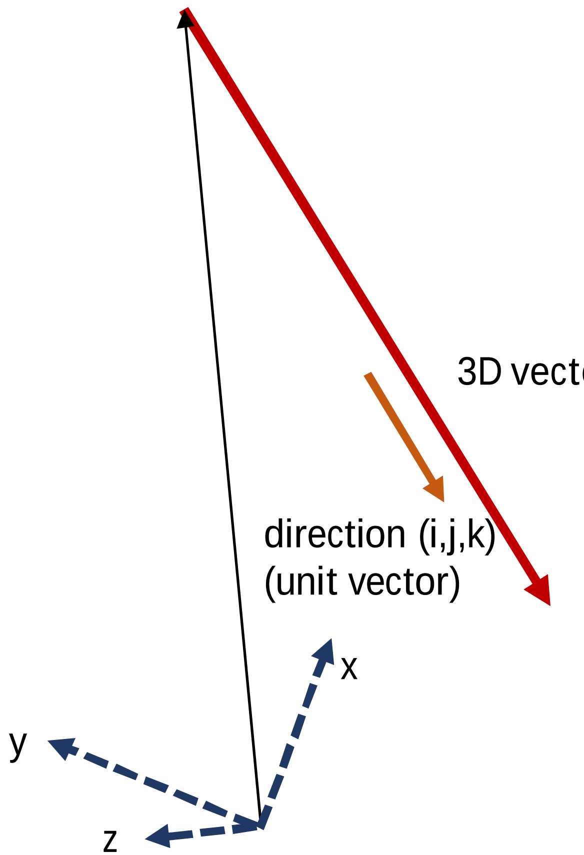


"*It is all about 3D light rays*" and
"*How accurately can we define their path/intersection and/or length*"

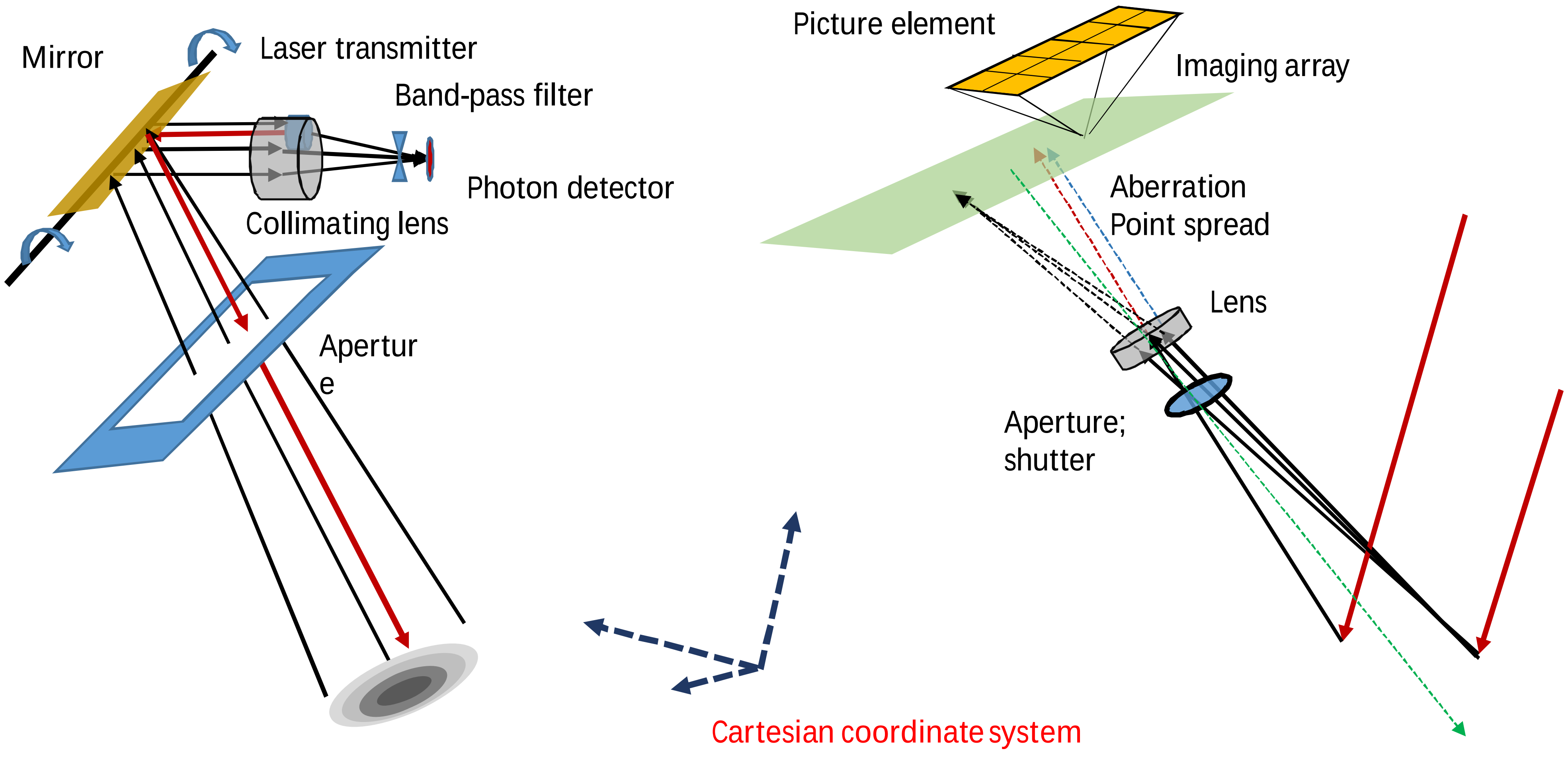
Straight, collinear lines. Spherical observations or spatial intersection

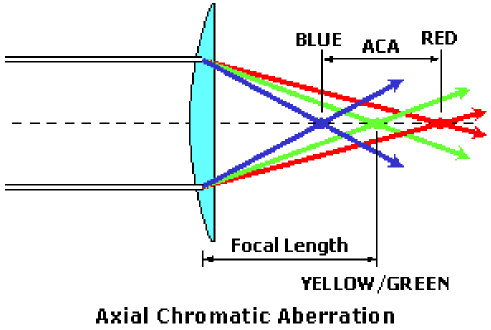


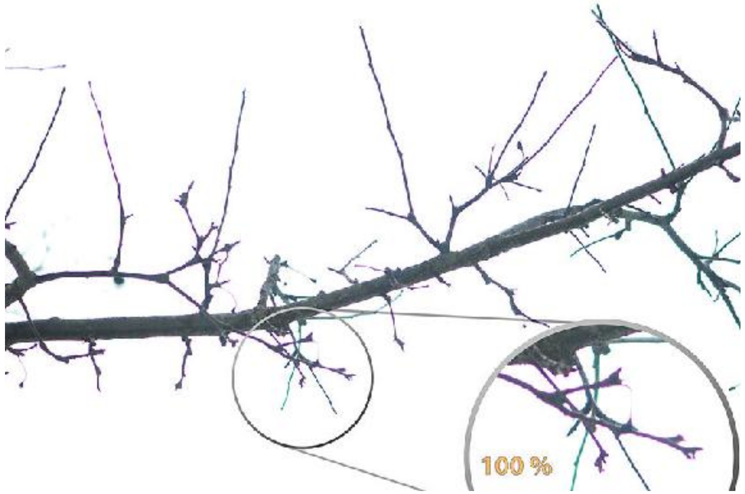




3D geometry and sensor models – From the world to pixel/photon detector



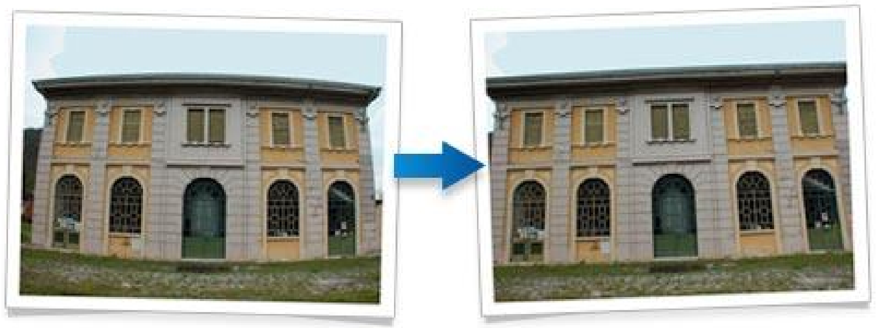




Assumption on collinearity

(straight 3D lines or image rays thru a single principal point in the lens) in a real camera is never realized

- chromatic aberration
- lens distortions



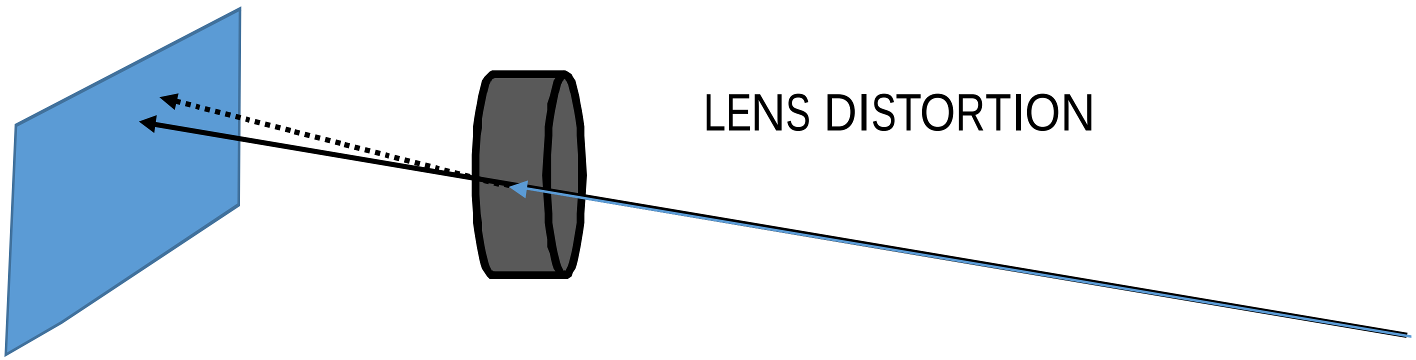
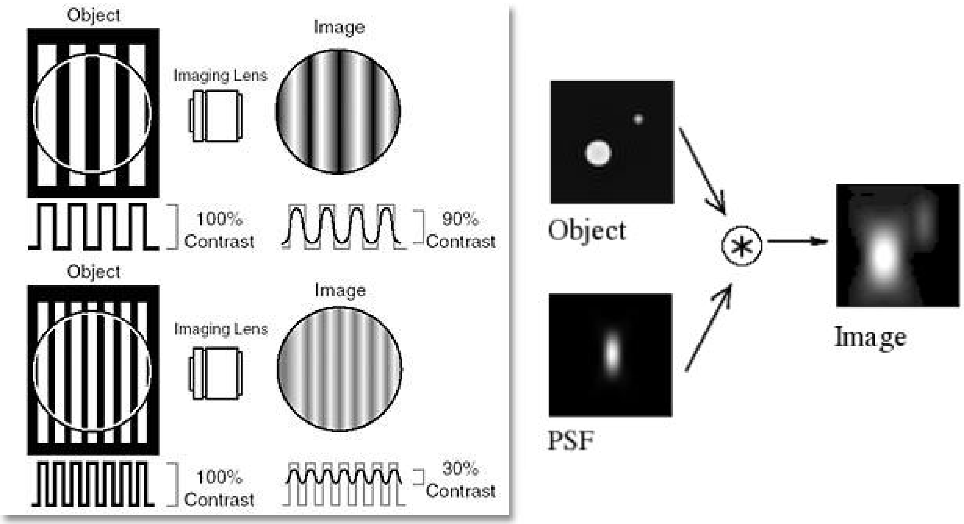
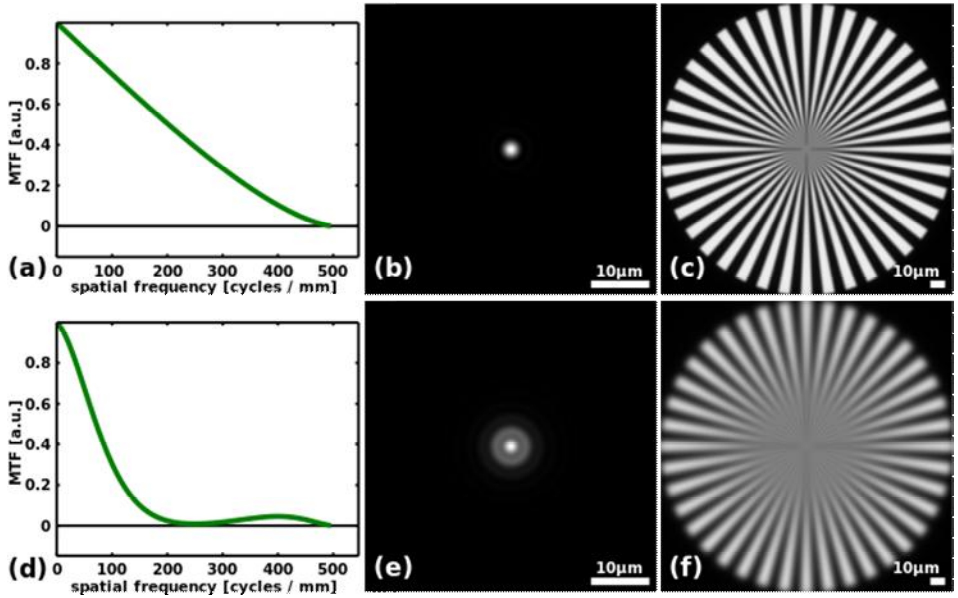


Image sharpness - Measuring the other end of the “3D target-sensor image ray”

Optical resolution

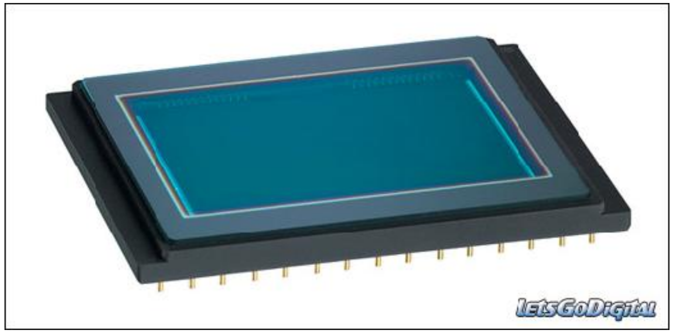
- Best at image center
- Depends on contrast (defined for a contrast ratio)
- Pixel views the world ‘thru a Gaussian lens’
- Decreasing the pixel size not necessarily always improves





Hasselblad H4D-50 images from 750 m. RGB Bayer-filter.
August 2015, May 28 2013, November 2011.

