MSC GEODETIC ENGINEERING

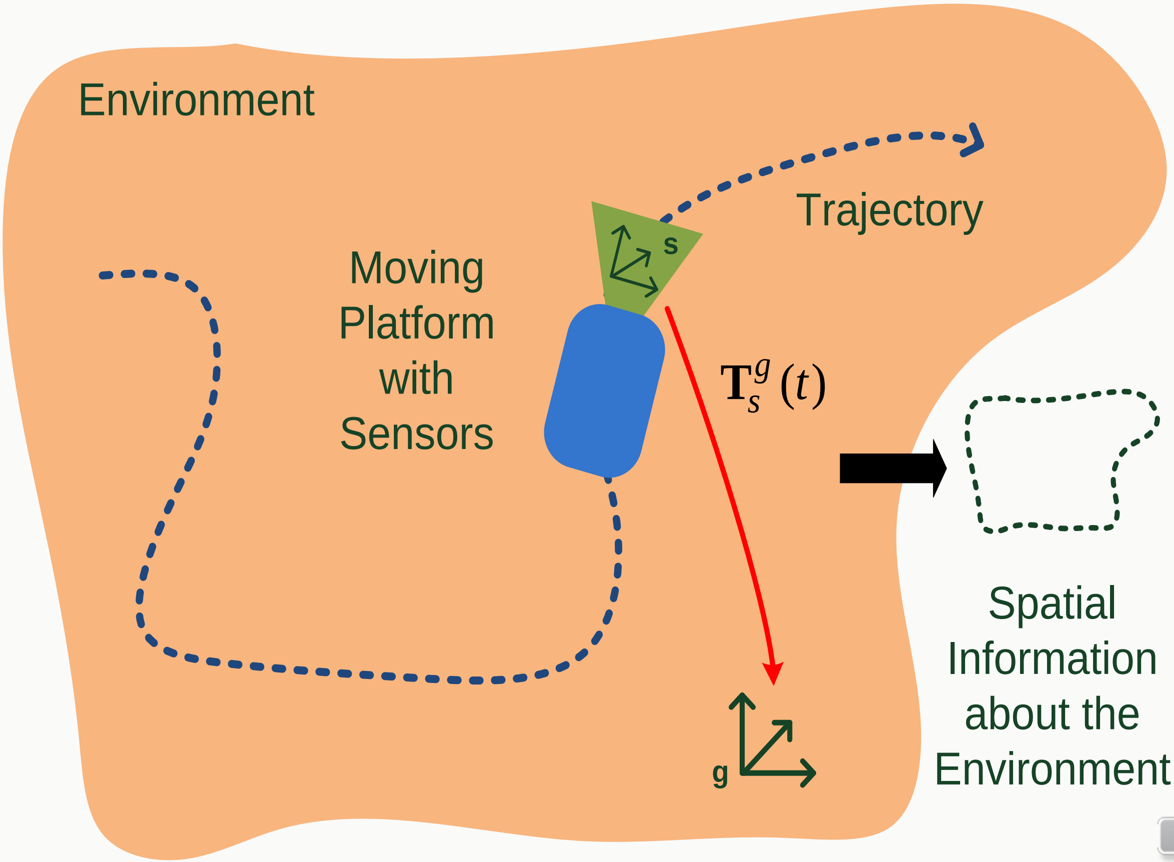
MSR-02: ADVANCED TECHNIQUES FOR MOBILE SENSING AND ROBOTICS (GEODESY TRACK)

01: MOBILE LASER SCANNING

DR. LASSE KLINGBEIL

INSTITUTE FOR GEODESY AND GEOINFORMATION
UNIVERSITY OF BONN

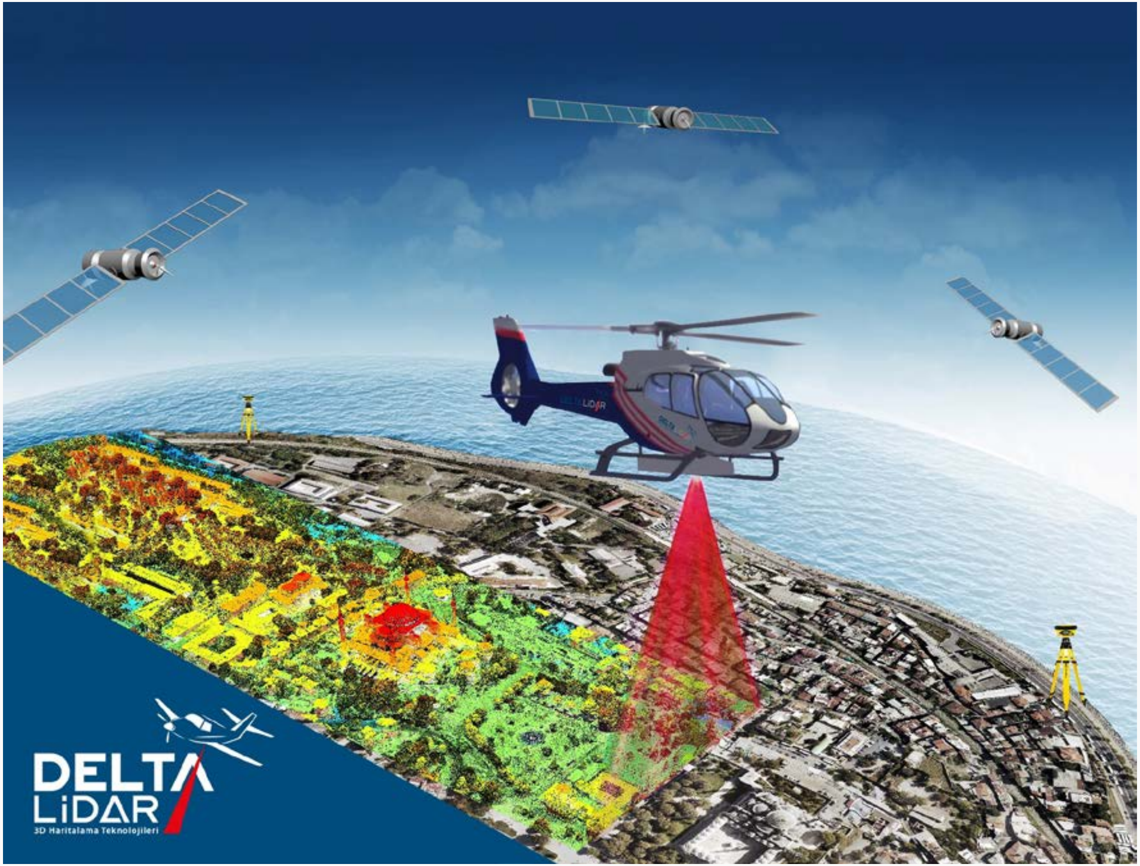
MOBILE MAPPING



EXAMPLES
CITY MODELS

Leica Pegasus

EXAMPLES
AIRBORNE LIDAR



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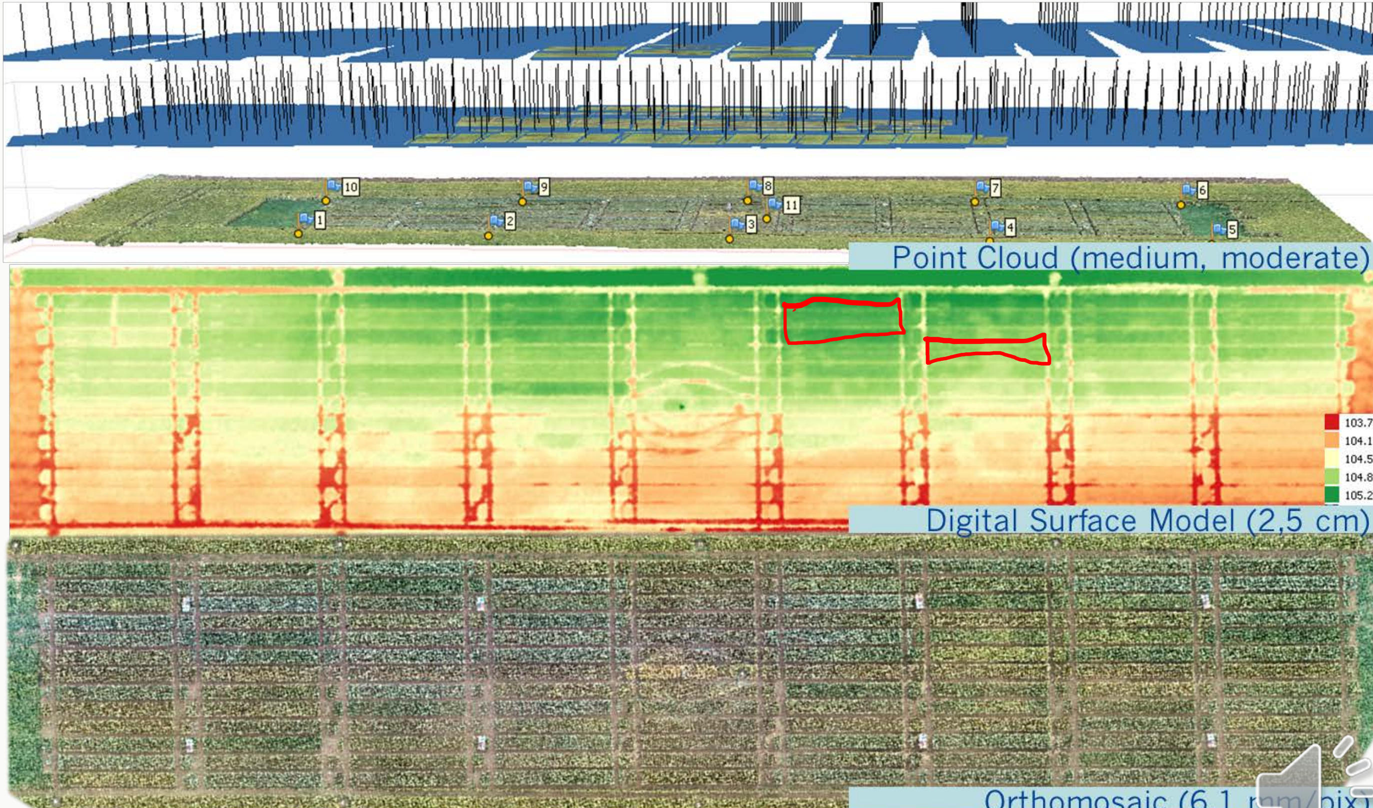
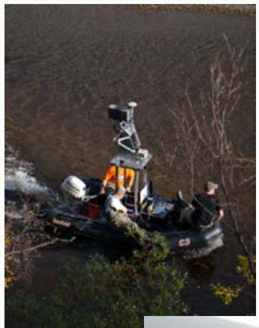
EXAMPLE
PRECISION AGRICULTURE

