MSC GEODETIC ENGINEERING

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

04: SENSOR SYNCHRONIZATION

DR. LASSE KLINGBEIL

INSTITUTE FOR GEODESY AND GEOINFORMATION
UNIVERSITY OF BONN

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)

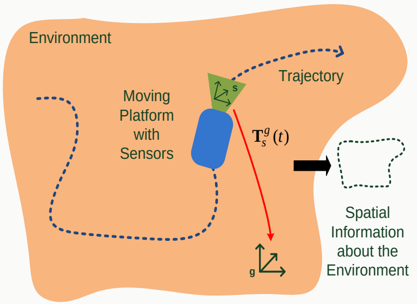
(6) Accuracy of Point Clouds I

(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



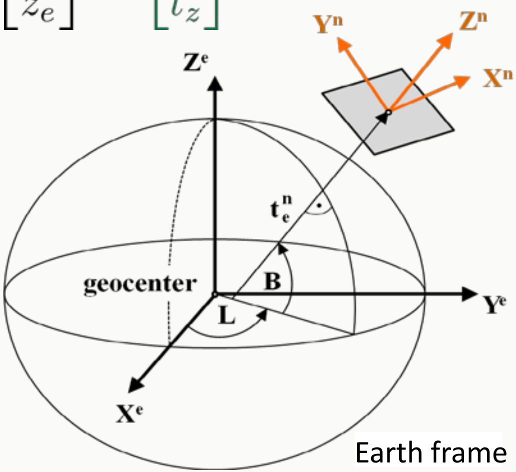
$$\mathbf{p}_{object}^{global}(t_s) = \mathbf{T}_{body}^{global}(t_s) \cdot \mathbf{T}_{sensor}^{body} \cdot \mathbf{p}_{object}^{sensor}(t_s)$$

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

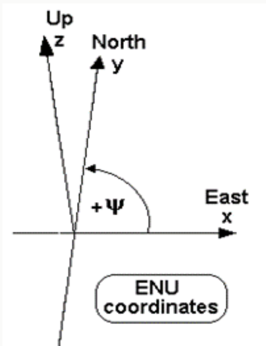
$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e(L,B)\,\mathbf{R}_b^n(\phi,\theta,\psi) \cdot \left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b(\alpha,\beta,\gamma) \cdot \begin{bmatrix} 0 \\ d \cdot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

CHAPTER 2: TRAJECTORY PARAMETERS

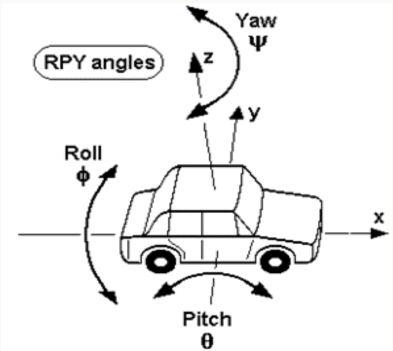
$$\begin{bmatrix} x_e \\ y_e \\ z_e \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \mathbf{R}_n^e\,(L, B)\,\mathbf{R}_b^n\,(\phi, \theta, \psi) \cdot \left[\begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \mathbf{R}_s^b\,(\alpha, \beta, \gamma) \cdot \begin{bmatrix}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



Earth frame



Navigation frame

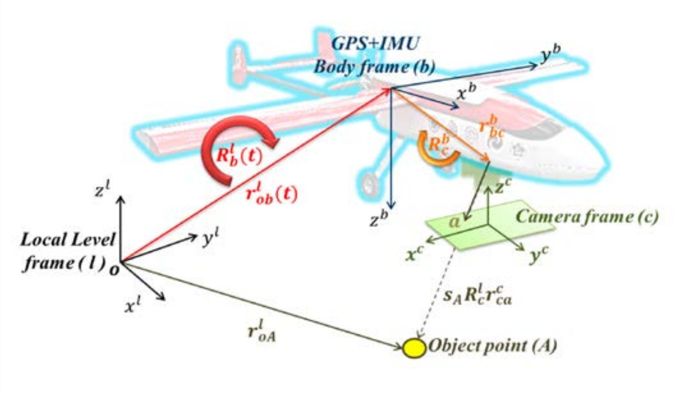


"body frame"