Instantaneous field of view – “pixel”



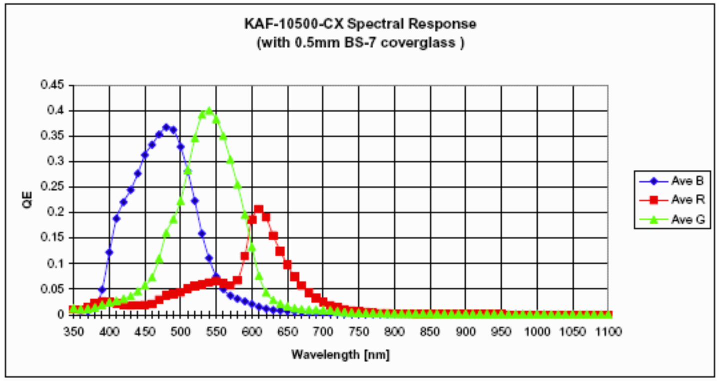
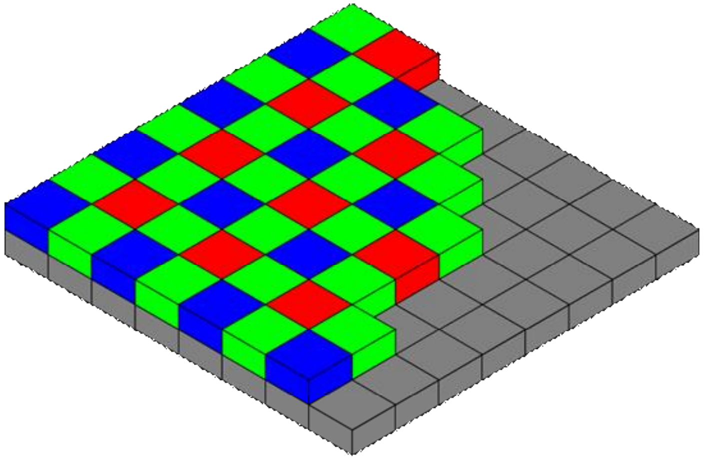
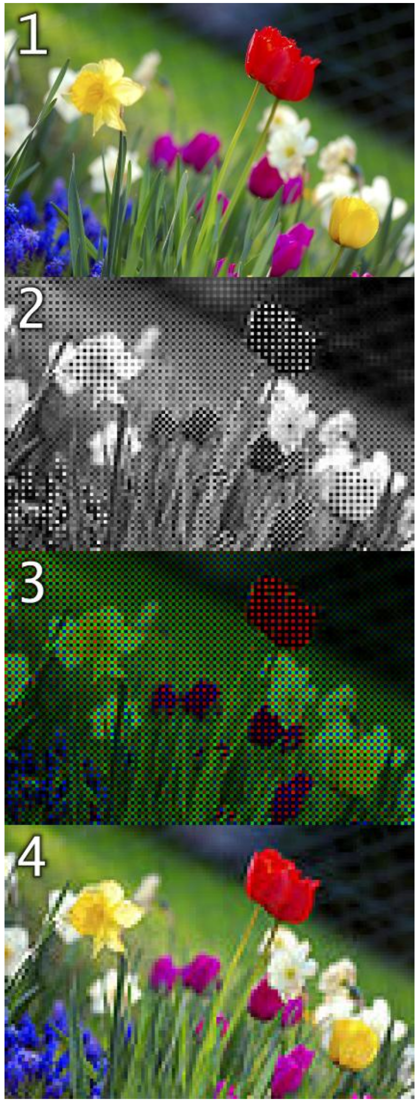
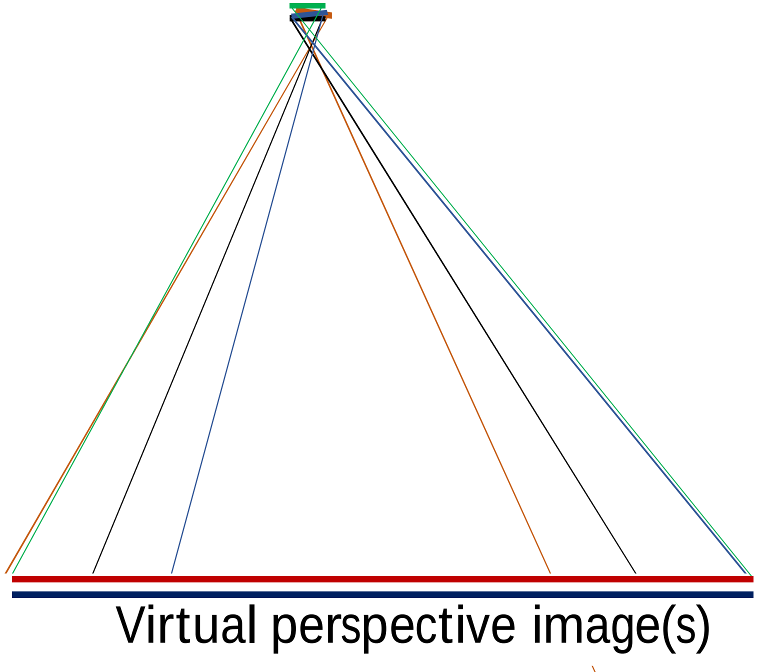


Figure 5: Typical Spectral Response with coverglass

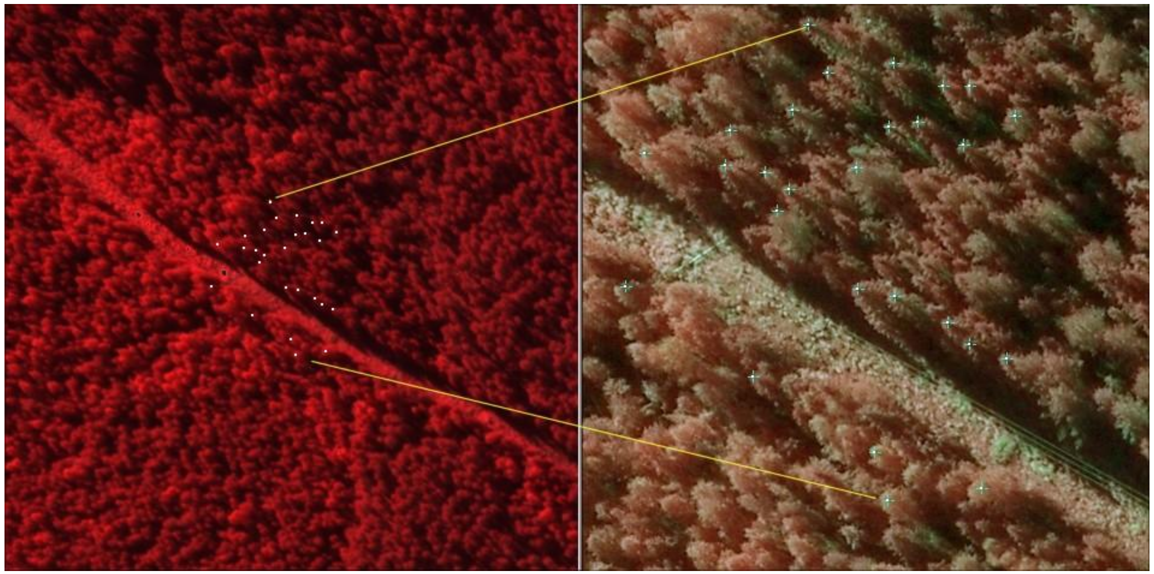






R,G,NIR

R,G,NIR + PAN

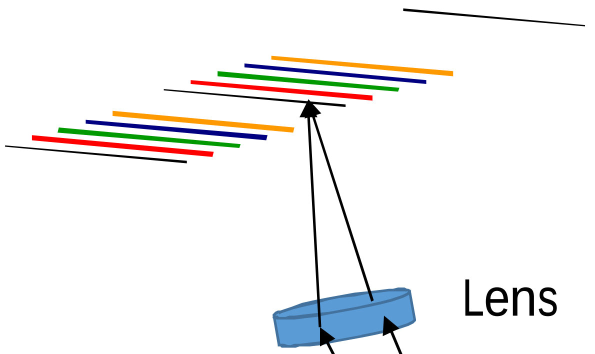


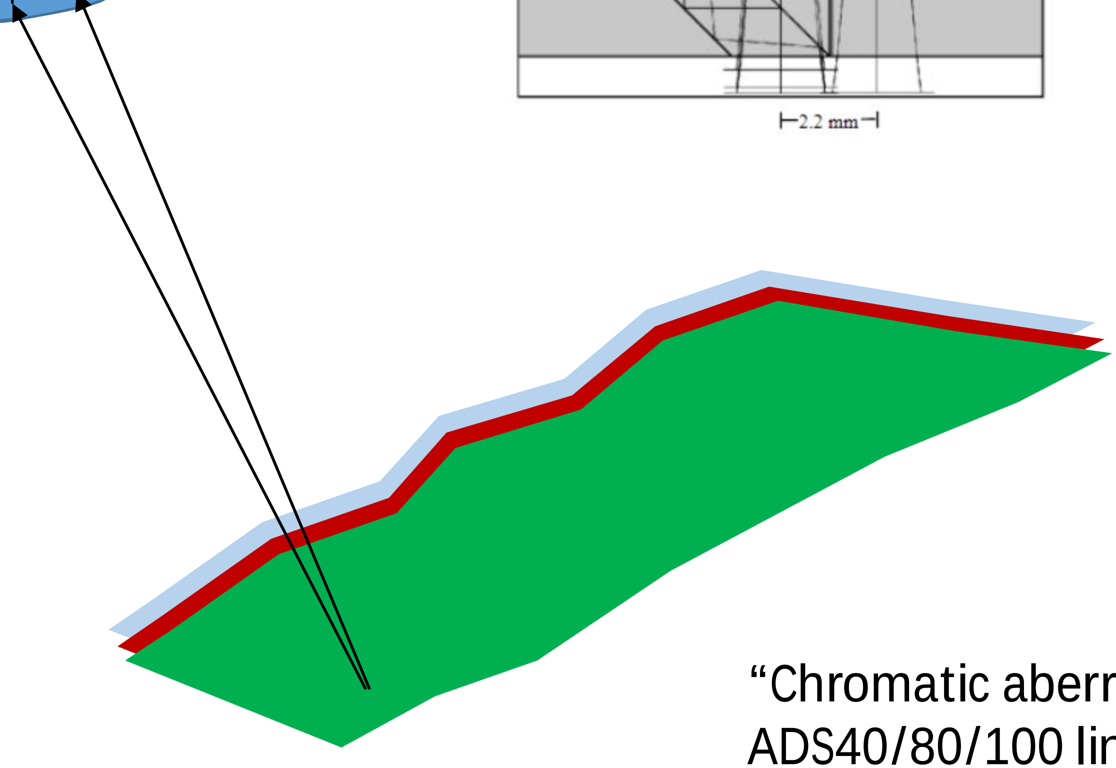
UltraCAM-D sensor

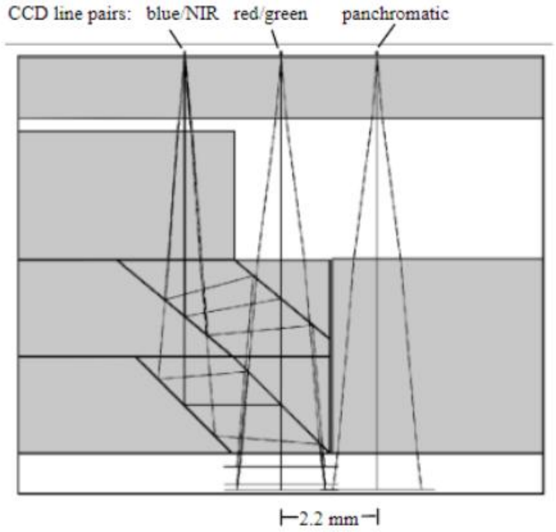
Four lenses (cameras) for high-resolution PANchromatic image. Four cameras for low-resolution R,G,B,NIR images.