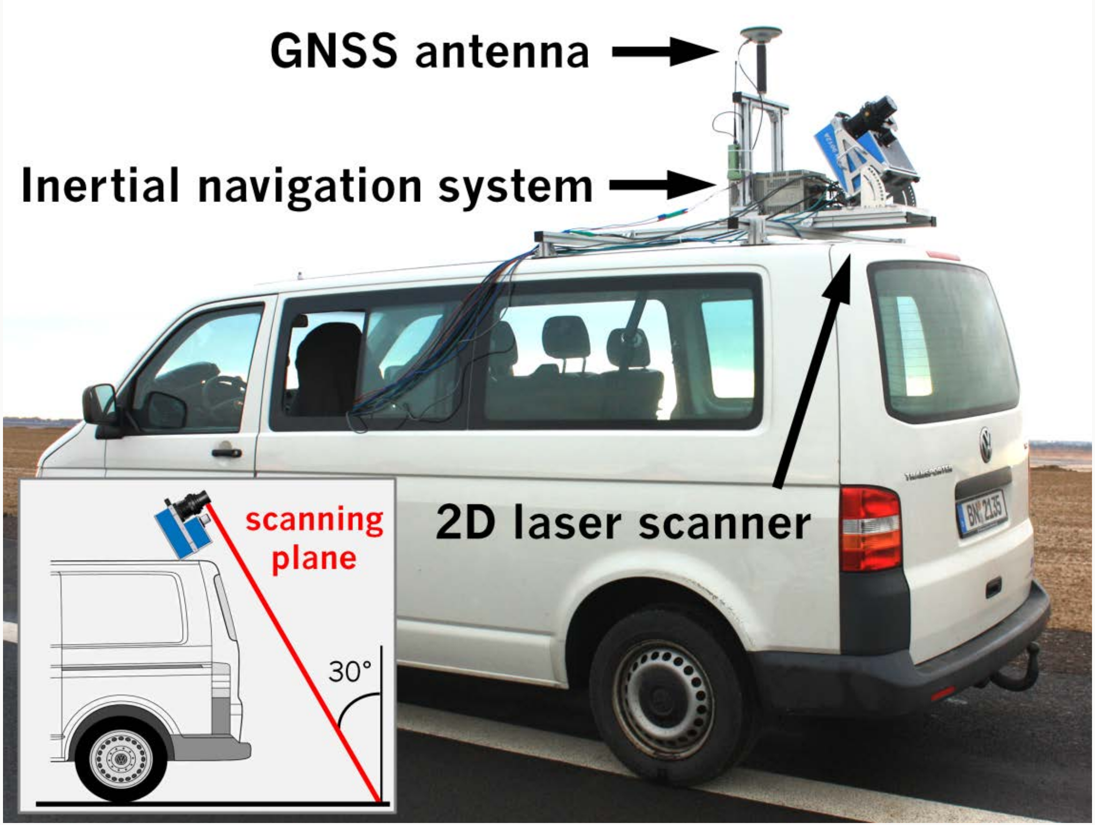


MOBILE MAPPING

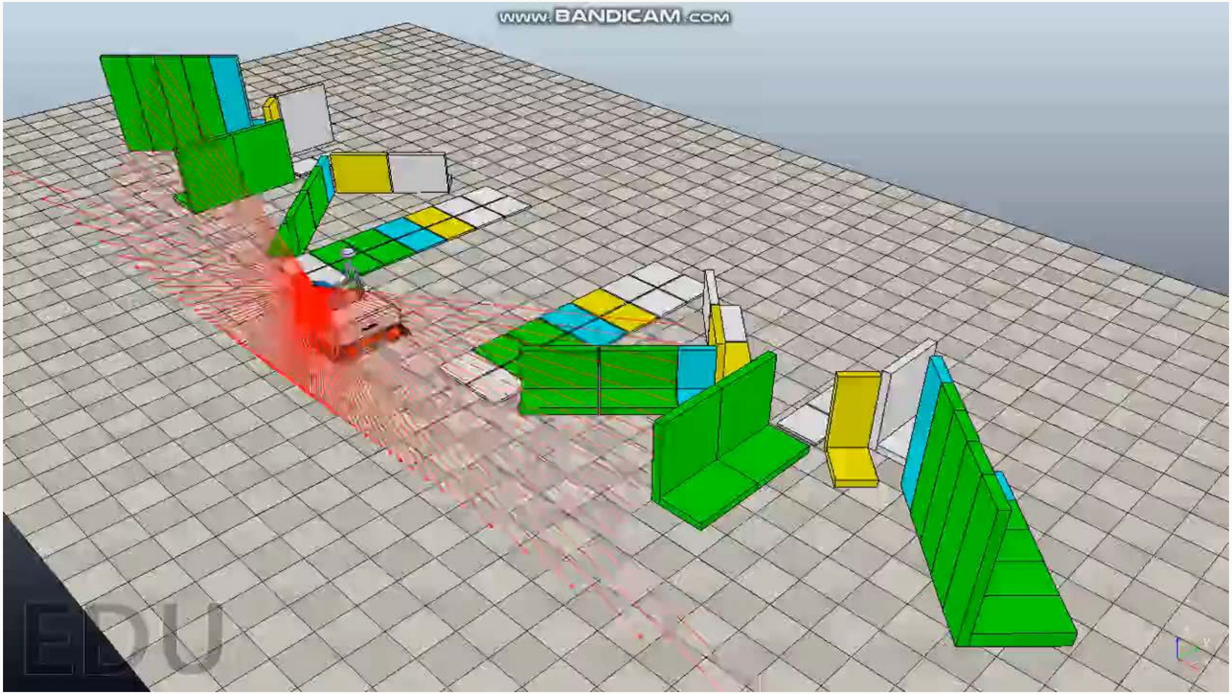


p3dsystems

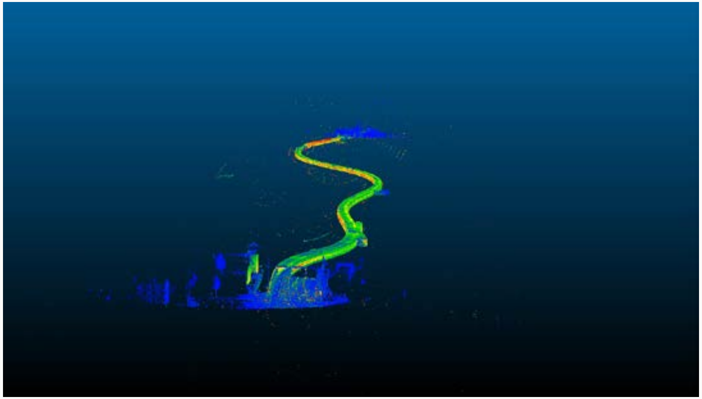
IGG MOBILE LASER SCANNING SYSTEM

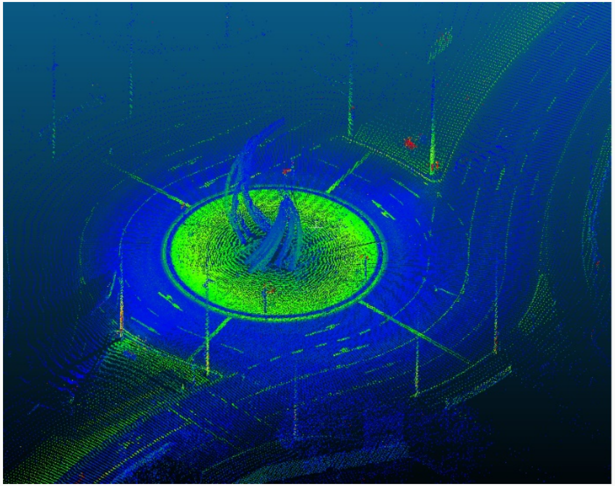


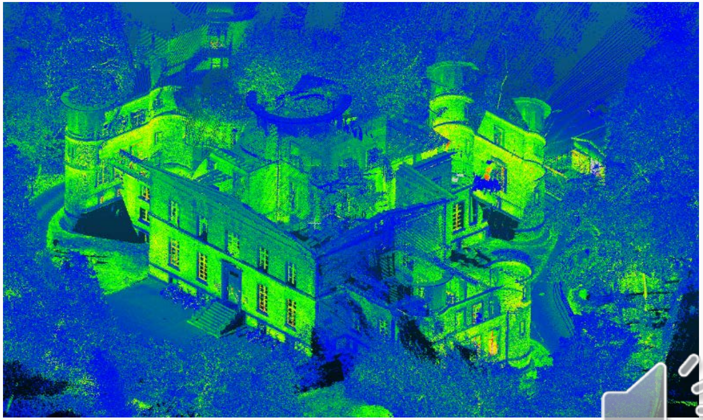
MOBILE LASER SCANNING PRINCIPLE



MOBILE LASER SCANNING RESULTS





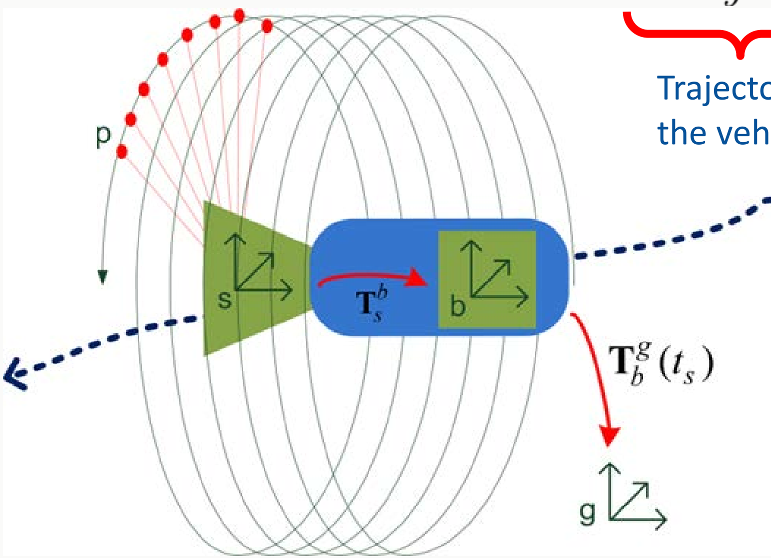


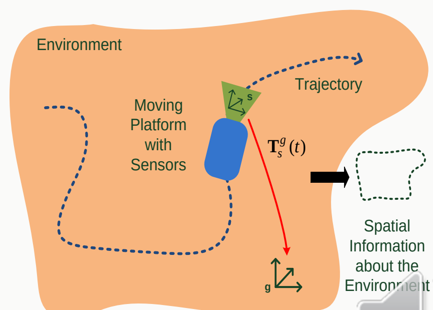
MOBILE LASER SCANNING TRANSFORMATIONS

T consists of a rotation R and a translation t (similarity transform without scale: 6 DOF)

$$
\begin{aligned}
\mathbf{p}^{global}_{object}(t_s) &= \mathbf{T}^{global}_{sensor}(t_s) \cdot \mathbf{p}^{sensor}_{object}(t_s) \\
&= \underbrace{\mathbf{T}^{global}_{body}(t_s)}_{\text{Trajectory of the vehicle}} \cdot \underbrace{\mathbf{T}^{body}_{sensor}}_{\text{System Calibration}} \cdot \mathbf{p}^{sensor}_{object}(t_s)
\end{aligned}
$$

T_s^{G}





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MOBILE LASER SCANNING

Sensor Synchronisation

$$
\begin{aligned}
\mathbf{p}^{global}_{object}(t_s) &= \mathbf{T}^{global}_{sensor}(t_s) \cdot \mathbf{p}^{sensor}_{object}(t_s) \\
&= \mathbf{T}^{global}_{body}(t_s) \cdot \mathbf{T}^{body}_{sensor} \cdot \mathbf{p}^{sensor}_{object}(t_s)
\end{aligned}
$$

object coordinate
In the global
coordinate system

position und orientierung
of the sensor (e.g.scanner)
in the global coordinate
system

System
calibration

object coordinate in
the sensor (e.g. scanner)
coordinate system

MOBILE LASER SCANNING – CONTEXT

Sensor Synchronisation

➔ this course

$$\begin{aligned}\mathbf{p}^{global}_{object}(t_s) &= \mathbf{T}^{global}_{sensor}(t_s)\cdot\mathbf{p}^{sensor}_{object}(t_s)\\ &= \mathbf{T}^{global}_{body}(t_s)\cdot\mathbf{T}^{body}_{sensor}\cdot\mathbf{p}^{sensor}_{object}(t_s)\end{aligned}$$