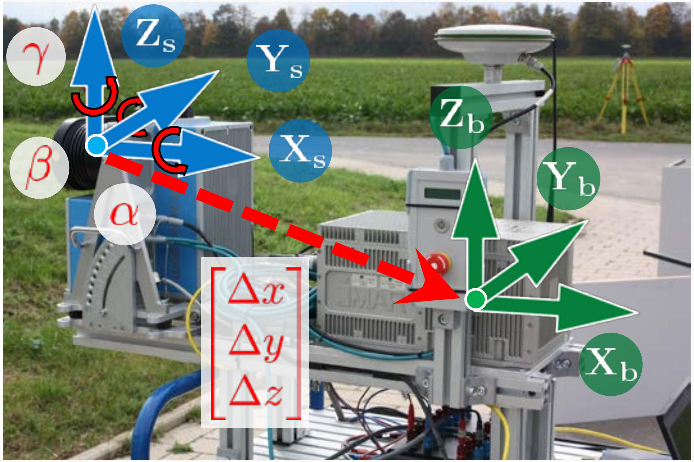
- Review of inertial navigation, strapdown integration and Kalman Filtering
- Introduced **Kalman Smoothing**
- Evaluation of **trajectory estimation**

CHAPTER 3: SYSTEM CALIBRATION

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



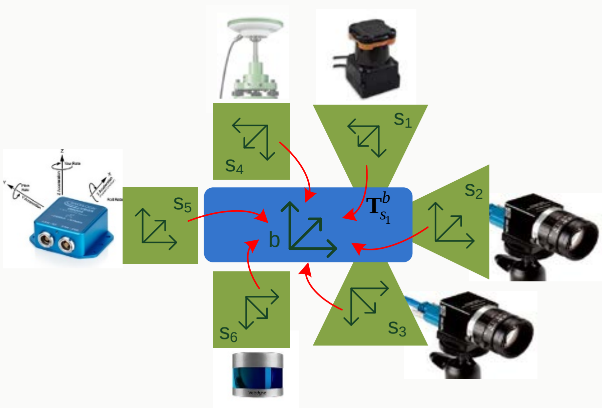
From: Chiang, K.-W.; Tsai, M.-L.; Naser, E.-S.; Habib, A.; Chu, C.-H. New Calibration Method Using Low Cost MEM IMUs to Verify the Performance of UAV-Borne MMS Payloads. Sensors 2015, 15, 6560-6585.

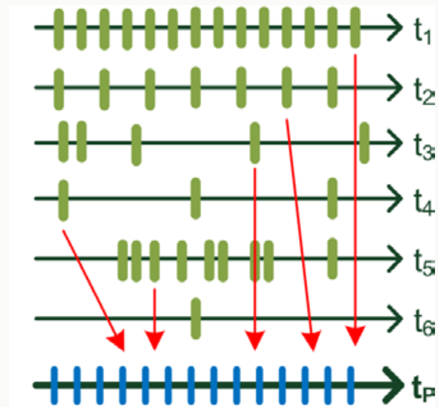


- Overview of **system calibration** methods
- Detailed derivation of **plane based calibration**

CHAPTER 4: SENSOR SYNCHRONISATION

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





- Why is sensor synchronization important?
- Methods for sensor synchronization

TYPICAL DATA RATES

Sensor	Typical rates
GNSS receiver	1-10Hz
Inertial measurement Unit	100-1000Hz
Laser scanner	100-1000kHz (point rate), 10-100Hz (profile rate)
Camera	1-100Hz
Depth Cameras	1-100Hz

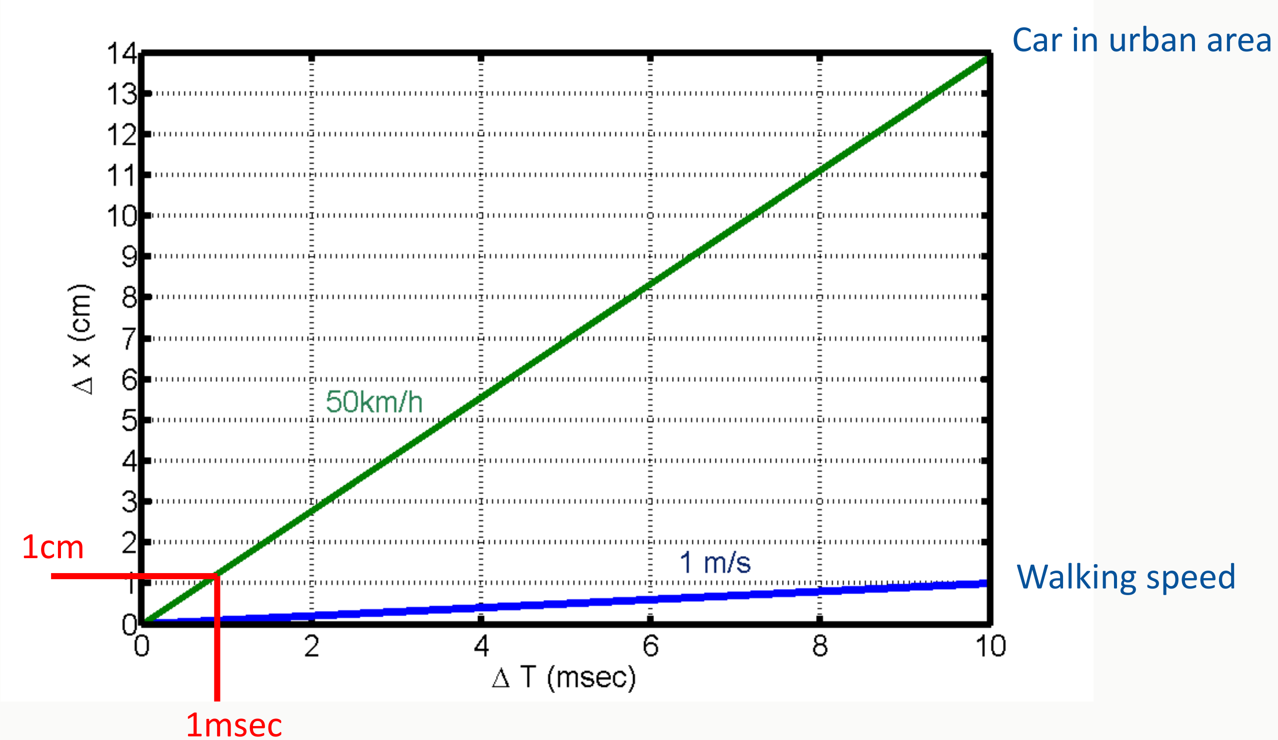
SENSOR SYNCHRONIZATION – WHY?