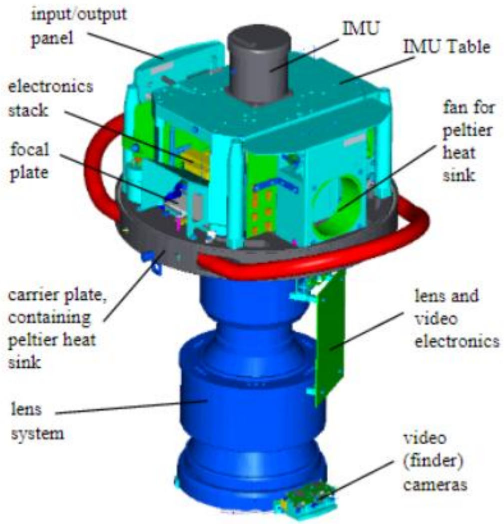
PAN-sharpening.

Focal plane with CCD line arrays



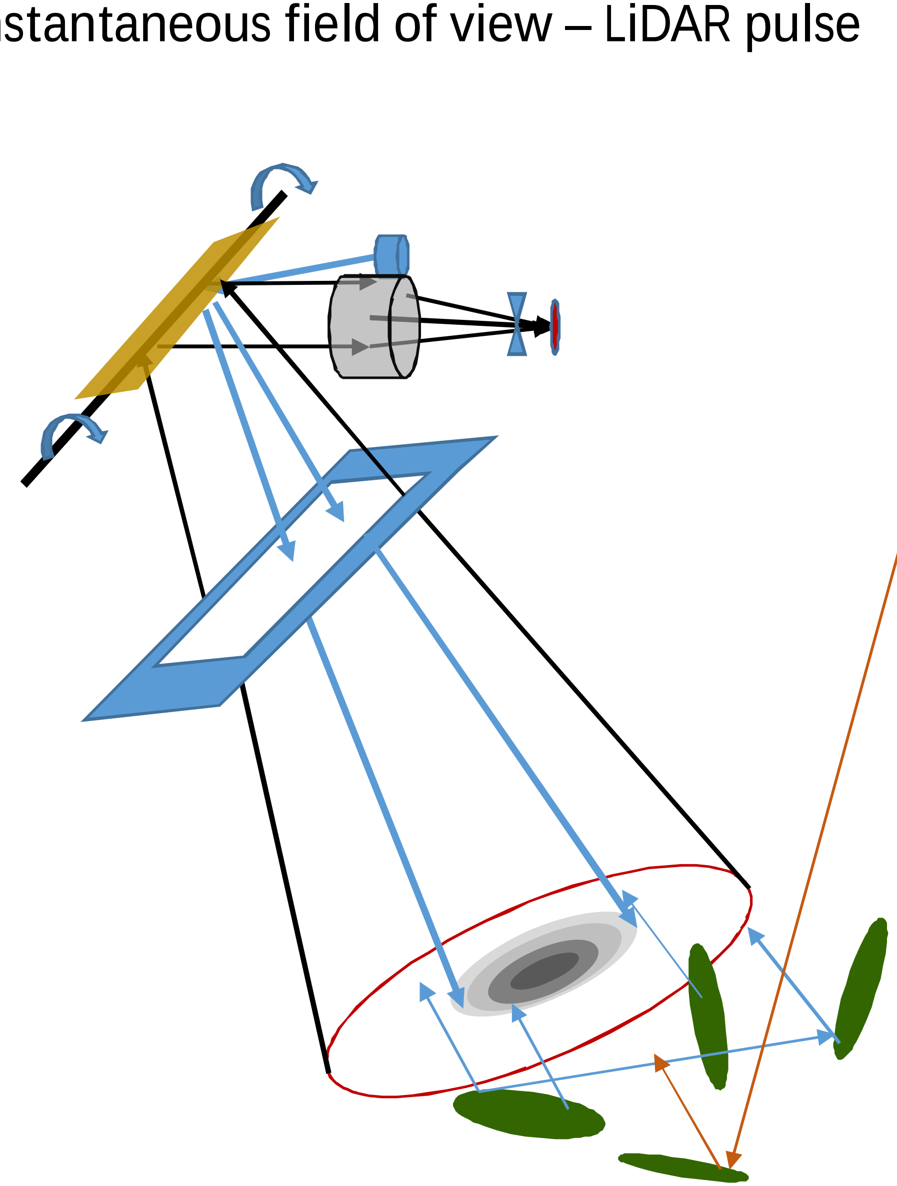






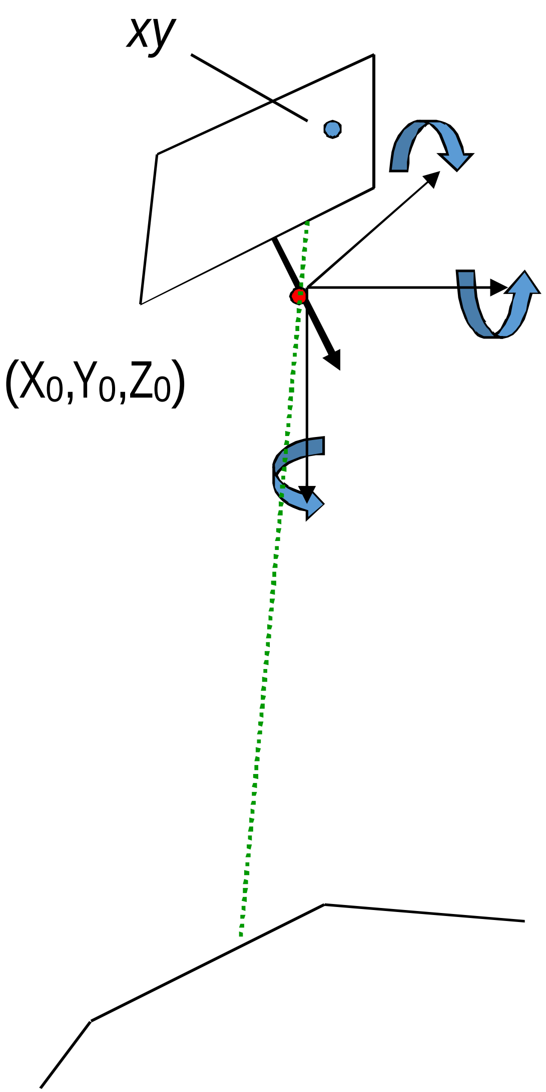
“Chromatic aberration” by purpose
ADS40/80/100 line camera.

Instantaneous field of view – LiDAR pulse



Backscattering from outside the 'footprint'

3D geometry and sensor models – From the world to pixel/photon detector



$$\mathbf{R}^{\mathrm{T}} = \begin{bmatrix} \cos\varphi \cos\kappa & \cos\omega \sin\kappa + \sin\omega \sin\varphi \cos\kappa & \sin\omega \sin\kappa - \cos\omega \sin\varphi \cos\kappa \\ -\cos\varphi \sin\kappa & \cos\omega \cos\kappa - \sin\omega \sin\varphi \sin\kappa & \sin\omega \cos\kappa + \cos\omega \sin\varphi \sin\kappa \\ \sin\varphi & -\sin\omega \cos\varphi & \cos\omega \cos\varphi \end{bmatrix}$$

$$\begin{cases} x - x_0 = -c\dfrac{r_{11}(X - X_0) + r_{12}(Y - Y_0) + r_{13}(Z - Z_0)}{r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0)} \\ y - y_0 = -c\dfrac{r_{21}(X - X_0) + r_{22}(Y - Y_0) + r_{23}(Z - Z_0)}{r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0)} \end{cases}$$

- (x_0,y_0) = offset of the principal point

* c = the calibrated focal length (INTERIOR ORIENTATION)
* ω, φ, κ = camera rotations in R
* (X_0,Y_0,Z_0) = position of principal point (EXTERIOR ORIENTATION)
* (x,y) = the focal plane coords of the 3D point (*Xa,Ya,Za*) in meters (cf. θ and φ in theodolite)
* if digital image, convert to (*x’,y’*) in the left-handed (row,col)coordinate system of the digital image.

GroundToImage.xls

Questions (2-4 students)

What do we need to know (about geometry of the camera - inside and outside) to establish the mathematical 3D ray from a given pixel to the scene?

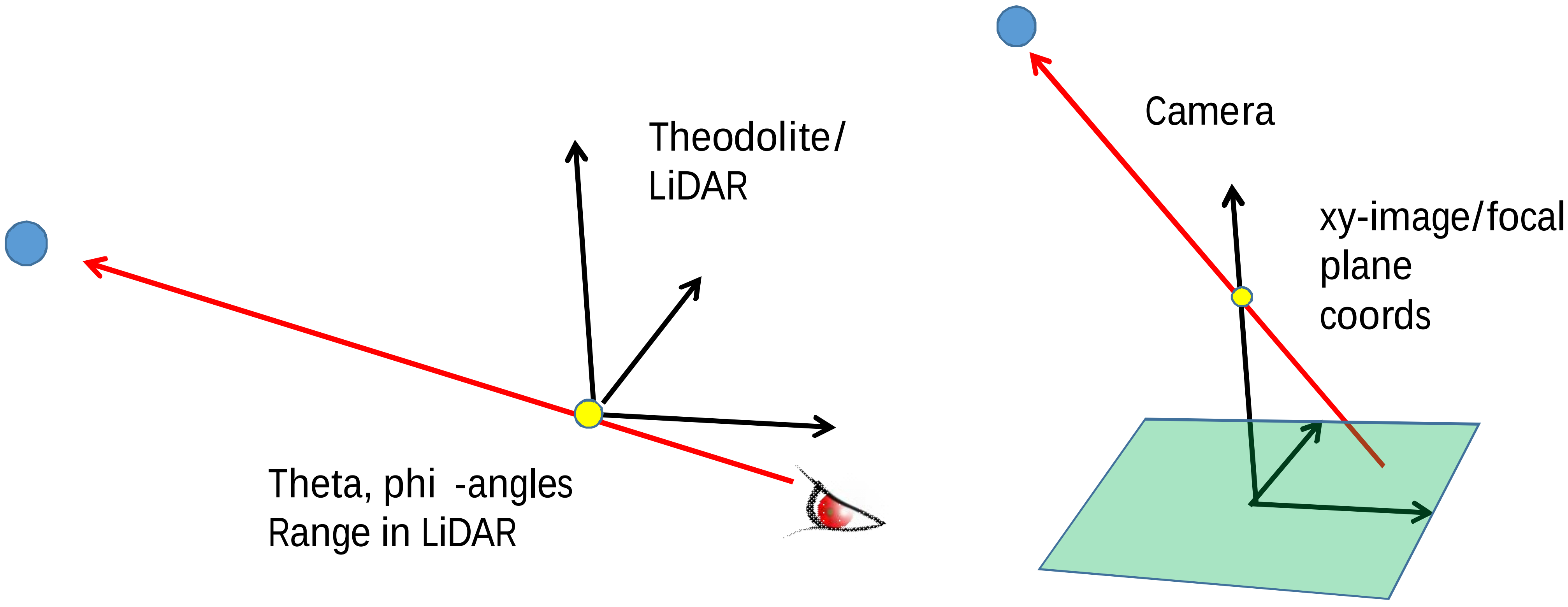
Can we use images and space intersection (of such image rays) to measure 3D coordinates of say large field crops, asphalt surfaces, brick walls, shape of ship’s surface, egg surface, glaciers etc.?

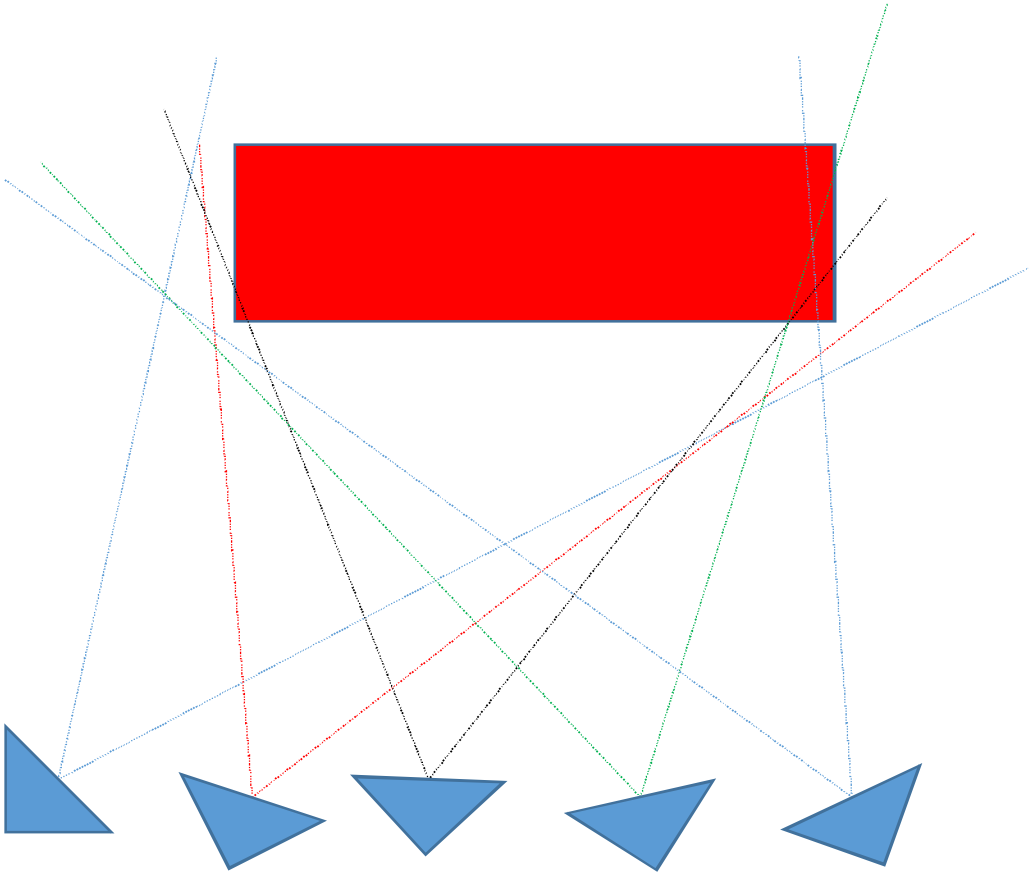
Can we measure the ground under closed forest canopies? With space intersection? With LiDAR?