object coordinate
In the global
coordinate system

➔ Sensors & State Estimation (MSR-01)

➔ Coordinate Systems (MGE-01)

➔ this course

position und orientierung
of the body ~~of the sensor (e.g.scanner)~~
in the global coordinate
system

➔ Sensors & State Estimation (MSR-01)

➔ GNSS (MGE-02)

➔ this course

System
calibration

➔ this course

object coordinate in
the sensor (e.g. scanner)
coordinate system

➔ Sensors & State Estimation (MSR-01)

ADVANCED TECHNIQUES FOR MOBILE SENSING AND ROBOTICS – LECTURE CONTENT

(1) Mobile Laser Scanning

(2) Trajectory Estimation

(3) System Calibration

(4) Sensor Synchronisation

(5) From Images to Point Clouds (SfM)

(6) Accuracy of Point Clouds I

(7) Accuracy of Point Clouds II

(8) Deformation Analysis with Point Clouds I

(9) Deformation Analysis with Point Clouds II

CHAPTER 1: MOBILE LASER SCANNING CONTENT

$$\mathbf{p}^{global}_{object}(t_s) = \mathbf{T}^{global}_{body}(t_s) \cdot \mathbf{T}^{body}_{sensor} \cdot \mathbf{p}^{sensor}_{object}(t_s)$$

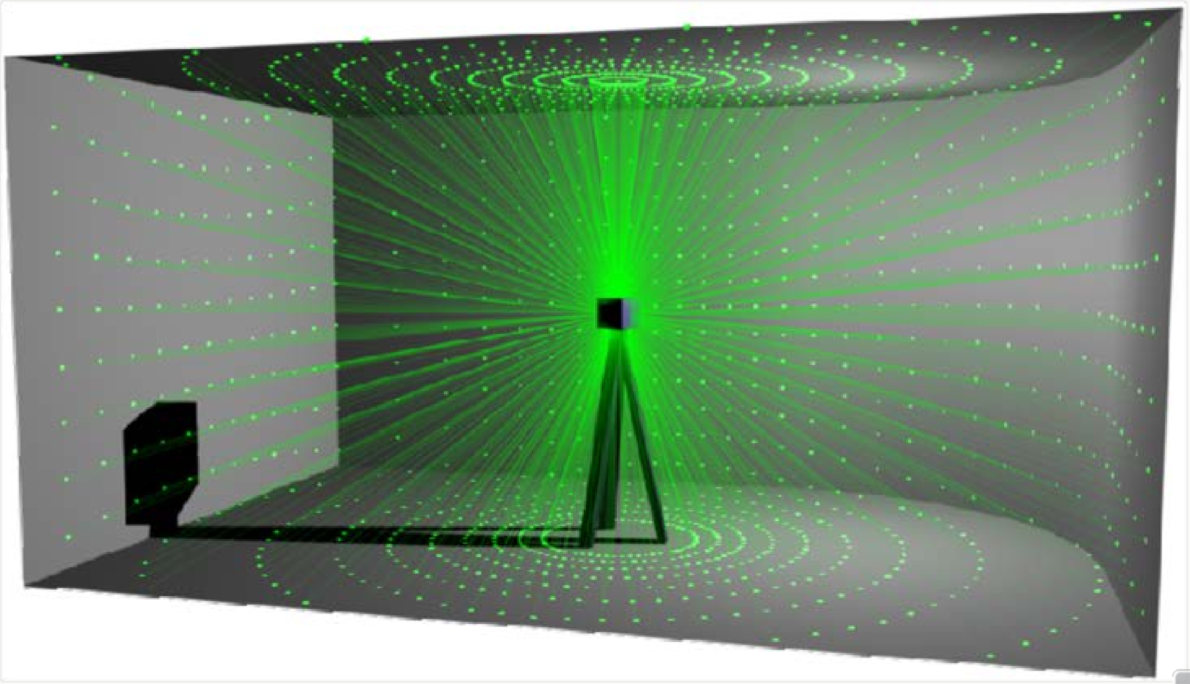
- Review of involved **coordinate systems /frames**
- Derivation of detailed georeferencing equation for the example of mobile laser scanning

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}^e_n(L,B)\,\mathbf{R}^n_b(\phi,\theta,\psi) \cdot \left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}^b_s(\alpha,\beta,\gamma) \cdot \begin{bmatrix} 0 \\ d \cdot \sin b \\ d \cdot \cos b \end{bmatrix} \right]$$

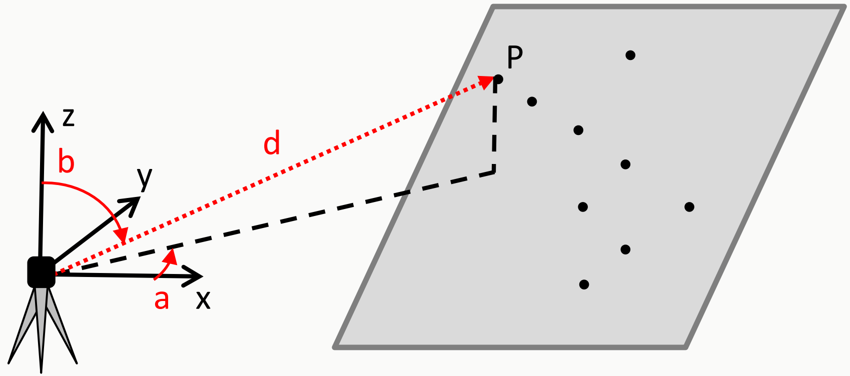
Attention: Usage of „frame“ and „coordinate system“ equivalent in this lecture