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

- Time difference **dt=dt‘-dt“** between scanner observation and trajectory parameter leads to wrong assignement of observations to the trajectory and therefore to a wrong transformation in the georeferencing equation
- Error depends on moving speed and rotation rate

SENSOR SYNCHRONIZATION – WHY?

TRANSLATION ERROR DUE TO TIME SYNC ERROR



UNIVERSITÄT BONN igg

SENSOR SYNCHRONIZATION – WHY?

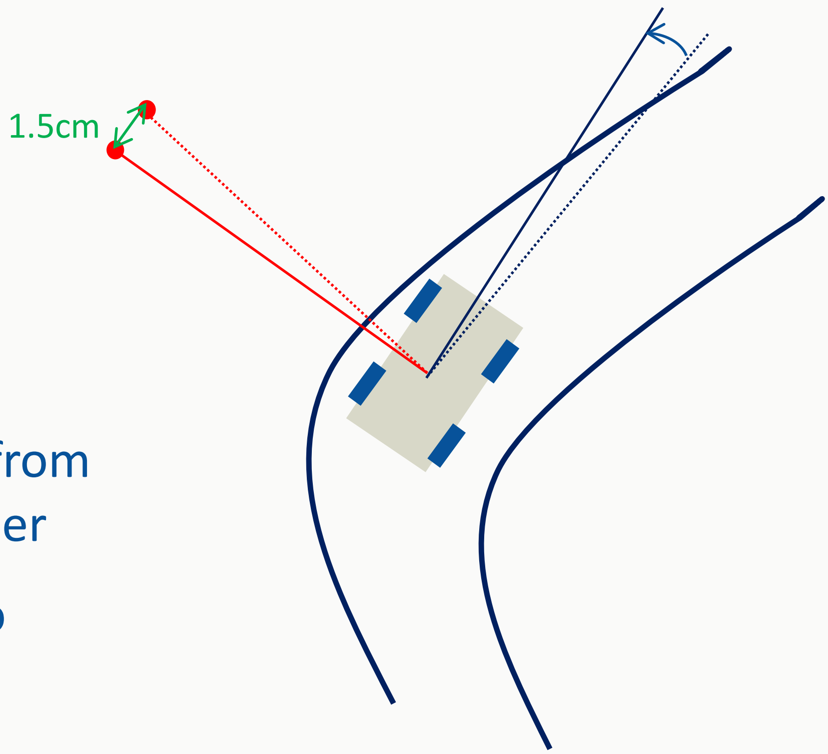
REQUIRED TIME RESOLUTION [MILLISECONDS]

			Spatial Resolution			
Velocity	km/h	m/s	1 mm	1 cm	1 dm	1 m
	3,6	1,0	1	10	100	1000
	10,8	3,0	0,3	3	33	333
	100,0	27,8	0,04	0,36	3,6	36
	200,0	55,5	0,02	0,18	1,8	18

SENSOR SYNCHRONIZATION – WHY?