LiDAR is based on the principle to carrying out distance measurements by measuring the two-way travel time of light. How far from the sensor is a target that gives the return after 1000 nanoseconds? (c = 300000 km/s).

How can we know the position of the LiDAR sensor and its attitude?

II: 3D geometry, from pixels to the world





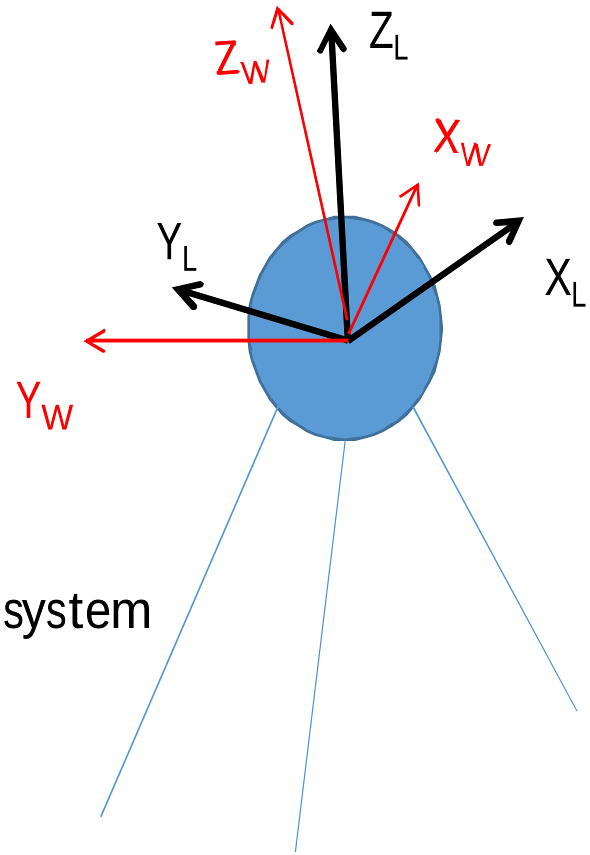
Intersection

Spherical

LIDAR and spherical coordinate system

$[x,y,z]_{Target} = [x,y,z]_{originL} + dist_L \times [\sin(\mathbf{q}_L)\cos(\mathbf{f}_L), \sin(\mathbf{q}_L)\sin(\mathbf{f}_L), \cos(\mathbf{q}_L)]$

f = azimuth -180..+180°
q = zenith -90..+90°



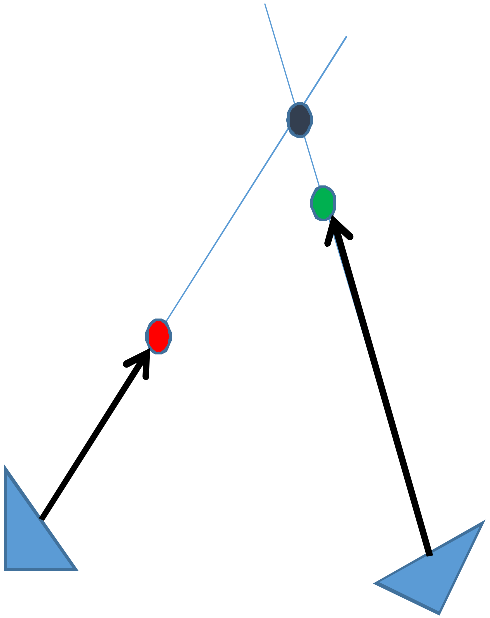
Terrestrial LiDAR; leveling with plumb line Þ Z_L || H
q is then rotation about the plumb line
f becomes defined on the plane for which plumb line is the normal

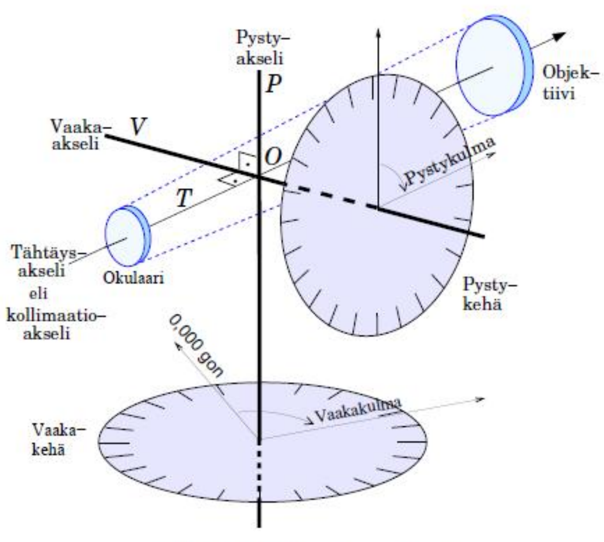
Observations $[x,y,z]_{Target}$ are 'local' – transformation to another system requires rotations (3) and offsets (DX, DY, DZ).

$[x,y,z]_{other} = [DX, DY, DZ] + dist_L \times R(rX, rY, rZ) \times [\sin(q_L)\cos(f_L), \sin(q_L)\sin(f_L), \cos(q_L)]$

LiDARin position   LiDAR attitude

XYZ measurements using images (2D observations of 3D lines that intersect) Camera @Theodolite





Kuva 5.2: Teodoliitin akselit ja kehät

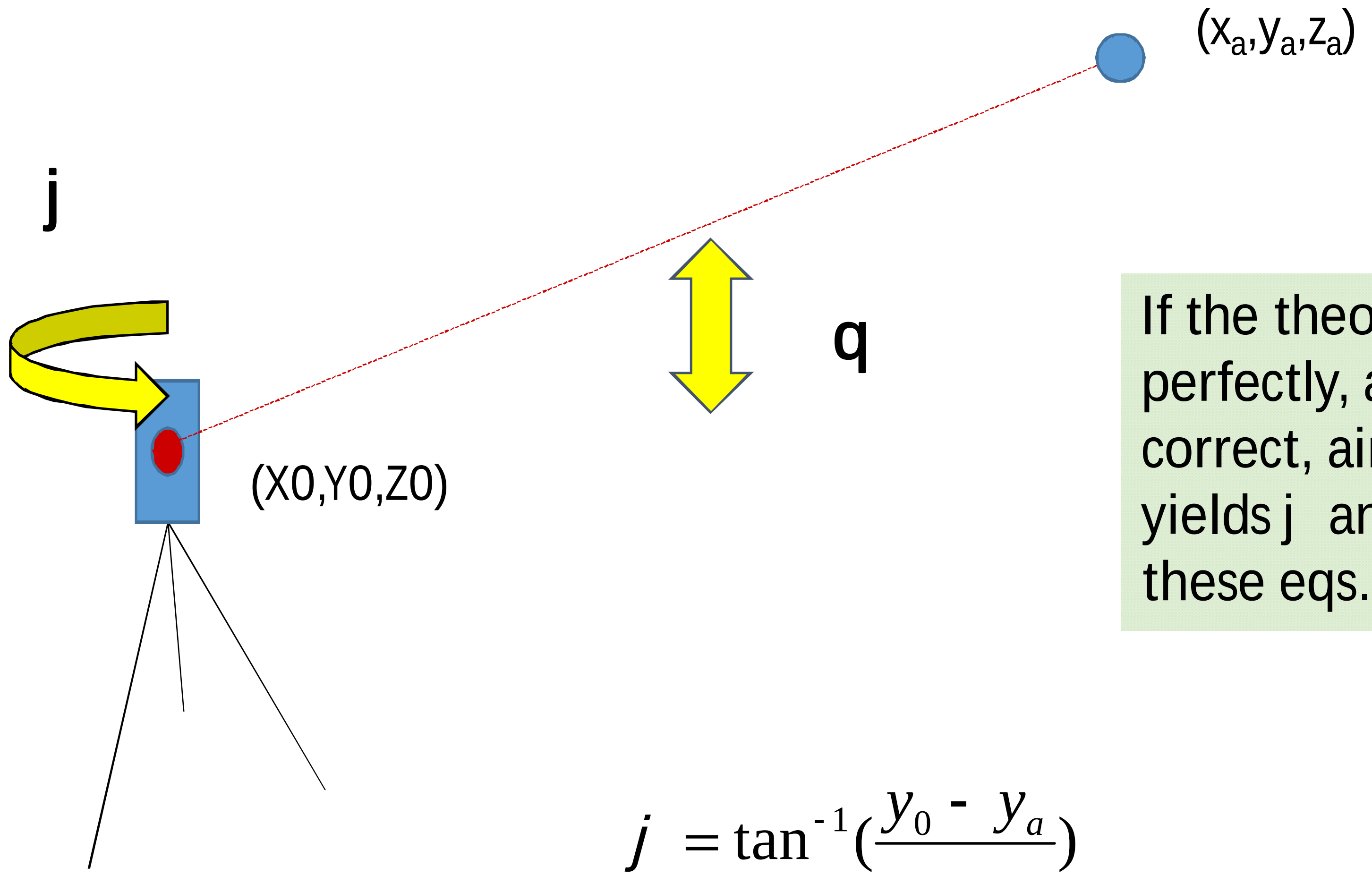
Teodoliitti(1) sij. origoon (0, 0, 0) .
Se kuplataan (Z || z_1).
Ja sen x-akseli suunnataan Teodoliitti(2):een (j_1 = 0.00°).

Teodoliitti(2) sijaitsee pisteessä (DX, 0, DZ).
Se kuplataan (Z || z_2 || z_1).
Sen negatiivinen x-akseli suunnataan Theodoliitti(1):een (j_2= ±180.00°)

Tämän seurauksena molempien Teodoliittien XYZ akselit ovat yhdensuuntaiset.

Oletetaan että DX ja DZ voidaan mitata.
Ensimmäinen on vaakaetäisyys teodoliittien välillä, ja toinen voidaan esim. vaaita.

Matching actual observations with computed observations

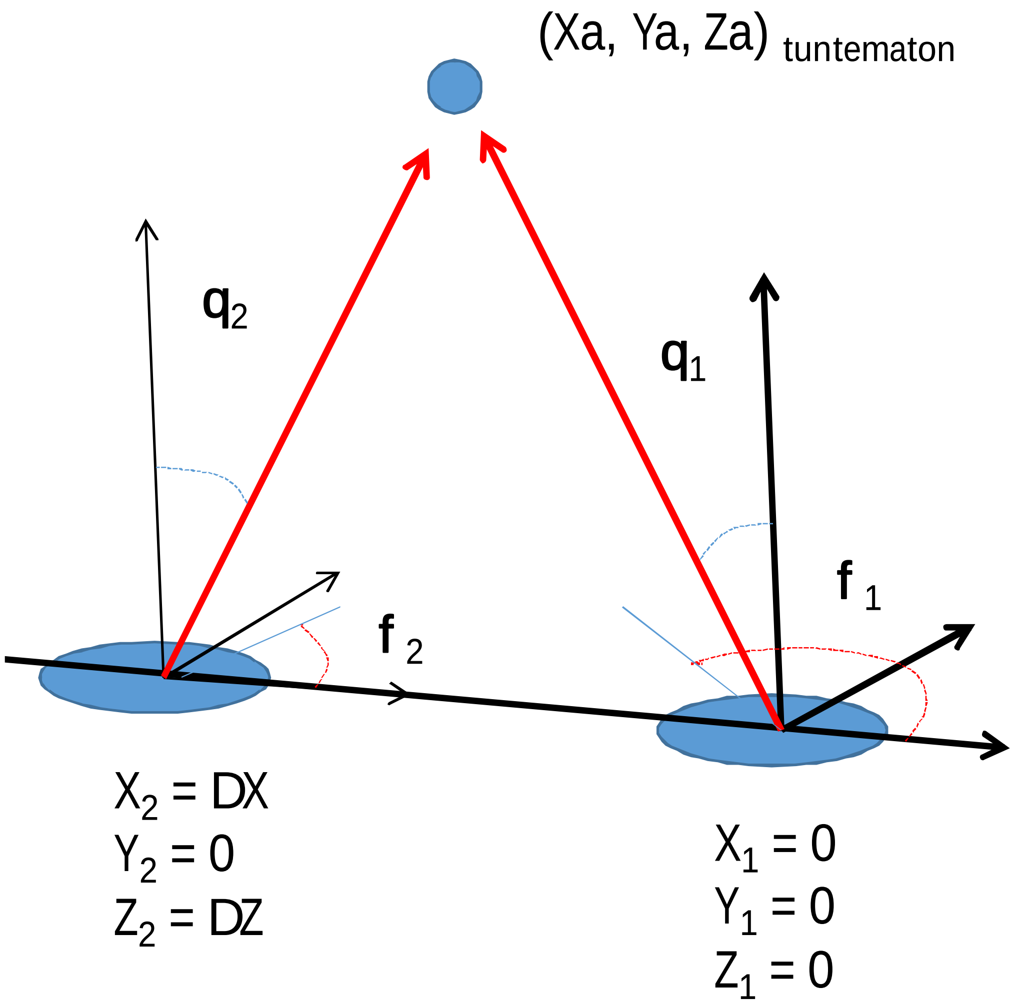


If the theodolite is aligned perfectly, and the position is correct, aiming at point Pa yields j and q, that match these eqs.

$$\varphi = \tan^{-1}\left(\frac{y_0 - y_a}{x_0 - x_a}\right)$$

$$\theta = \cos^{-1}\left(\frac{(z_0 - z_a)}{\sqrt{(x_0 - x_a)^2 + (y_0 - y_a)^2 + (z_0 - z_a)^2}}\right)$$

Unknowns (XYZ) in a non-linear regression



Jos tuntematon piste on (Xa,Ya,Za), näkyy se atsimuutti (**f**) ja zeniitti (**q**) suunnissa, jotka ao. tan^{-1} ja cos^{-1} lausekkeet määräävät teodoliitin ja tuntemattoman pisteen koordinaateista.