SENSOR FRAME
LASER SCANNER

- Frame, which is fixed to the sensor and in which the observations are given



SENSOR FRAME LASER SCANNER

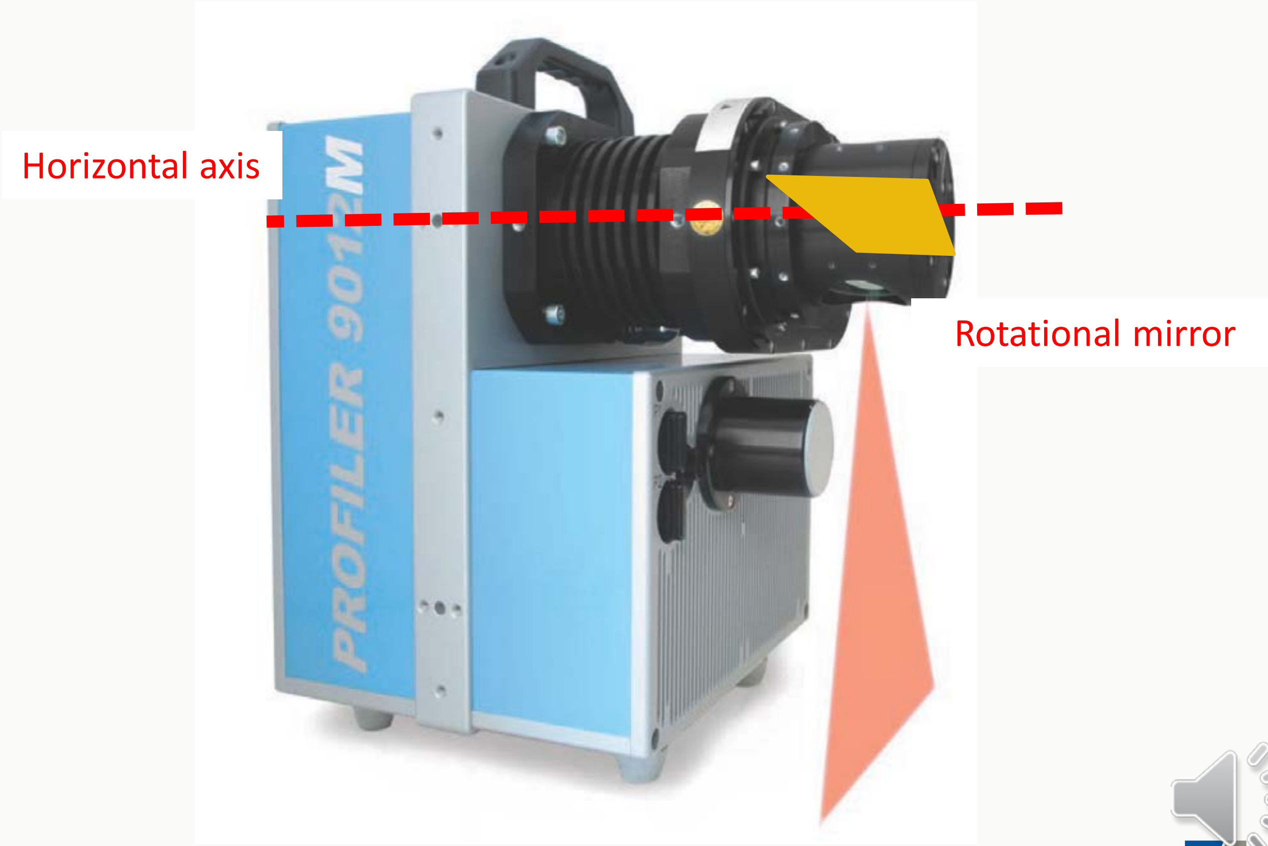


$$\begin{bmatrix} x_s \\ y_s \\ z_s \end{bmatrix} = \begin{bmatrix} d \cdot \sin b \cdot \sin a \\ d \cdot \sin b \cdot \cos a \\ d \cdot \cos b \end{bmatrix} \Longleftrightarrow \begin{bmatrix} d \\ b \\ a \end{bmatrix} = \begin{bmatrix} \sqrt{x_s{}^2 + y_s{}^2 + z_s{}^2} \\ \arccos\left(z_s / d\right) \\ \arctan\left(y_s / x_s\right) \end{bmatrix}$$

Cartesian Coordinates

Polar Coordinates

SENSOR FRAME
PROFILE SCANNER



SENSOR FRAME
PROFILE SCANNER

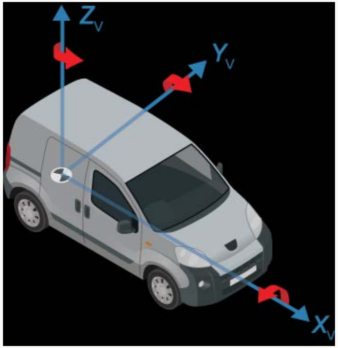
- No rotation around the vertical axis (a=0)

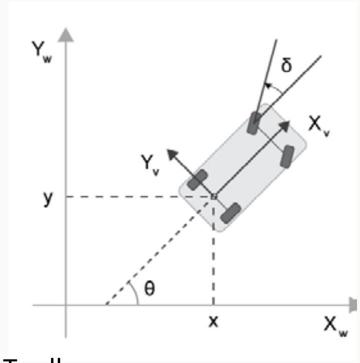
$$\begin{bmatrix} x_s \\ y_s \\ z_s \end{bmatrix} = \begin{bmatrix} d \cdot \sin b \cdot \sin a \\ d \cdot \sin b \cdot \cos a \\ d \cdot \cos b \end{bmatrix} = \begin{bmatrix} 0 \\ d \cdot \sin b \\ d \cdot \cos b \end{bmatrix}$$

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e (L, B) \mathbf{R}_b^n (\phi, \theta, \psi) \cdot \left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b (\alpha, \beta, \gamma) \cdot \begin{bmatrix} 0 \\ d \cdot \sin b \\ d \cdot \cos b \end{bmatrix} \right]$$

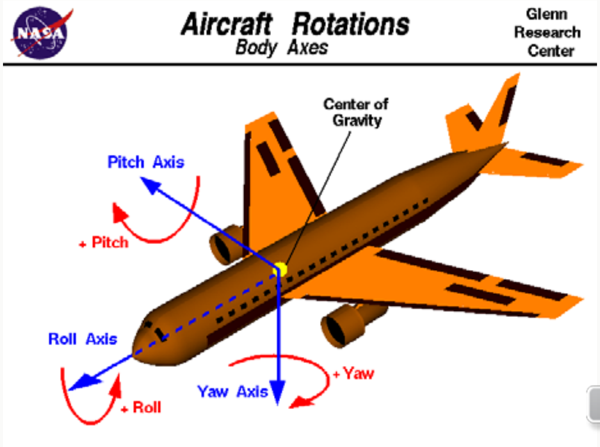
BODY/VEHICLE/PLATFORM FRAME

- Frame which is fixed to the moving platform
- Usually the origin and the axis of this system are known in some ‚world frame' (see later)
- Usually the body frame is not the same as the sensor frame



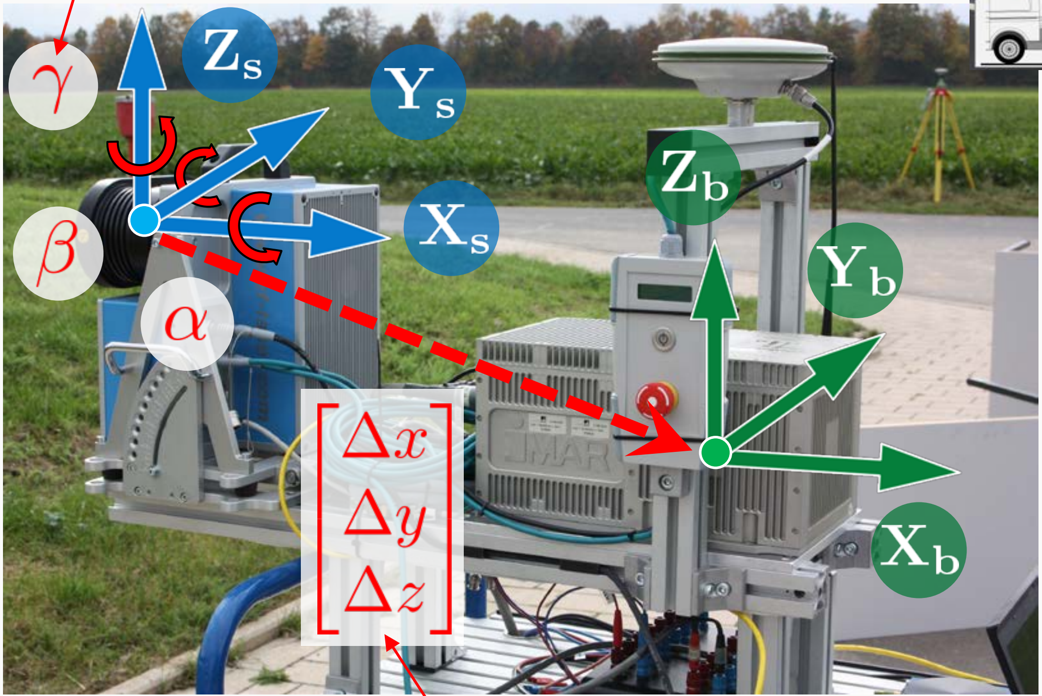


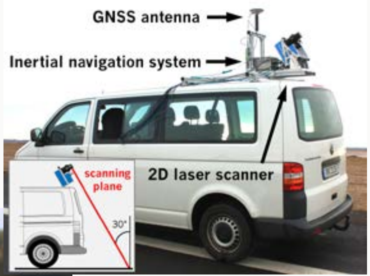
Matlab Autonomous Driving Toolbox



BODY FRAME
KINEMATIC LASER SCANNING

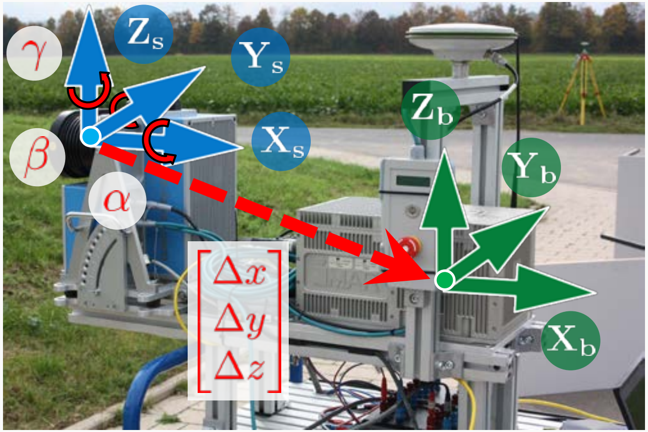
Boresight angles





Lever arm

SYSTEM CALIBRATION



- **System Calibration**: Determination of the transformation (lever arm and boresight angles) between sensor frame and body/platform/vehicle frame