ROTATION ERROR ➔ SCAN POINT ERROR DUE TO TIME SYNC ERROR

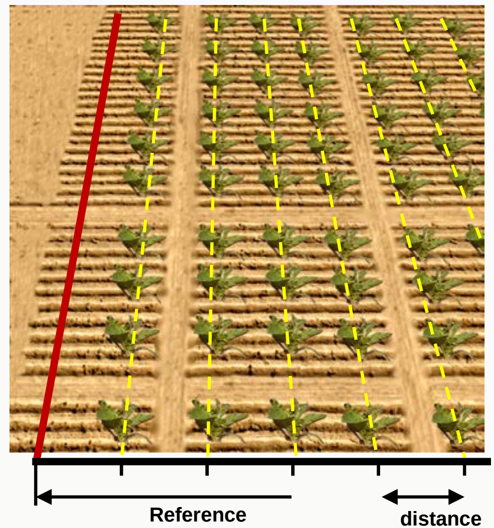
- Assume a 90° turn in 1 seconds
- rotation rate 90 °/sec
- dt = **1msec** leads to 0.1° angle error
- Assume 10m distance from the object to the scanner
- 0.1° Angle error lead to **1.5cm position** error



SENSOR SYNCHRONIZATION – WHY?

MANIPULATING THE ENVIRONMENT, CONTROL AND ACTION

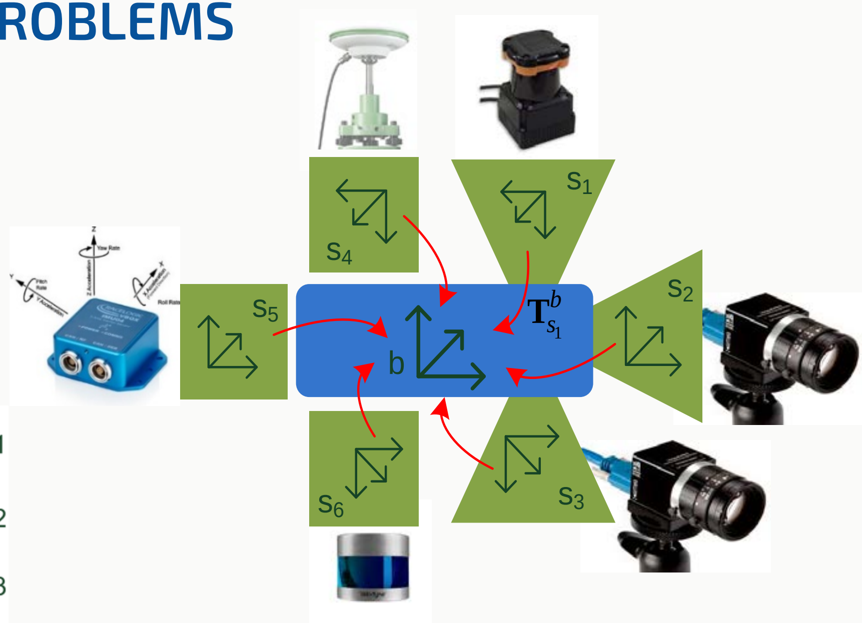
- Perfoming an action at a specific position also needs high synchronization accuracy, depending on movement speed

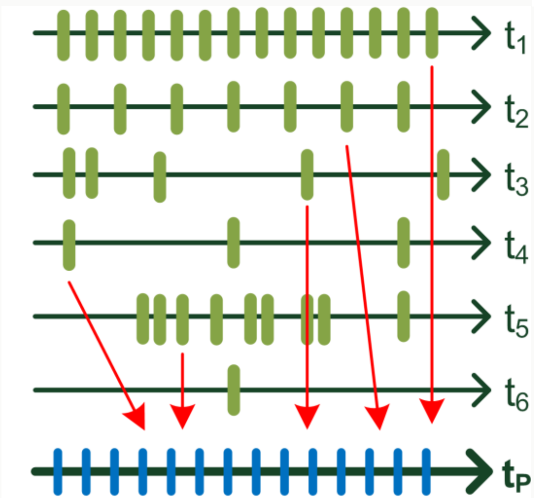


Example: GNSS controlled sugar beet seeding

SYNCHRONIZATION PROBLEMS

Problem 1) How to assign a time stamp to a measurement?