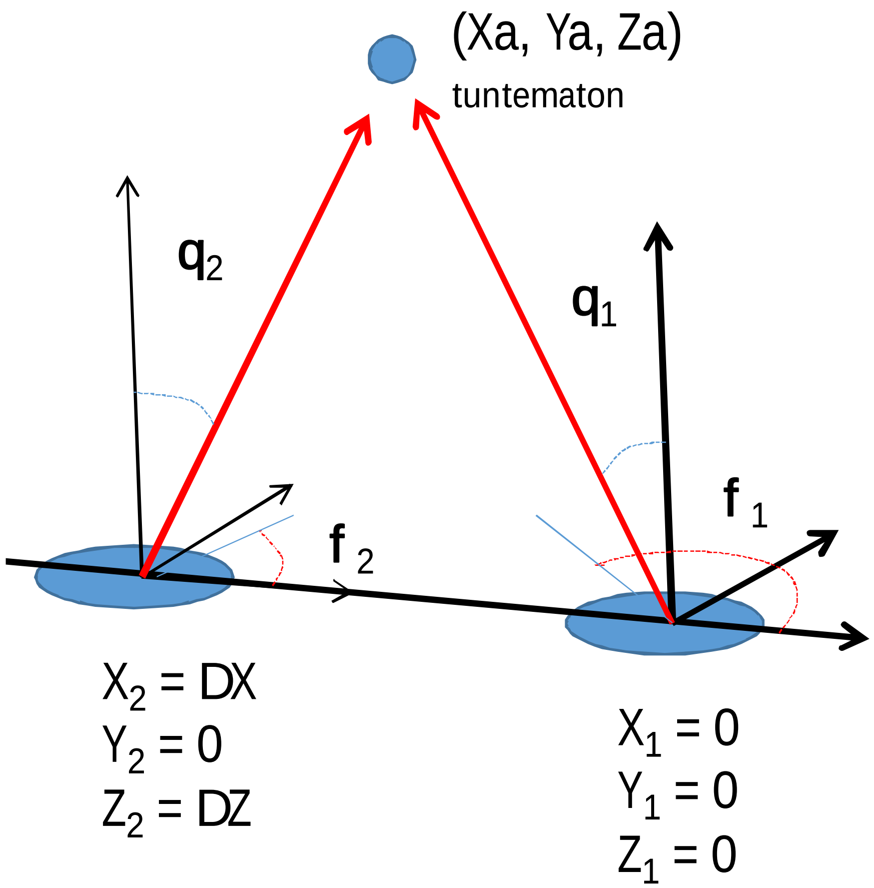
$$\arctan\left(\frac{Y_i - Y_a}{X_i - X_a}\right) - f_i = 0$$

$$\arccos\left(\frac{(Z_i - Z_a)}{\sqrt{(X_i - X_a)^2 + (Y_i - Y_a)^2 + (Z_i - Z_a)^2}}\right) - q_i = 0$$

Havaitut suunnat ovat (**f** $_i$) ja (**q**$_i$). Jos lasketun ja havaitun (arctan(), arccos()) välillä on pieni ero, on sijainti havaintoon nähden uskottava.

Kolme tuntematonta
Yksi teodoliitti Þ yhtälöpari
Kaksi teodoliittia Þ neljä yhtälöä

Epälineaarinen regressioanalyysi / PNS-tasoituslaskenta



Kaksi teodoliittia:
Tuntematon (Xa,Ya,Za) tuottaa neljä poikkemaa:
y = [**Df** , **Dq**, **Df** , **Dq**]

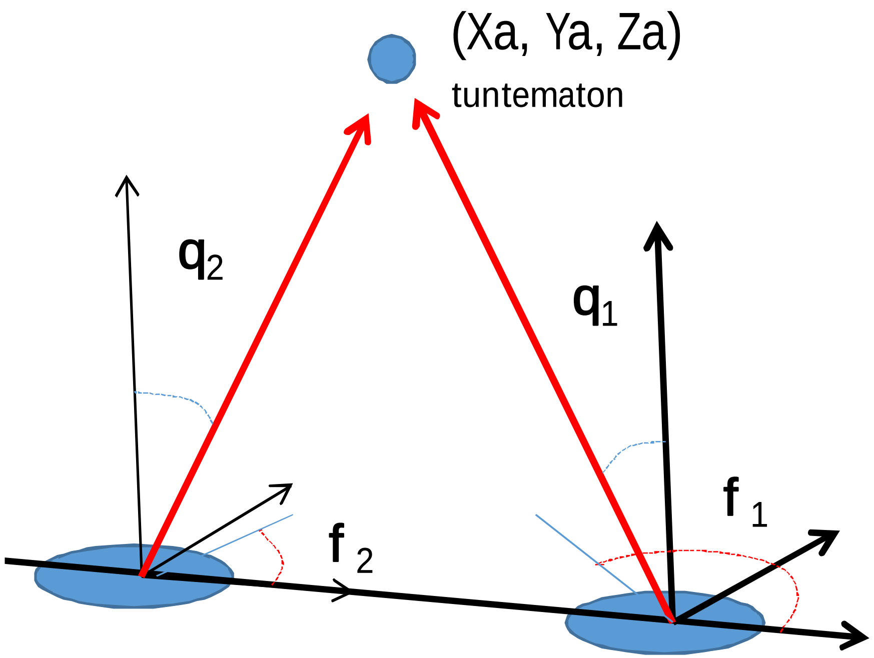
Kuinka lasketaan parempi (Xa,Ya,Za), s.e. poikkemat pienenevät, eli “tuntematon istuu havaintoihin”? PNS-tasoituslaskenta!

Tarvitaan havaintoyhtälöparista osittaisderivaatat:
$d\mathbf{q}/dX_a$, $d\mathbf{q}/dY_a$, $d\mathbf{q}/dZ_a$
$d\mathbf{f}/dX_a$, $d\mathbf{f}/dY_a$, $d\mathbf{f}/dZ_a$

Muodostetaan 4 x 3 havaintomatriisi (A) näistä, käyttämällä (Xa,Ya,Za):n sen hetkisiä arvioita/arvoja.
$d\mathbf{q}_1/dX_a$, $d\mathbf{q}_1/dY_a$, $d\mathbf{q}_1/dZ_a$
$d\mathbf{f}_1/dX_a$, $d\mathbf{f}_1/dY_a$, $d\mathbf{f}_1/dZ_a$
$d\mathbf{q}_2/dX_a$, $d\mathbf{q}_2/dY_a$, $d\mathbf{q}_2/dZ_a$
$d\mathbf{f}_2/dX_a$, $d\mathbf{f}_2/dY_a$, $d\mathbf{f}_2/dZ_a$

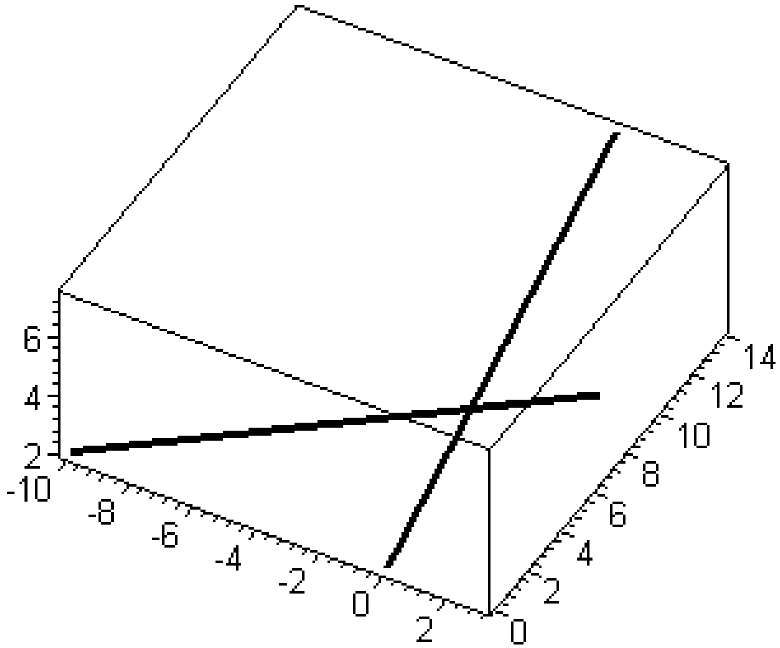
Ratkaistaan [DX, DY, DZ] = $(A^TA)^{-1}A^Ty$
(Xa, Ya, Za) + [DX, DY, DZ] = parempi paikka.

Havaintoja enemmän kuin tuntemattomia, tarkkuusestimaatit



$X_2 = -10$
$Y_2 = 0$
$Z_2 = 0$

$X_1 = 0$
$Y_1 = 0$
$Z_1 = 0$

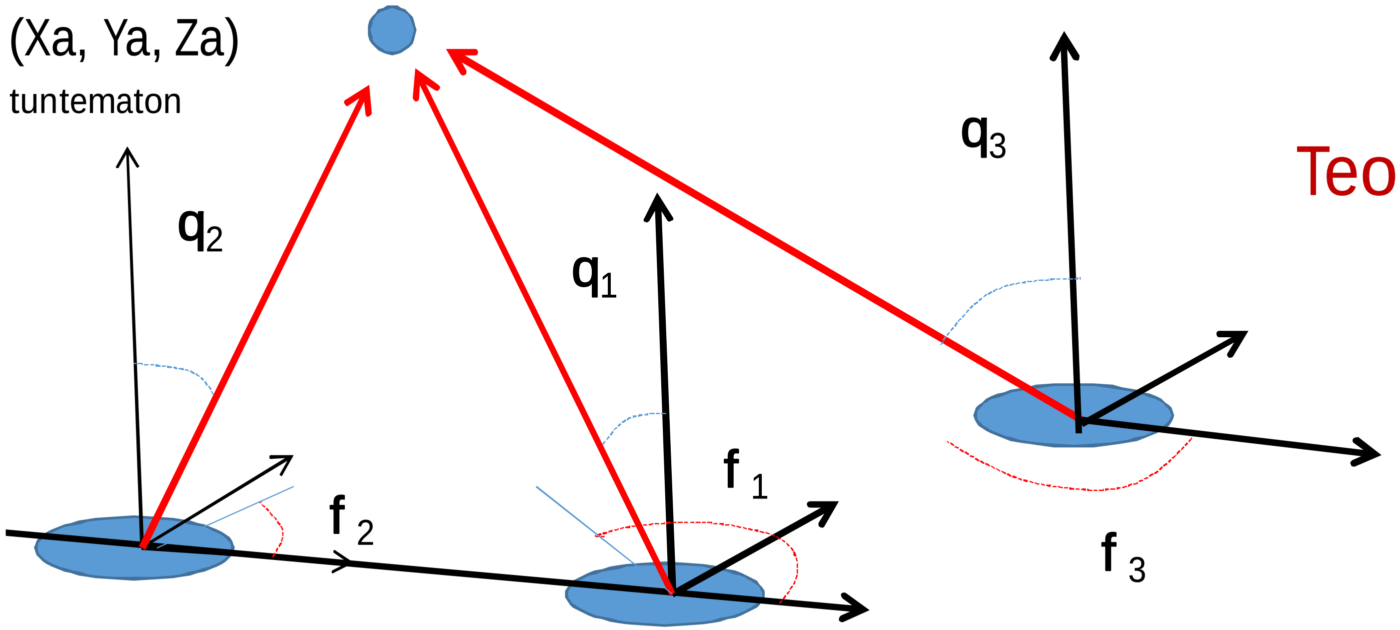


observations	
1.2	vertical angle
1.575	azimuth angle
1.4	vertical angle
0.48	azimuth angle