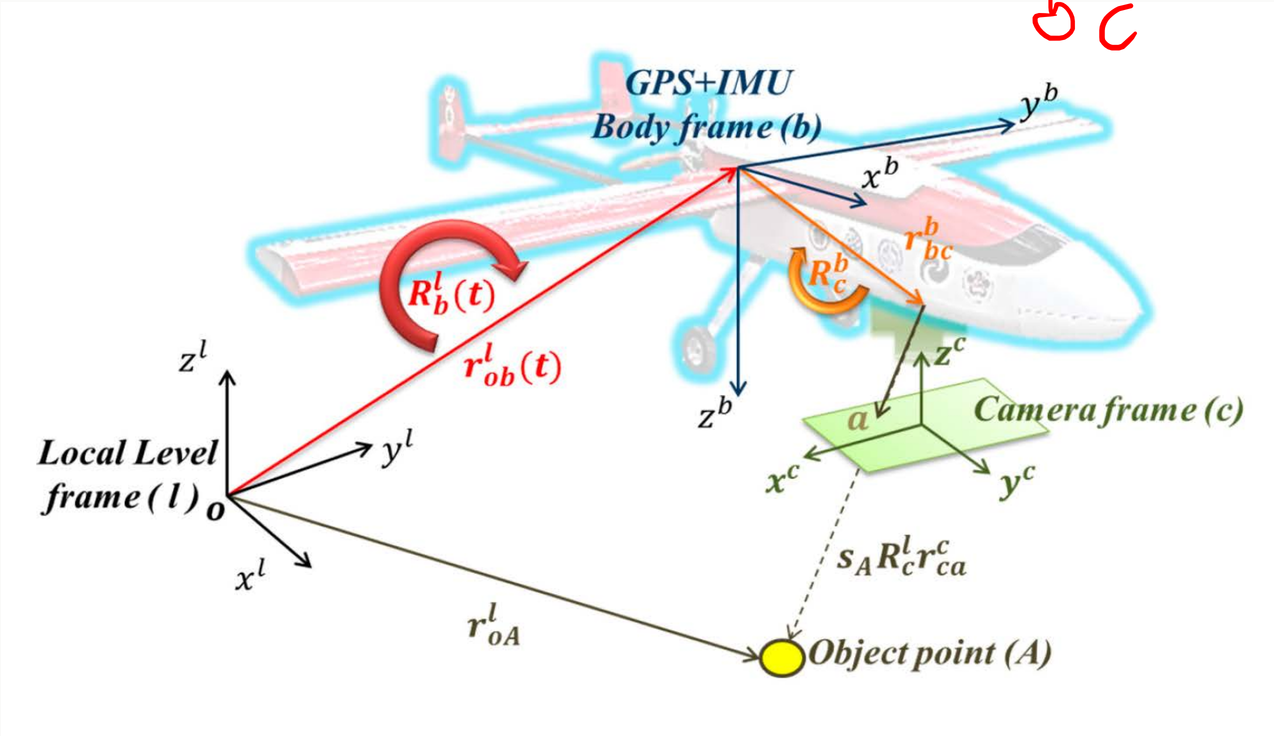
➔ Chapter System Calibration

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e\,(L, B)\,\mathbf{R}_b^n\,(\phi, \theta, \psi) \cdot \left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b\,(\alpha, \beta, \gamma) \cdot \begin{bmatrix} 0 \\ d \cdot \sin b \\ d \cdot \cos b \end{bmatrix} \right]$$

$$\mathbf{R}_s^b\,(\alpha, \beta, \gamma) = \begin{bmatrix} \cos(\beta)\cdot\cos(\gamma) & \cos(\alpha)\cdot\sin(\gamma) + \cos(\gamma)\cdot\sin(\alpha)\cdot\sin(\beta) & \sin(\alpha)\cdot\sin(\gamma) - \cos(\alpha)\cdot\cos(\gamma)\cdot\sin(\beta) \\ -\cos(\beta)\cdot\sin(\gamma) & \cos(\alpha)\cdot\cos(\gamma) - \sin(\alpha)\cdot\sin(\beta)\cdot\sin(\gamma) & \cos(\gamma)\cdot\sin(\alpha) + \cos(\alpha)\cdot\sin(\beta)\cdot\sin(\gamma) \\ \sin(\beta) & -\cos(\beta)\cdot\sin(\alpha) & \cos(\alpha)\cdot\cos(\beta) \end{bmatrix}$$

EXAMPLE AERIAL IMAGING

$\vec{v}^{e}_{eb}$ $\vec{r}^{b}_{bc}$ R^{b}_{c} ↑



From: Chiang, K.-W.; Tsai, M.-L.; Naser, E.-S.; Habib, A.; Chu, C.-H. New Calibration Method Using Low Cost MEMS IMUs to Verify the Performance of UAV-Borne MMS Payloads. Sensors 2015, 15, 6560-6585.

BODY FRAME TO GLOBAL FRAME (TRAJECTORY)

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi) \cdot \left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b(\alpha,\beta,\gamma) \cdot \begin{bmatrix} 0 \\ d \cdot \sin b \\ d \cdot \cos b \end{bmatrix} \right]$$

$$= \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi) \cdot \begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix}$$

Object point in body frame

Transformations from body frame to global frame

➔ Body is moving with respect to the global frame

➔ Transformation parameters are changing

➔ Trajectory estimation (➔ Trajectory Estimation)

NAVIGATION FRAME

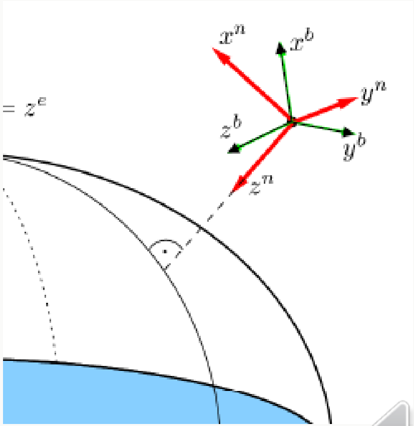
$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e\left(L, B\right) \boxed{\mathbf{R}_b^n\left(\phi, \theta, \psi\right)} \cdot \begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix}$$

Rotation from body to navigation frame, parametrized by 3 angles

- **Navigation frame**:

  Origin: origin of body frame
  Axis: North-East-Down (NED) or East-North-Up (ENU)

- The Navigation frame is usually the reference frame for attitudes



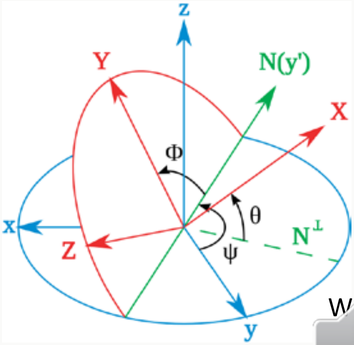
NAVIGATION FRAME

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi) \cdot \begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix}$$

Direction Cosine Matrix

$$\mathbf{R}_b^n = \begin{bmatrix} \cos(\theta)\cdot\cos(\psi) & -\cos(\phi)\cdot\sin(\psi)+\sin(\phi)\cdot\sin(\theta)\cdot\cos(\psi) & \sin(\phi)\cdot\sin(\psi)+\cos(\phi)\cdot\sin(\theta)\cdot\cos(\psi) \\ \cos(\theta)\cdot\sin(\psi) & \cos(\phi)\cdot\cos(\psi)+\sin(\phi)\cdot\sin(\theta)\cdot\sin(\psi) & -\sin(\phi)\cdot\cos(\psi)+\cos(\phi)\cdot\sin(\theta)\cdot\sin(\psi) \\ -\sin(\theta) & \sin(\phi)\cdot\cos(\theta) & \cos(\phi)\cdot\cos(\theta) \end{bmatrix}$$

- Euler angles
  - o Roll: ϕ (Phi)
  - o Pitch: θ (Theta)
  - o Yaw: ψ (Psi), also called heading