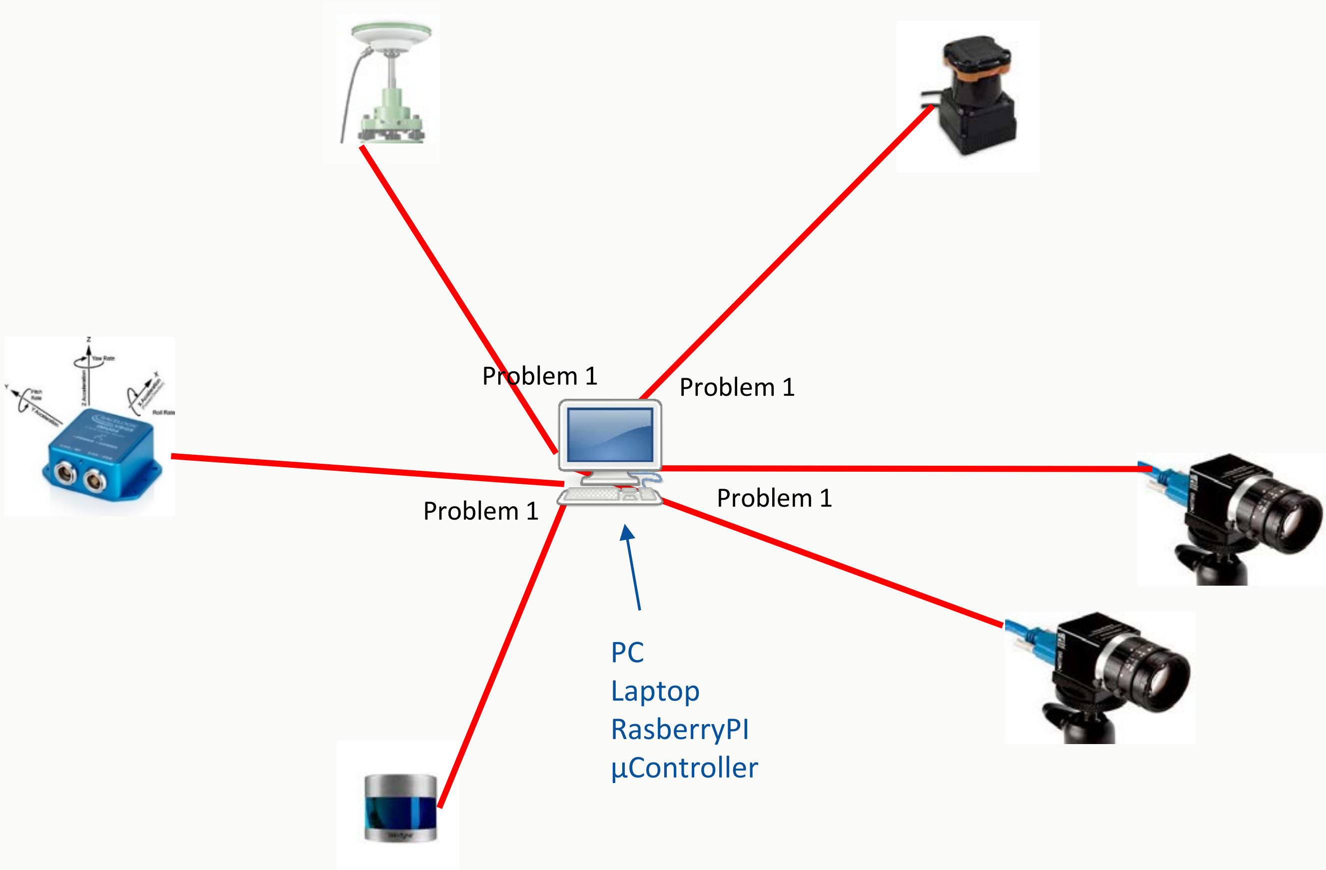


Problem 2) What clock to use for time stamping?