Teodoliitti2.xls

	Solution	SDEV	
X	-0.022	0.030	m
Y	5.174	0.072	m
Z	3.996	0.039	m

Havaintoja enemmän kuin tuntemattomia, tarkkuusestimaatit



Teodoliitti3.xls

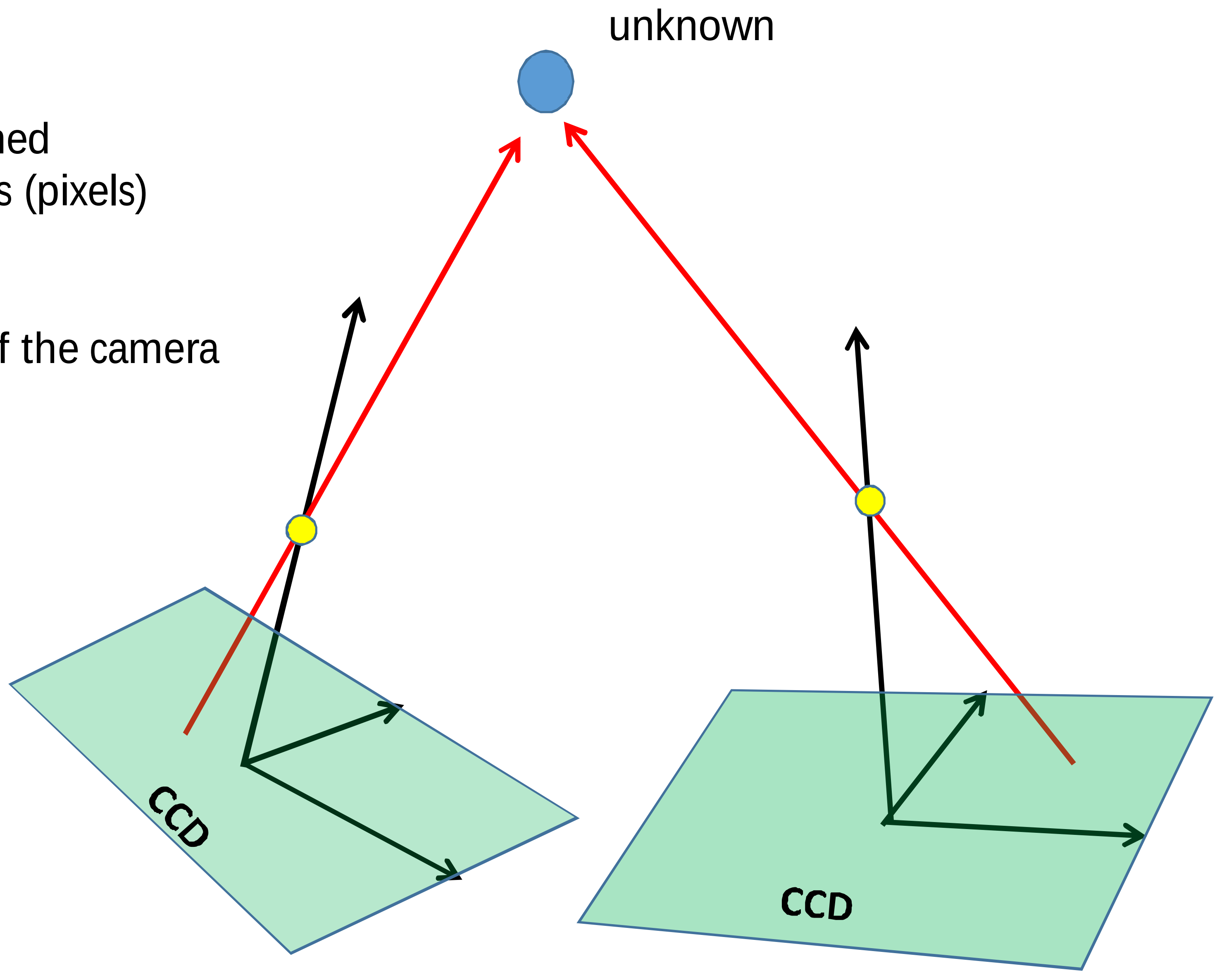
Painotettu pienimmän neliösumman tasoituslasku “kulmahavainnoista XYZ-koordinaateiksi”. Kameran tapauksessa pikselikoordinaatit ovat “kulmahavaintoja kameran sisällä”. Tasoituslaskennassa minimoidaan pikselivirheitä (xy), kun teodoliitissa minimoidaan kulmavirheitä.

Painot = havaintotarkkuuksien käänteislukuja, suuri hajonta pieni paino.
Esimerkeissä painot olivat samat pysty- ja vaaka-kulmille, kaikilla teodoliiteilla.
Kuvahavainnoilla painot, esim. 5 um.

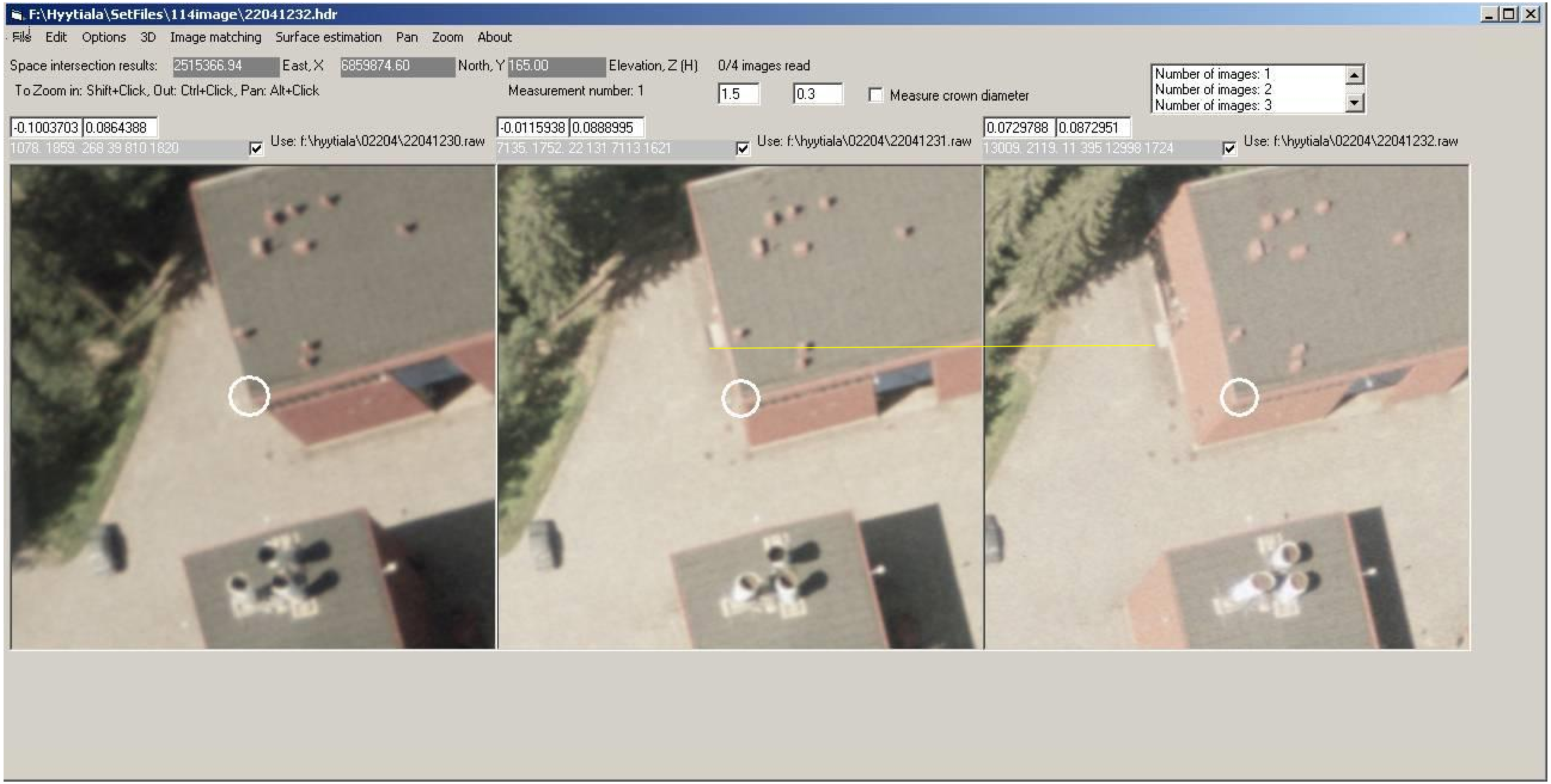
General, image intersection

- Not levelled
- Position usually planned
- Lots of measurements (pixels)
- At shutter-release:
  - XYZ focal point
  - rX, rY, rZ rotations of the camera