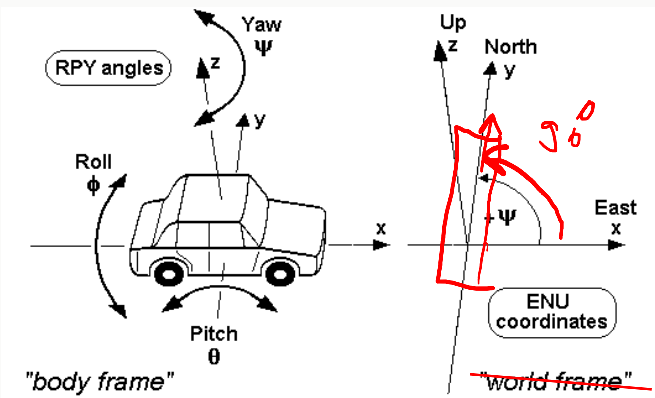
Wikipedia

Euler Angles rotate from Navigation to body frame

NAVIGATION/BODY FRAME

GROUND BASED VEHICLES

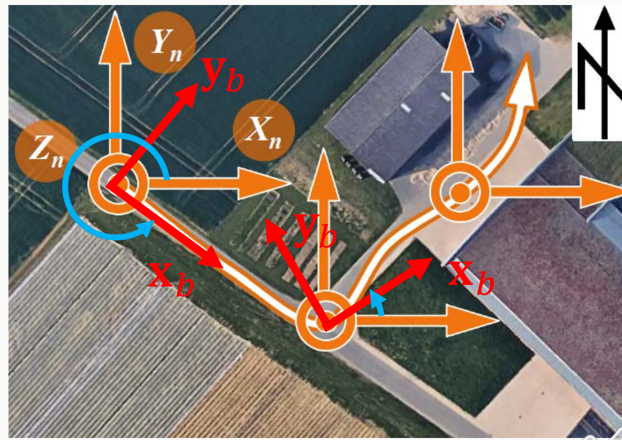
n-frame: East-North-Up
b-frame: forward-left-up
➔Heading towards North: Phi = Yaw = Heading = 90°



Wikipedia

Navigation frame

Yaw = 315°

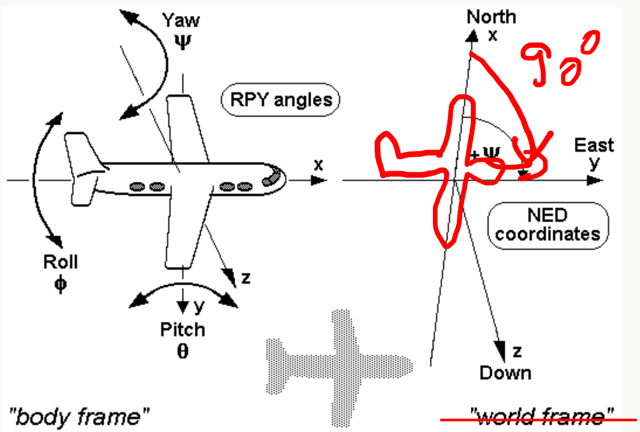


Yaw = 45°

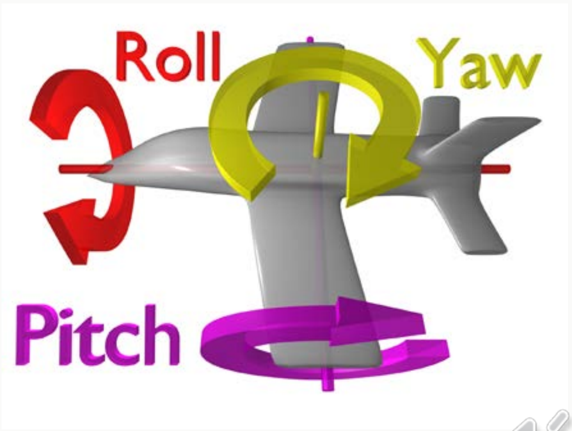
NAVIGATION/BODY FRAME

AERIAL VEHICLES

n-frame: North-East-Down
b-frame: forward-right-down
➔Heading towards East: Phi = Yaw = Heading = 90°



Wikipedia



Navigation frame

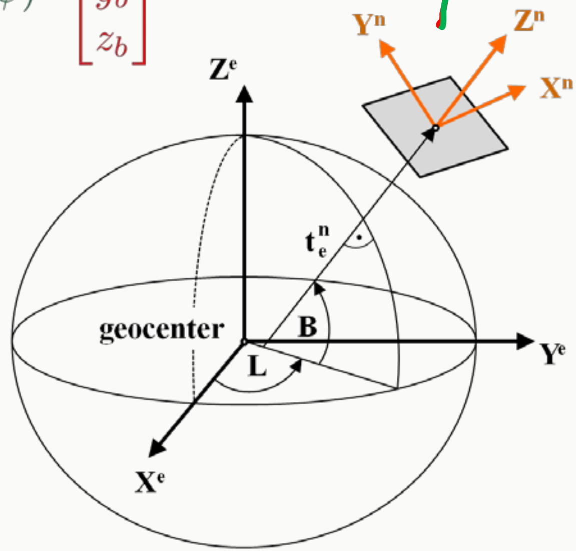
NAVIGATION FRAME TO EARTH FRAME

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi)\cdot\begin{bmatrix} x_b \\ y_b \\ z_b \end{bmatrix}$$

$$= \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\cdot\begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix}$$

Latitude L

Longitude B



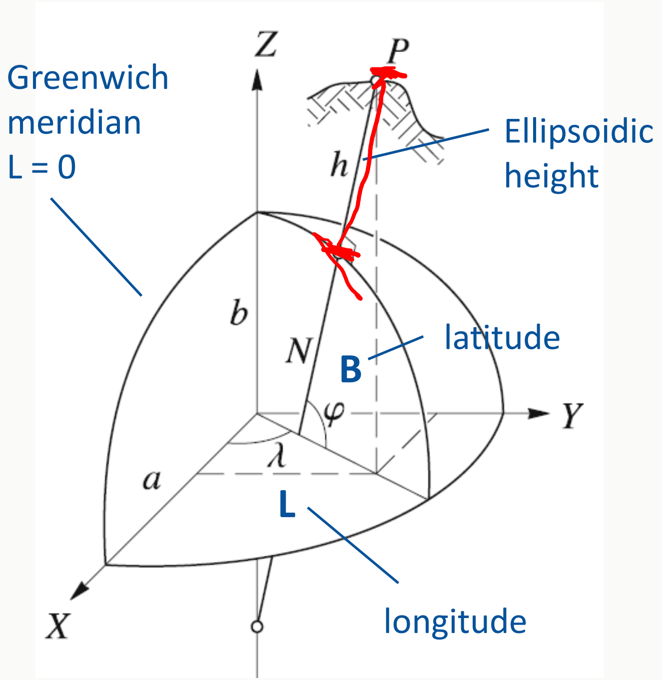
$$\mathbf{R}_n^e = \begin{bmatrix} -\sin(L) & -\sin(B)\cdot\cos(L) & \cos(B)\cdot\cos(L) \\ \cos(L) & -\sin(B)\cdot\sin(L) & \cos(B)\cdot\sin(L) \\ 0 & \cos(B) & \sin(B) \end{bmatrix}$$

Does not need to be calculated every time within a local area. Only Every 100-200m

EARTH FRAME COORDINATES

- ECEF
  (Earth Centred Earth Fixed)
  X^e, Y^e, Z^e
  ➔ cartesian, but not with reference to the Earth surface, good for calculations

- Geodetic /ellipsoidal
  B, L, h
  ➔ useful on a global scale, reference surface is the ellipsoid, not cartesian,
  need information about ellipsoid



Hofmann-Wellenhof et al. (2008), Fig.8.1

Slide by C.Holst

*CONVERSION TO ELLIPSOIDAL COORDINATES

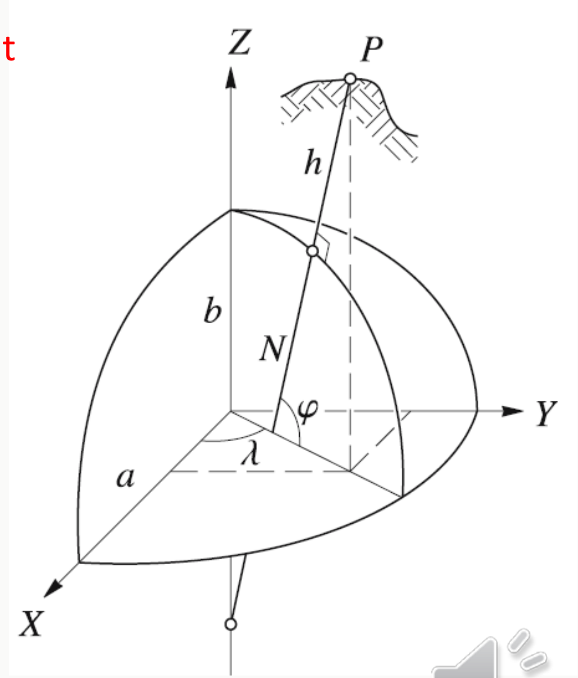
- Ellipsoidal coordinates are easier to interpret on earth
- Ellipsoidal coordinates need the definition of an reference ellipsoid (e.g. GRS80, WGS84, Bessel)
- λ… longitude, φ… latitude, h… ellipsoidal height

- $\boldsymbol{\lambda, \varphi, h \Rightarrow X, Y, Z}$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} (N(\varphi)+h)\cdot\cos\varphi\cdot\cos\lambda \\ (N(\varphi)+h)\cdot\cos\varphi\cdot\sin\lambda \\ \left(\frac{b^2}{a^2}N(\varphi)+h\right)\cdot\sin\varphi \end{bmatrix}$$

$$N(\varphi) = \frac{a^2}{\sqrt{a^2\cdot\cos^2\varphi + b^2\cdot\sin^2\varphi}}$$

… transverse radius of curvature



Hofmann-Wellenhof et al. (2008), Fig.8.1

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*CONVERSION TO ELLIPSOIDAL COORDINATES