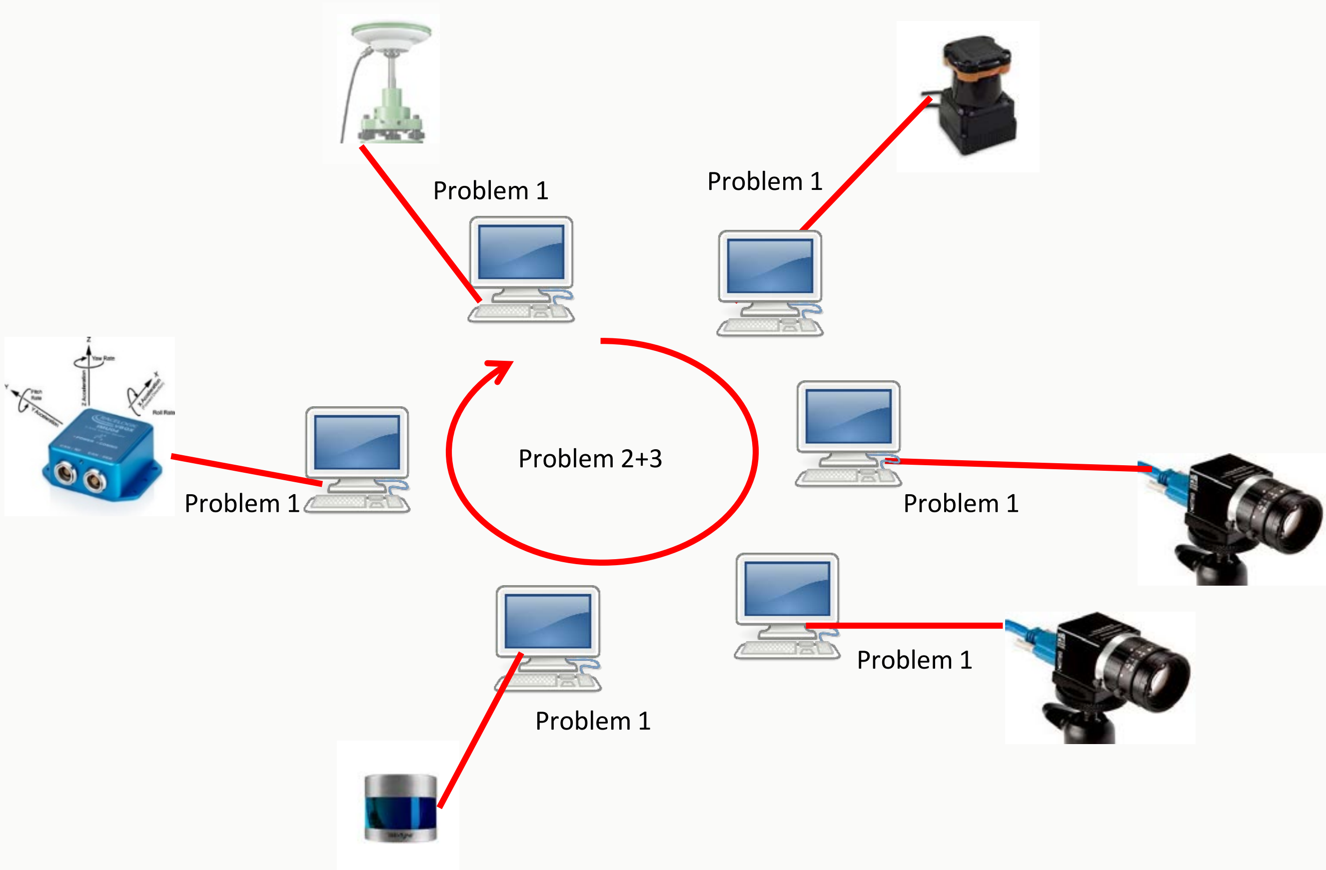
Problem 3) How to synchronize multiple clocks