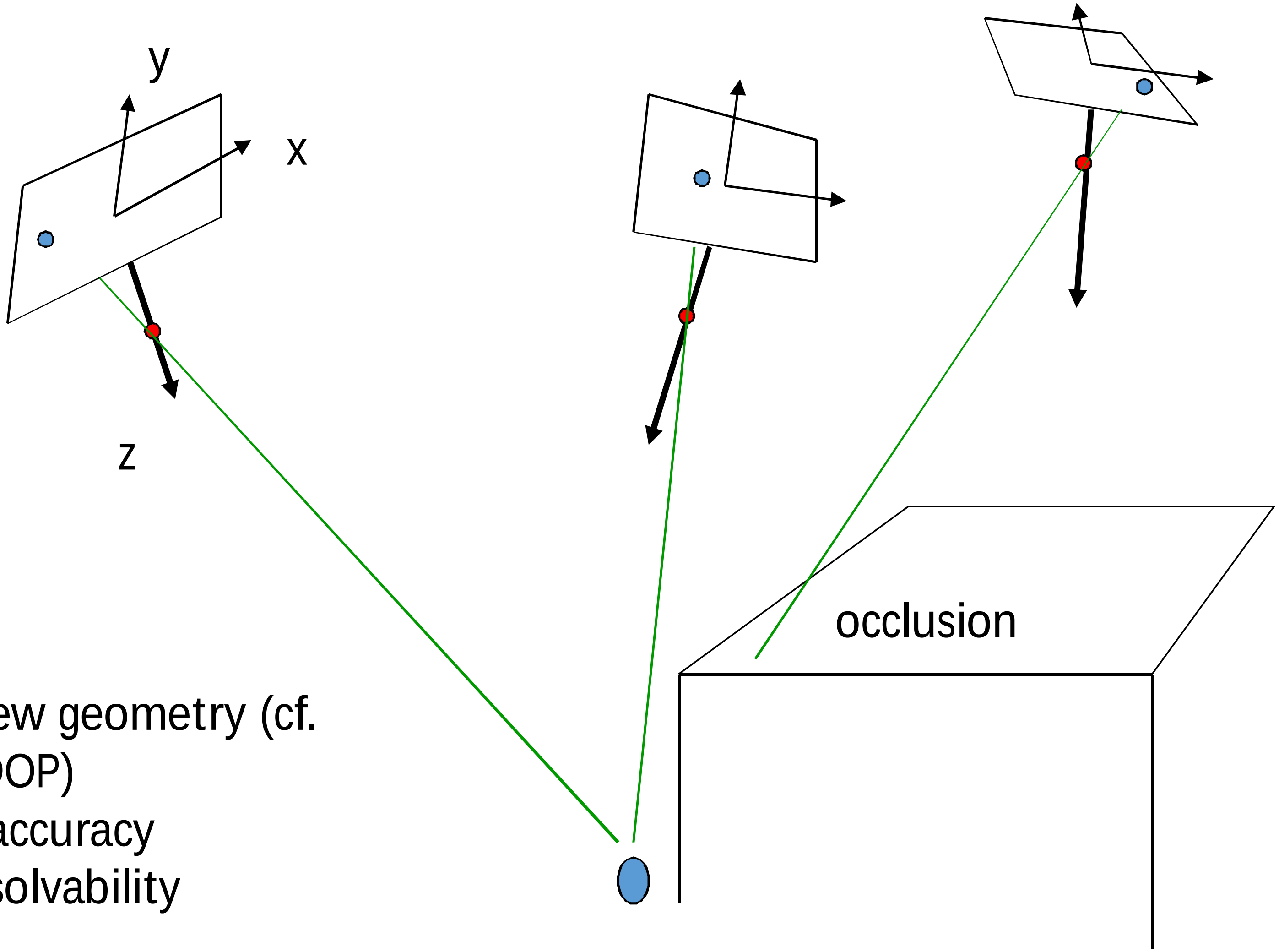
Correspondence
Occlusion



Correspondence
Occlusion
Shading



3D reconstruction in images



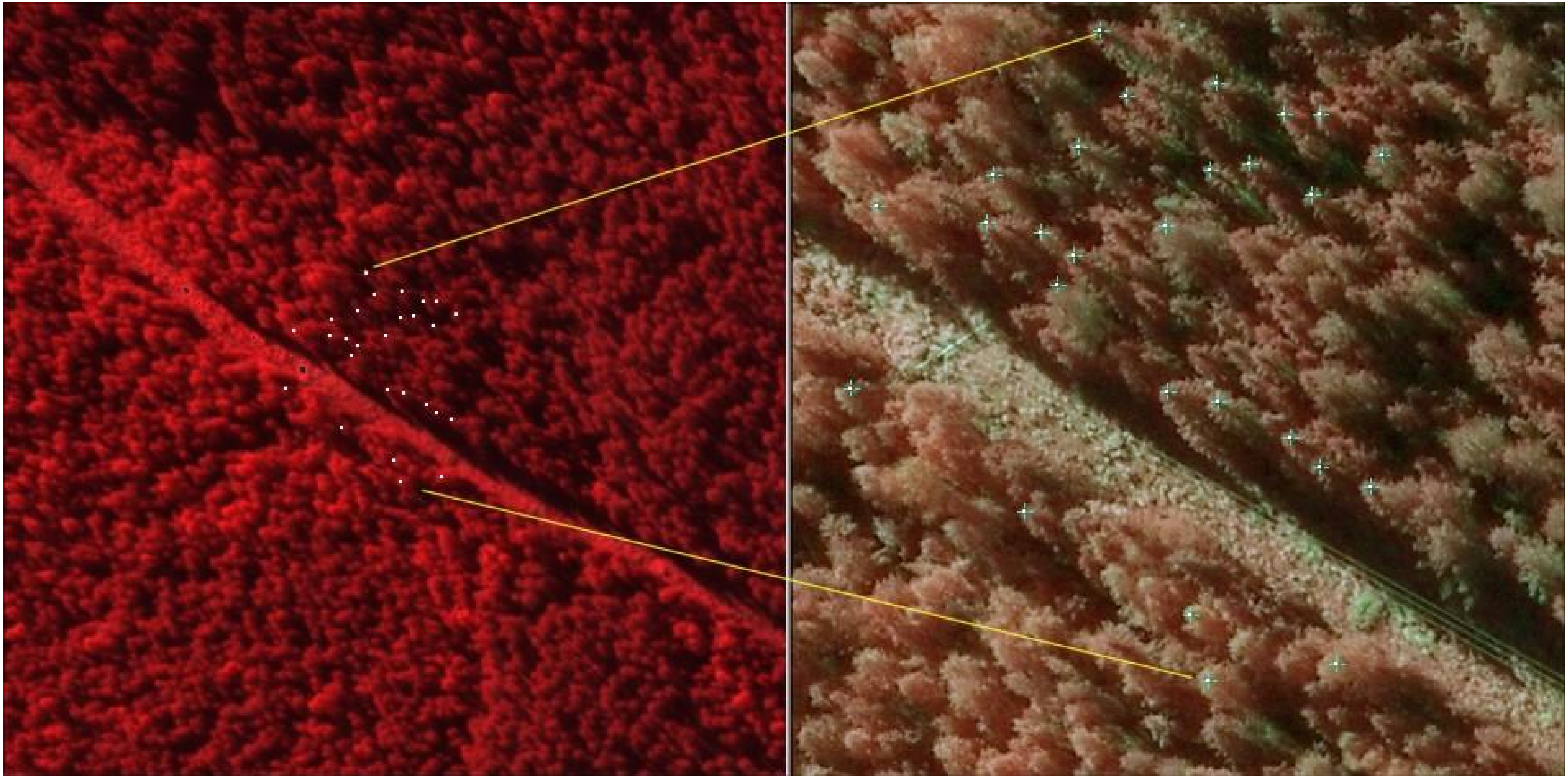
More views with accurate rays intersecting, the better XYZ accuracy

View geometry (cf. PDOP)
* accuracy
* solvability

Correspondence problem (image matching)

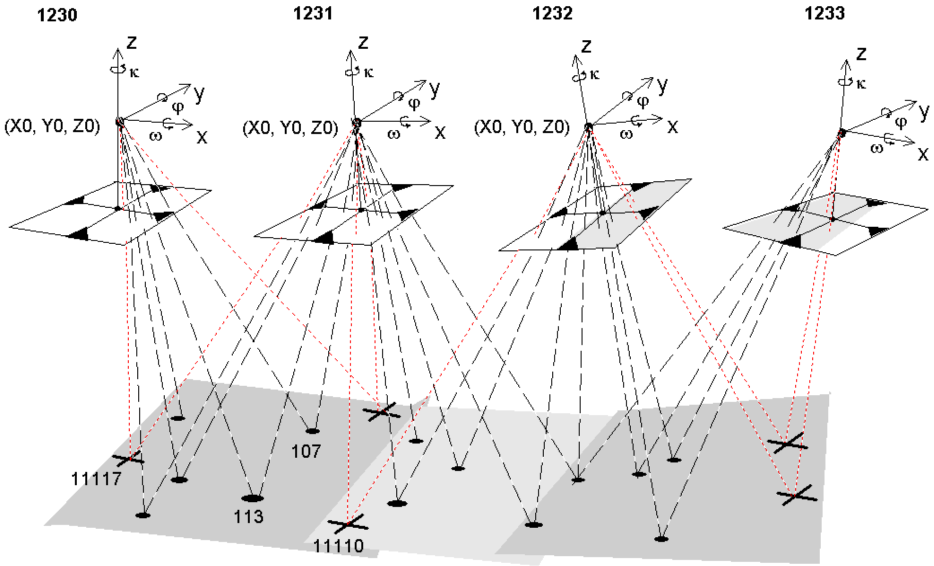
Not all points map to an image (not everything is seen) (cf. LiDAR!)
Occlusion and shading

Occlusion in closed-canopy forests
Illumination conditions



Photogrammetry – Aerial Triangulation

$$
\begin{cases}
x - x_0 = -c\dfrac{r_{11}(X - X_0) + r_{12}(Y - Y_0) + r_{13}(Z - Z_0)}{r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0)} \\
y - y_0 = -c\dfrac{r_{21}(X - X_0) + r_{22}(Y - Y_0) + r_{23}(Z - Z_0)}{r_{31}(X - X_0) + r_{32}(Y - Y_0) + r_{33}(Z - Z_0)}
\end{cases}
$$



Unknowns to be solved:

EO parameters (and IO + additional)

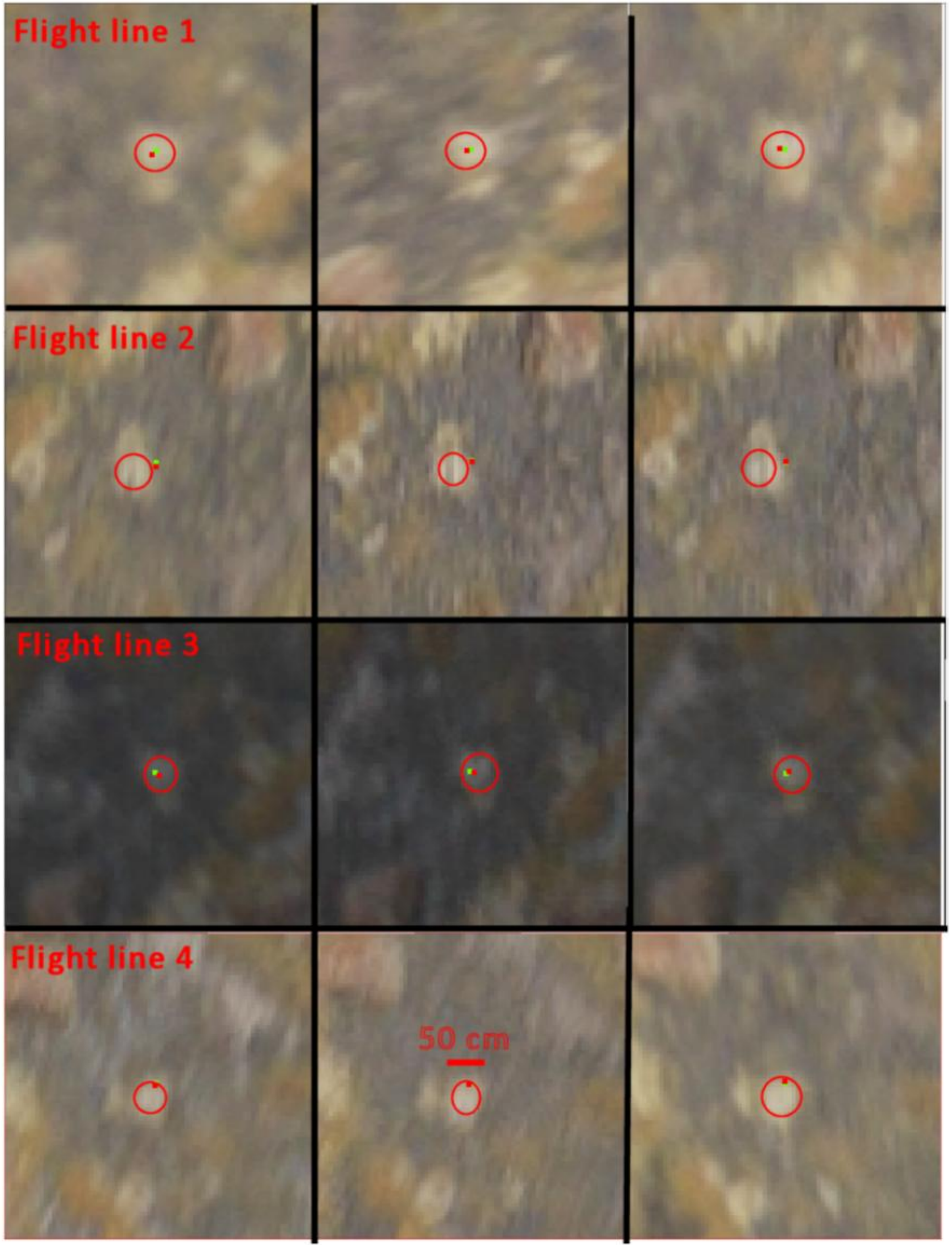
‘Known’:

XYZ, XY, Z control points, distances, EO parameters (GNSS, imu), image points (of tie and control points).

Observation equations (regression model components):

1) Image points
2) XYZ Distances
3) XY Distances
4) Z Distances
5) Observations of unknowns