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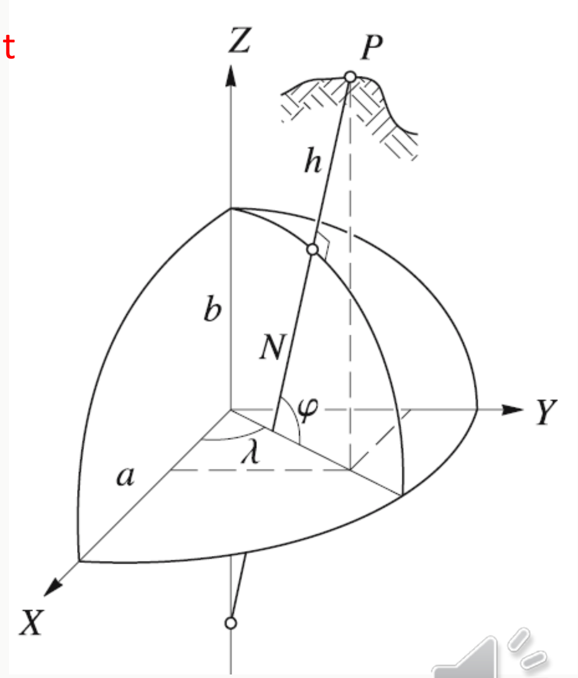
- Ellipsoidal coordinates need the definition of an reference ellipsoid (e.g. GRS80, WGS84, Bessel)
- λ… longitude, φ… latitude, h… ellipsoidal height

- $\boldsymbol{X, Y, Z \Rightarrow \lambda, \varphi, h}$

$$\begin{bmatrix}\varphi\\ \lambda\\ h\end{bmatrix} = \begin{bmatrix}\tan^{-1}\left(\frac{Z}{\sqrt{X^2+Y^2}}\cdot\left(1-\frac{a^2-b^2}{a^2}\cdot\frac{N(\varphi)}{N(\varphi)+h}\right)^{-1}\right)\\ \tan^{-1}\left(\frac{Y}{X}\right)\\ \frac{\sqrt{X^2+Y^2}}{\cos\varphi}-N(\varphi)\end{bmatrix}$$

- Iterate: $N(\varphi) = \frac{a^2}{\sqrt{a^2\cdot cos^2\,\varphi+b^2\cdot sin^2\,\varphi}}$



Hofmann-Wellenhof et al. (2008), Fig.8.1

Slide by C.Holst

*REFERENCE ELLIPSOIDS

- A reference ellipsoid has to be definied in combination with a reference frame
- $e^2 = \frac{a^2 - b^2}{a^2}$; $f = \frac{a-b}{a}$
- e... eccentricity
- f... flattening
- a... semi-major axis
- b... semi-minor axis

Misra und Enge (2001), Fig. 3.3

	a	**1/f**
WGS84	6378137.000	298.25722356300
GRS80	6378137.000	298.25722210088
Bessel	6377387.155	299.15281285000
PZ90.11	6378136.000	298.25783930300

*EARTH FRAME COORDINATES

- ECEF
  (Earth Centred Earth Fixed)
  X^e, Y^e, Z^e
  ➔ cartesian, but not with reference to the Earth surface, good for calculations

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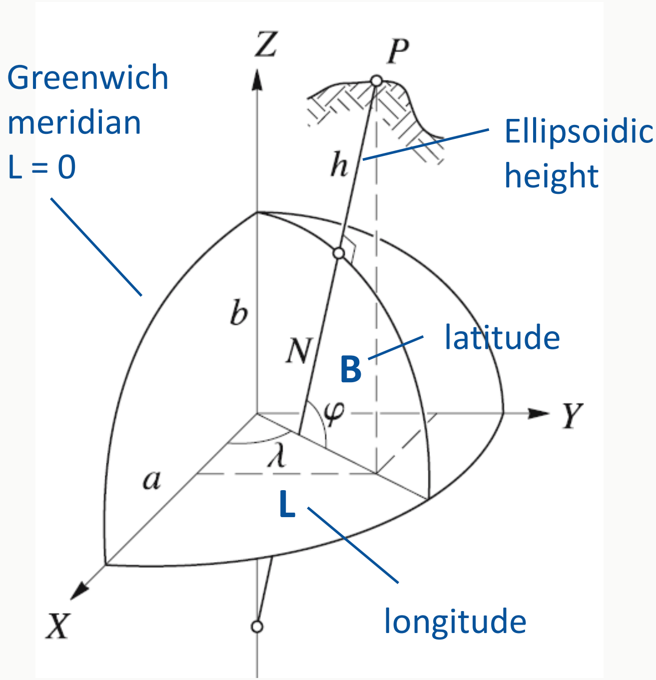
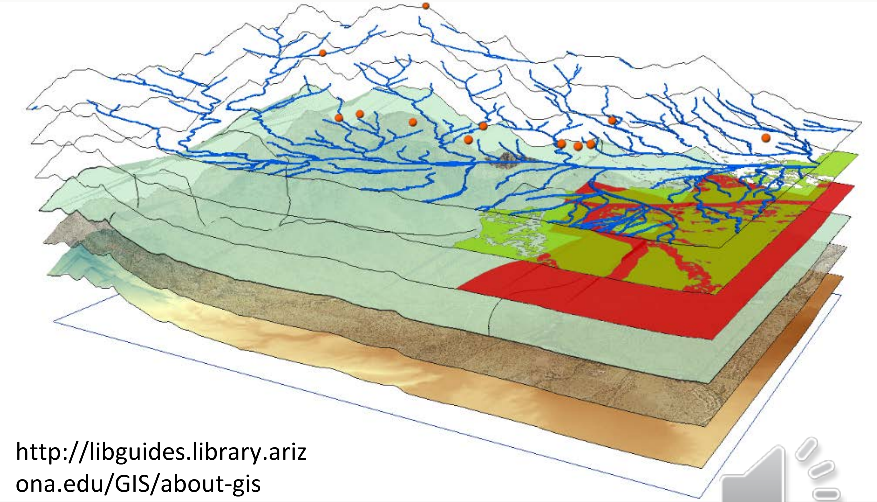


Hofmann-Wellenhof et al. (2008), Fig.8.1

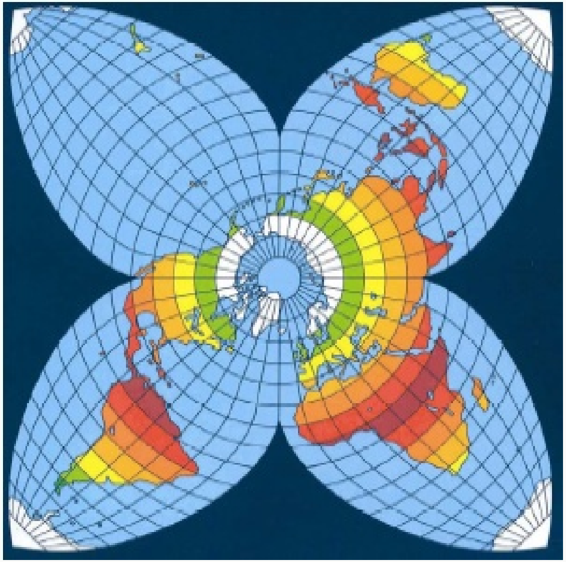
EARTH FRAME COORDINATES

- **Wanted:**
  - Metric coordinates (no longitude/latitude)
  - Levelled local reference plane
  - Separation of 2D-positions and heights
  - Intuitive ‚coordinates' (a map plus heights)



http://libguides.library.arizona.edu/GIS/about-gis

HOW TO FLATEN THE EARTH?



Projection of 3D coordinates in 2D plane =>

Not applicable without distortion

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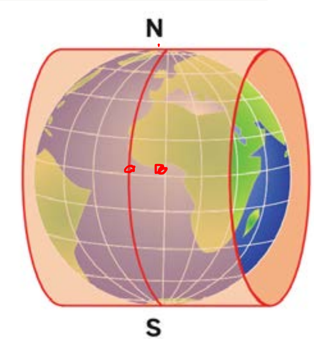
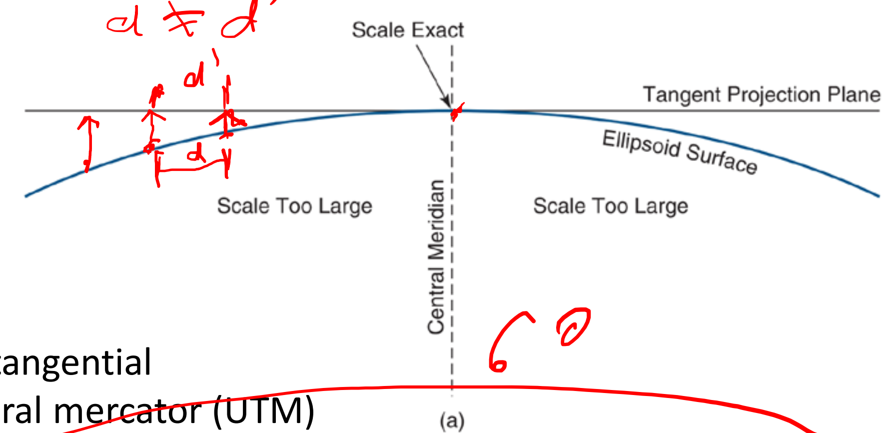
REALIZATION OF MAP PROJECTION