UNIVERSITÄT BONN igg

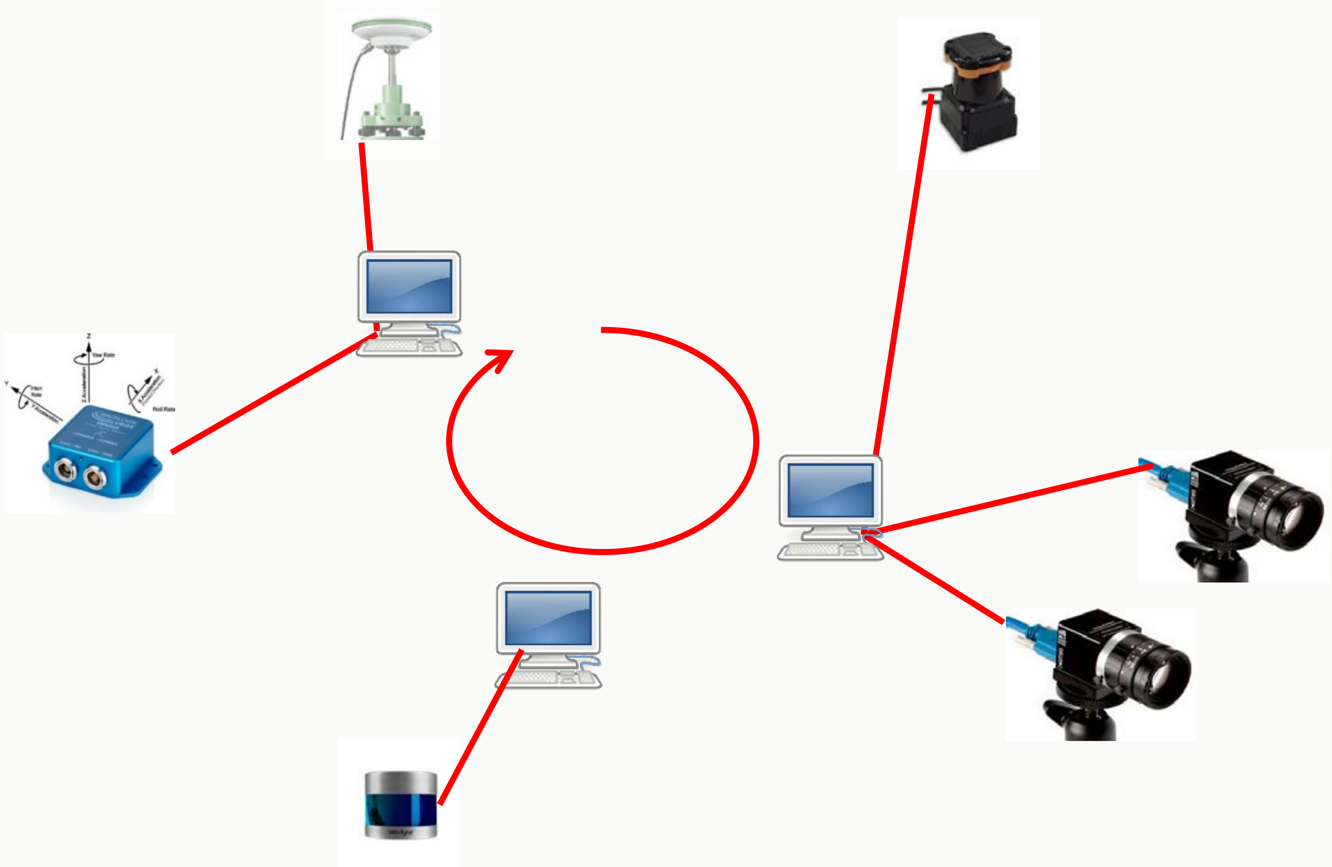
SYNCHRONIZATION PROBLEMS



SYNCHRONIZATION PROBLEMS



SYNCHRONIZATION PROBLEMS



PROBLEM 1

HOW TO ASSIGNE A TIME STAMP TO A MEASUREMENT?

- **Option 1**: The sensor already already provides you with properly time tagged measurements
  ➔go directly to Problem 2 (what is the time base?)
- **Option 2**: The sensor provides an electronic signal (e.g. pulse) at the moment when the measurement happens
- **Option 3**: The sensors performs the measurement at the moment it receives a trigger in form of an electronic signal (e.g. pulse)

PROBLEM 1 – OPTION 1 (STAMPED DATA)

GNSS RECEIVERS

- GNSS receivers always provide data which are properly time stamped in *Coordinated Universal Time* (UTC) (**more on that later**)

- Most Inertial measurement systems, which contain a GNSS receiver, also provide data (position, orientation, accelaration, velocity, angular rate) time stamped in UTC

UNIVERSITÄT BONN igg

PROBLEM 1 – OPTION 2 (RECEIVE PULSE)

GNSS RECEIVERS

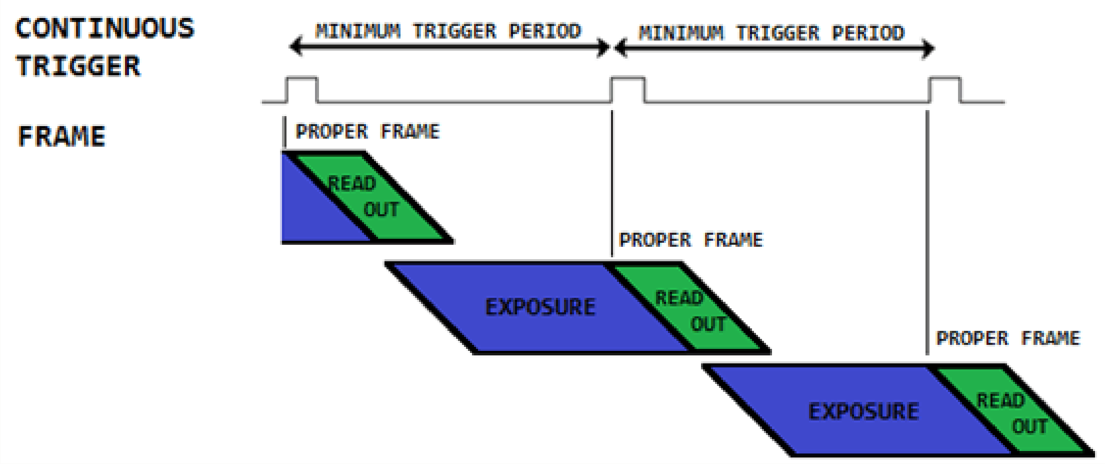
- Higher grade GNSS receivers provide an electronic signal (PPS: Pulse Per Second) at the time a GNSS measurement is performed
- This PPS can be also used to synchronize other clocks

(More on that later)

PROBLEM 1 – OPTION 2 (RECEIVE PULSE)