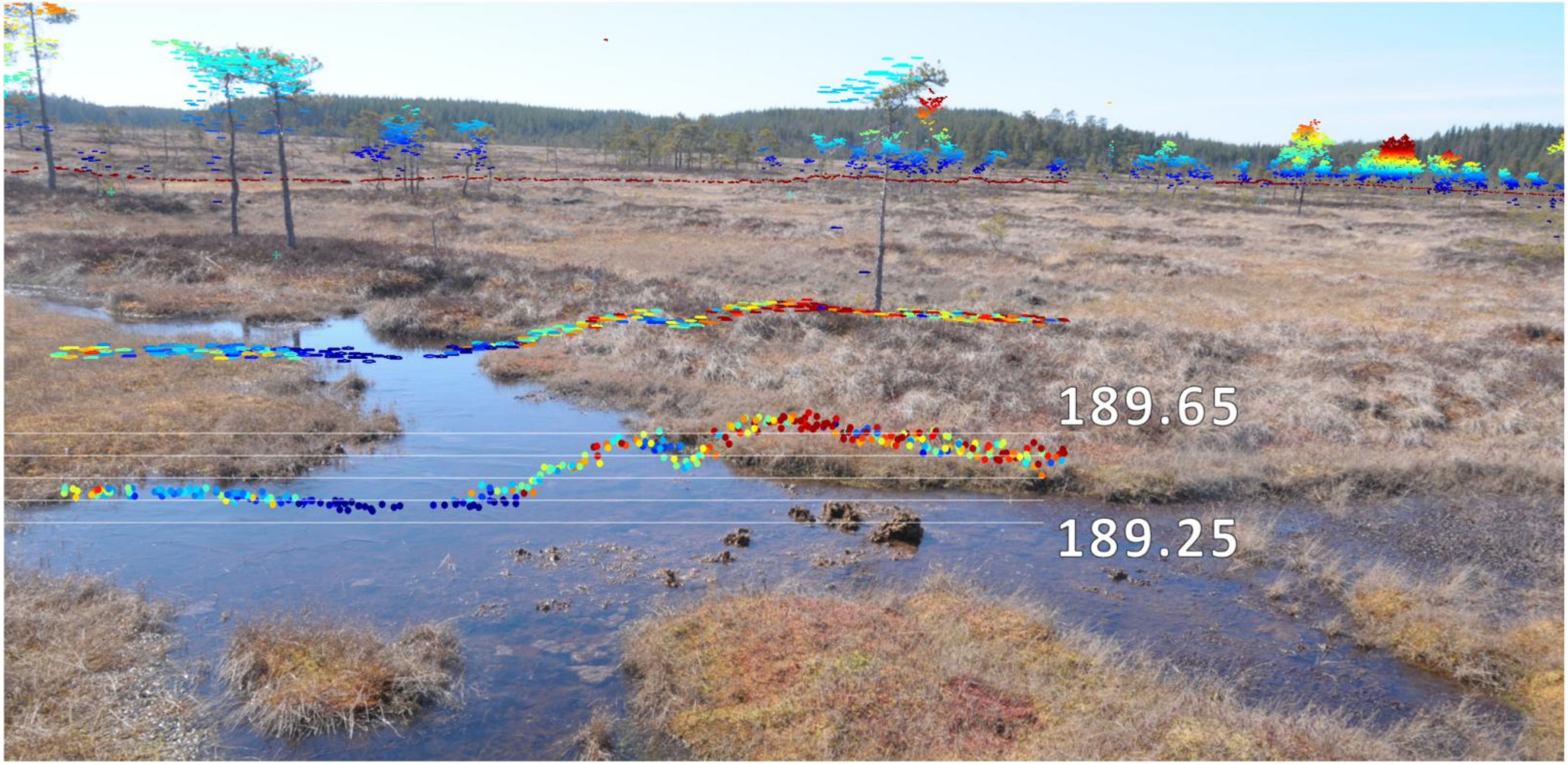
® Weighted non-linear regression



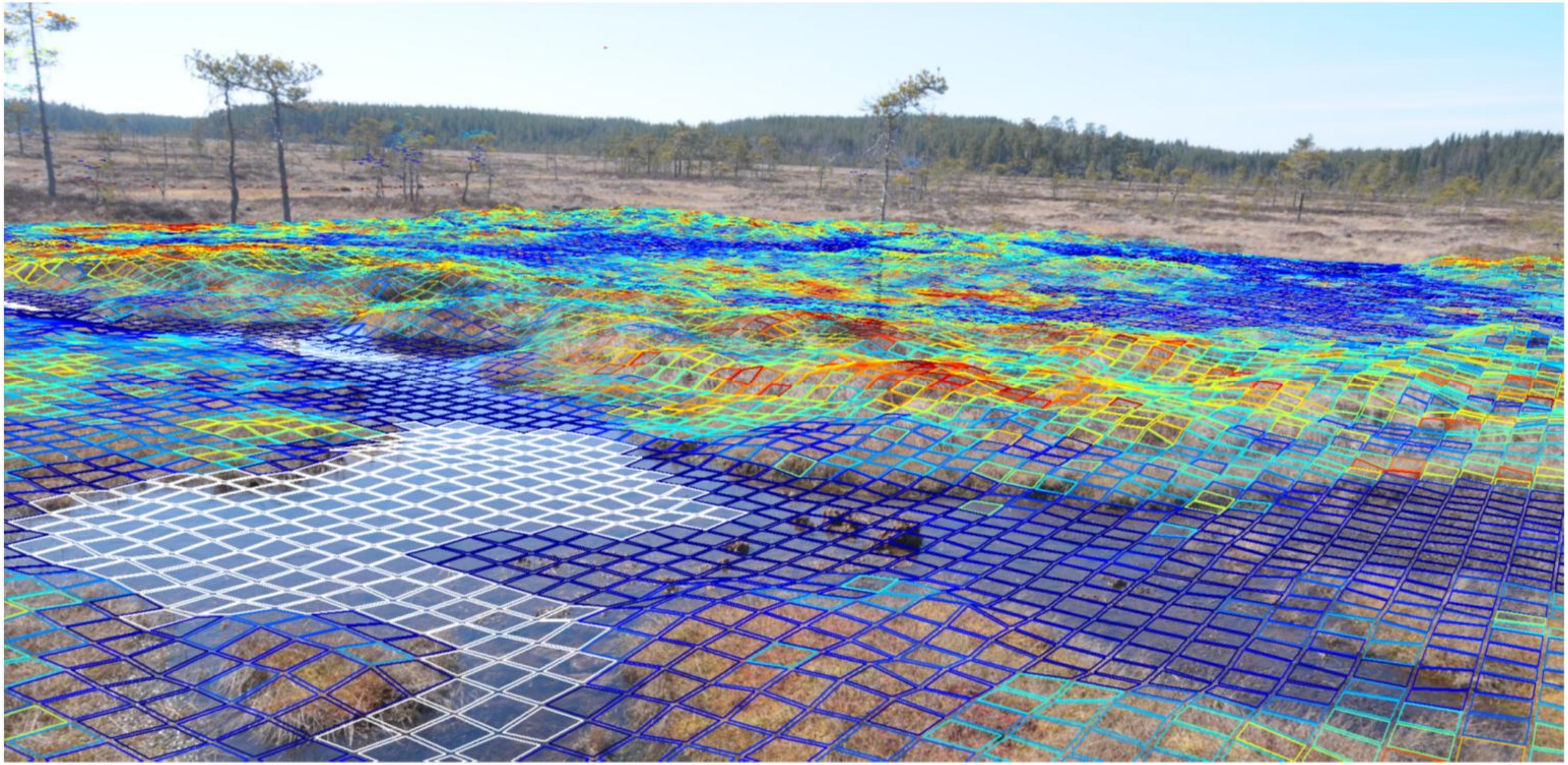
* Image blur
* Residual errors in aerial triangulation

LiDAR WF amplitude values superimposed in an image pair

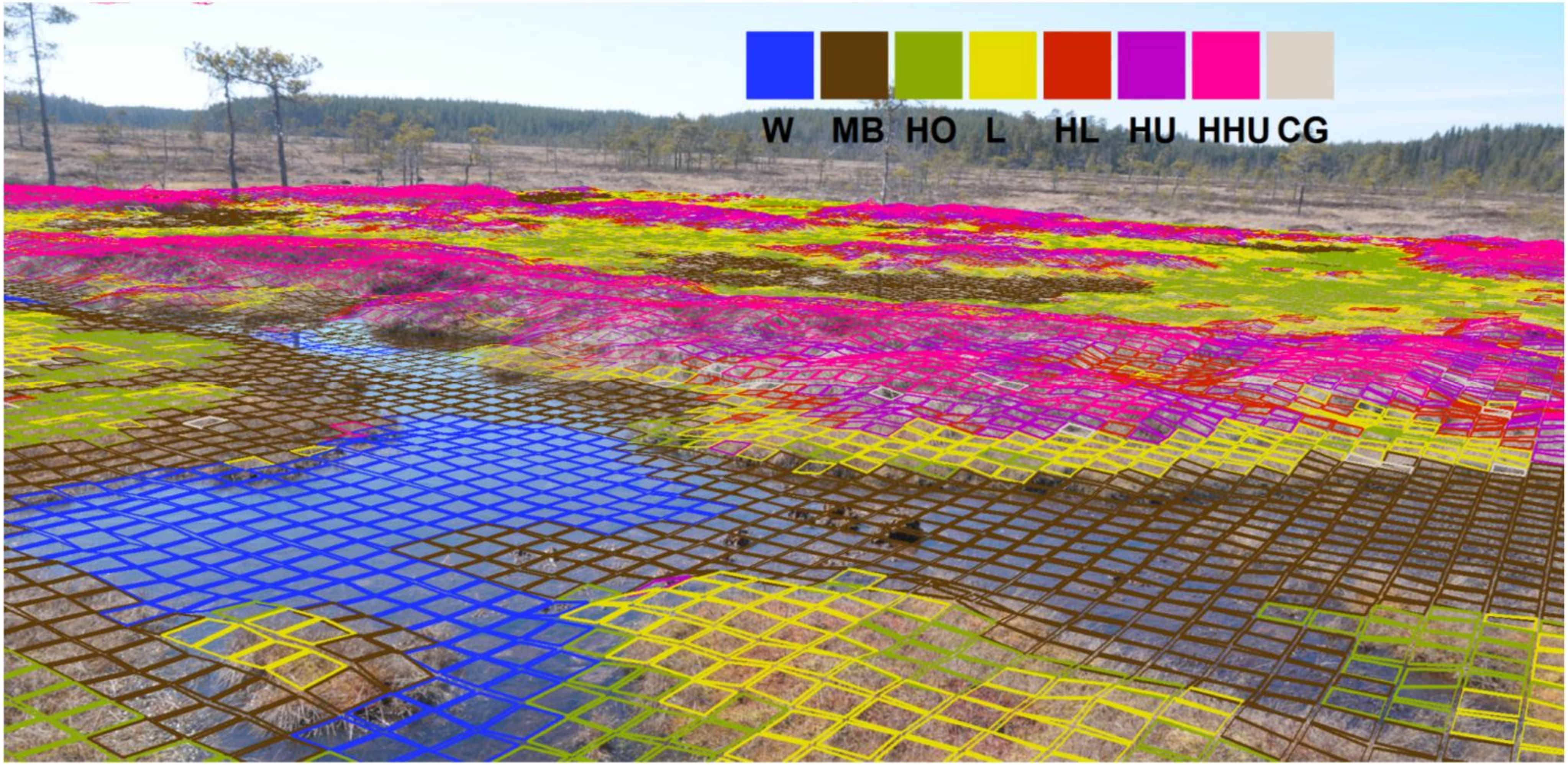
LiDAR point data superimposed in a close-range view



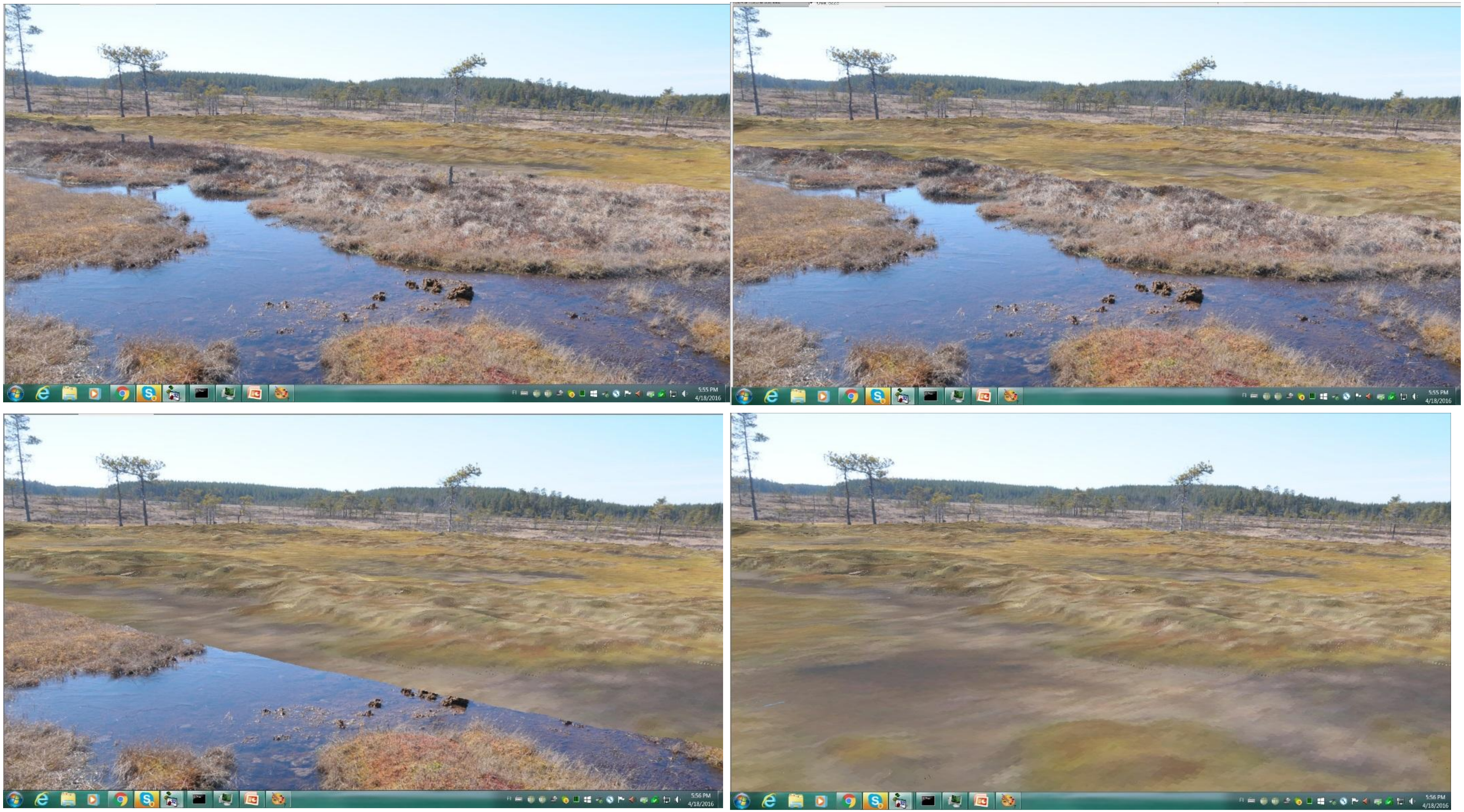
LiDAR intensity data interpolated in a 20x20-cm grid and data superimposed in a close-range view



Classification grid (20x20-cm grid) based on LiDAR and aerial image data - superimposed in a close-range view microforms on a patterned bog



Sequence showing warping of aerial image on a DEM, then projected to the close-range view



Summary

Be it theodolite, camera, airborne or terrestrial LiDAR sensor – it is important to know the position of the instrument as well as the attitude, both require six parameters.

In image/theodolite the observations that establish the ‘other end’ of the 3D half-line are the position on the focal or the zenith and azimuth rotations of the theodolite’s telescope. Camera has a rigid body, zoom may change focal length. Pixels view a large FOV, while it is cumbersome to turn the theodolite. LiDAR is turned (deflected) by a mirror, its attitude is very accurate.

Getting the XYZ coordinates requires the solution of the seventh parameter, which is the range (two-way travel time of the laser pulse) in LiDAR, or the intersection of the half-lines in the case of images.

LiDAR is without redundancy, no control over random errors. Two images already provide redundancy.

Occlusion influences less LiDAR, because…