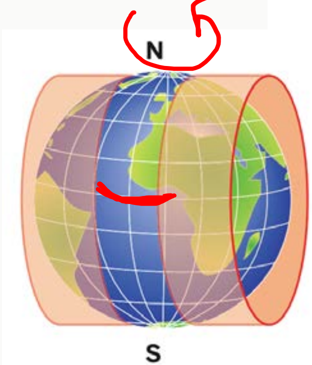


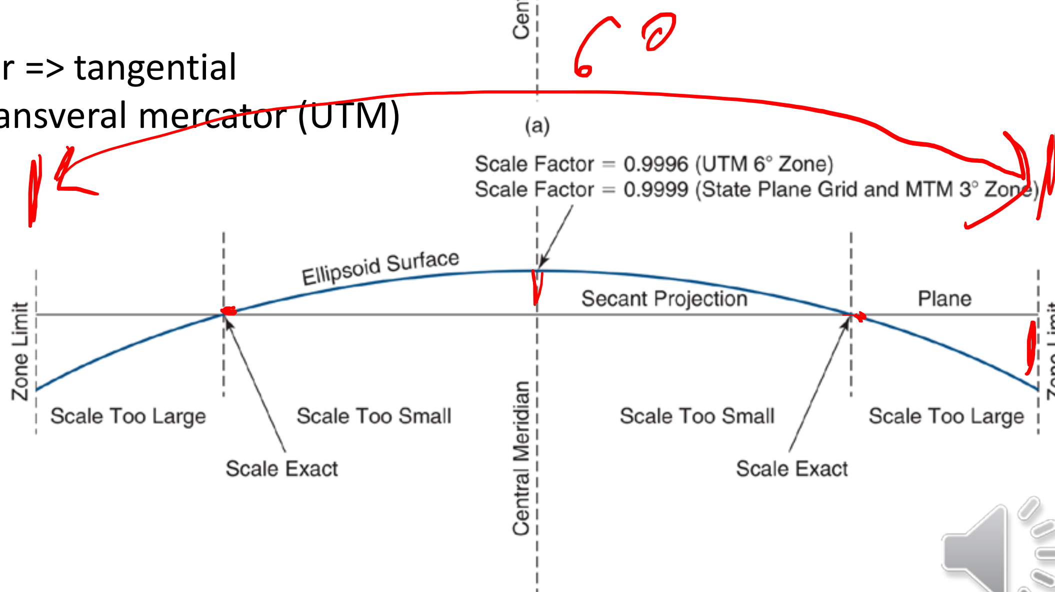


Above: Gauß-Krüger => tangential

Below: Universal transversal mercator (UTM)

=> intersectional





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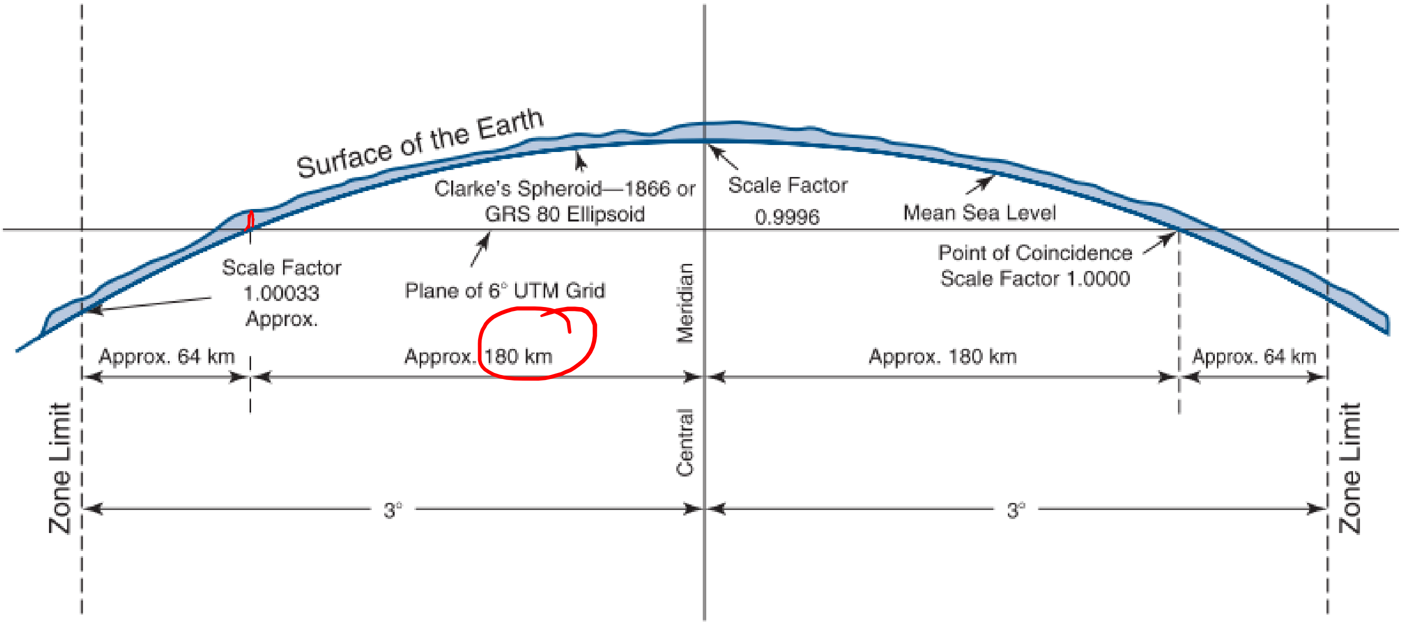
UTM PROJECTION: SCALE



Source: Kavanagh (2014)

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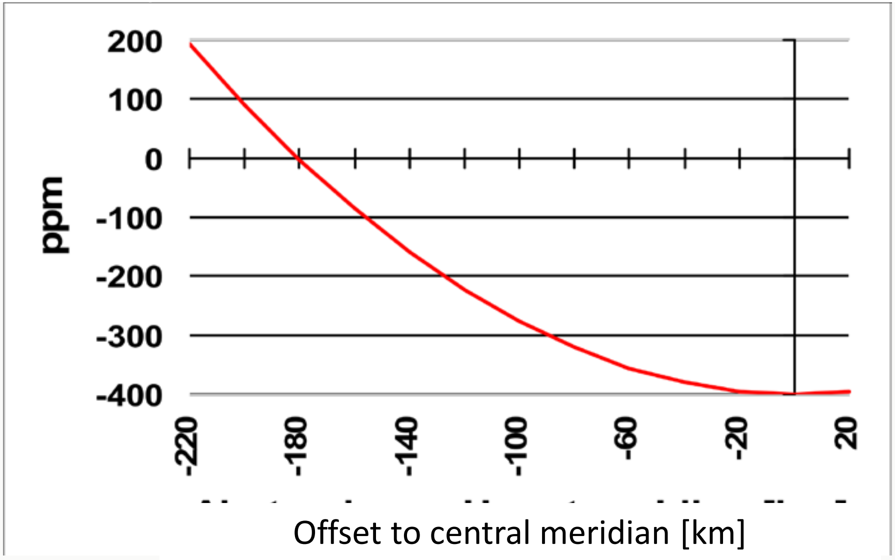
DISTORTION DUE TO PROJECTION

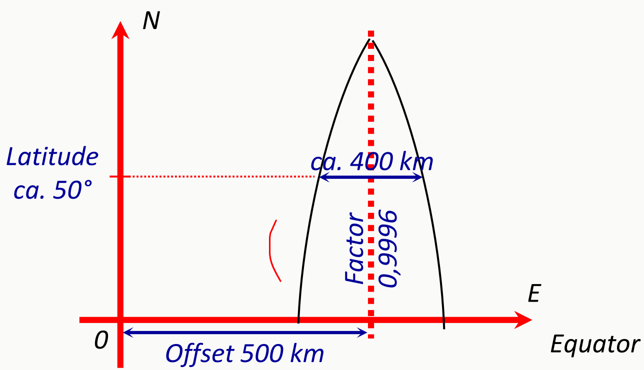
Offset to central meridian [km]	Distortion in distance [mm] (distance 100 m, height = 0 m above GRS80 ellipsoid)
0	- 40
100	- 28
180	0
200	+ 9



Source: Benning (2009)

UTM CHARACTERISTICS

- Zone is 6° wide
- Projection is isogonal / equal of angle
- Northing value of the equator: N = 0 m
- Easting value of each central meridian: E = 500‘000 m
- Scale factor at central meridian: 0.9996
- Zone numbering commences with 1 in the zone 180°W to 174°W and increases eastward to zone 60 at the zone 174°E to 180°E
- Projection limits of latitude 80°S to 80°N



East [m]	32 364939
North [m]	5621299

WRAP UP – GEOREFERENCING EQUATION

$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi)\cdot\left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b(\alpha,\beta,\gamma)\cdot\begin{bmatrix} 0 \\ d\cdot\sin b \\ d\cdot\cos b \end{bmatrix}\right]$$

Trajectory parameters (position and orientation)

System calibration usually constant over time

Sensor observations of an object point

Global coordinates of an object point

optional

Transformation to „useful“ coordinates (e.g. UTM)

TRAJECTORY DATA ARE GIVEN IN UTM COORDINATES?

$$\overset{\text{UTM}}{\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix}} = \overset{\text{UTM}}{\begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}} + \underbrace{\cancel{\mathbf{R}_n^e (L, B)}}_{= 1} \mathbf{R}_b^{\cancel{n}\,\text{UTM}} (\phi, \theta, \psi) \cdot \left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b (\alpha, \beta, \gamma) \cdot \begin{bmatrix} 0 \\ d \cdot \sin b \\ d \cdot \cos b \end{bmatrix} \right]$$

- Navigation frame and global frame already have the same axis directions
  ➔ global frame serves as reference frame for roll, pitch yaw
  ➔ Navigation to Earth Rotation is not necessary
- Distance measurements of the scanner has to be scaled along their East component (according to the distance to the central meridian)

WHAT YOU HAVE LEARNED TODAY

- What is mobile mapping, especially mobile laser scanning
- How is the transformation chain from a local sensor observation in the sensors coordinate system to a global coordinate system (**georeferencing equation**)
- What coordinates systems are involved?
- What parameters are needed in this chain and where do they come from?

WHAT YOU WILL LEARN IN THE REST OF THE COURSE

- How are trajectory parameters calculated and how accurate are they (repetition + smoothing and accuracies)?
- How are system calibration parameters derived?
- How can sensors can be synchronized?
- How are point clouds derived from images?
- How accurate are point clouds?
- How can you do deformation analysis with point clouds?

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THANKS