INDUSTRY CAMERAS

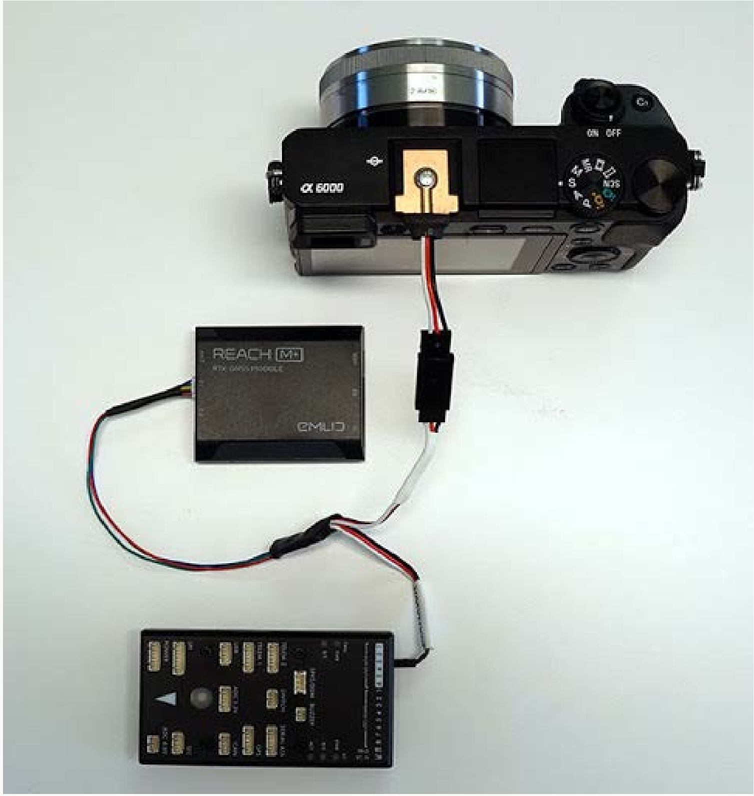
- Industry cameras usually provide a trigger output synchronized with the shutter



PROBLEM 1 – OPTION 2 (RECEIVE PULSE)

CONSUMER CAMERAS

- With some camera the hot shoe (flash synchronization) can be used to generate an electronic signal
- Not possible with all cameras
- Sometimes restricts exposure time

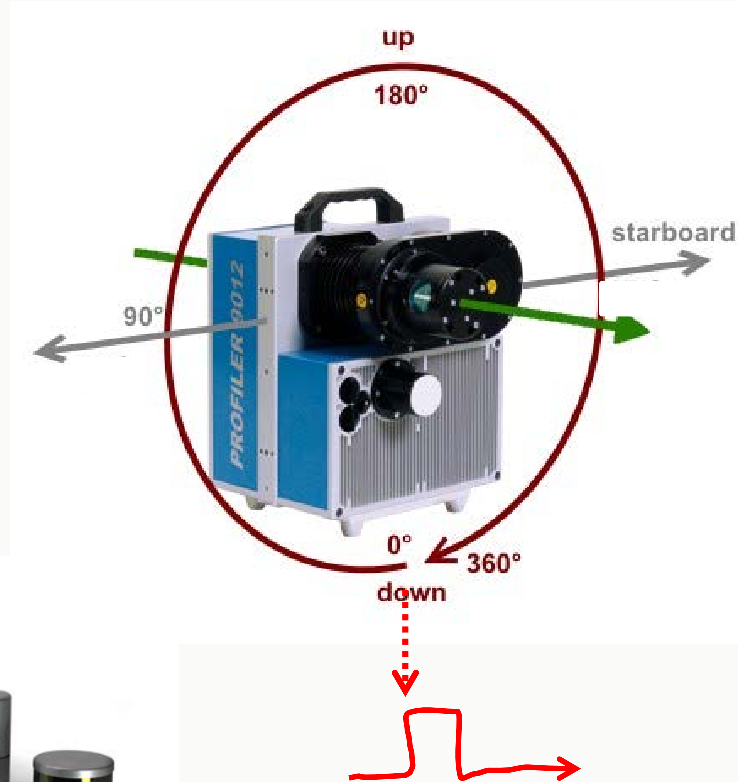


UNIVERSITÄT BONN igg

PROBLEM 1 – OPTION 2 (RECEIVE PULSE)

LASER SCANNERS

- Most scanners provide a signal when the profile crosses 0°



PROBLEM 1: OPTION 3 (SEND TRIGGER)

LASER SCANNERS

- Some scanner mirror rotations can
  be synchronized with an external
  oszillation
- Does not really help with time
  synchronization, because it synchronizes
  oszillations not single events

PROBLEM 1: OPTION 3 (SEND TRIGGER)

CAMERAS

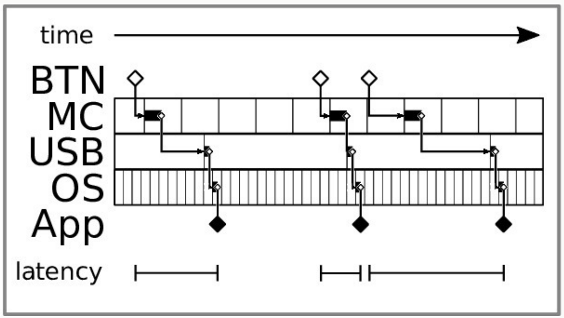
- Industry Cameras usually provide a trigger input signal
- Some consumer cameras also provide similar options

- Problem: It is not always clear, what happens between the trigger signal and the actual moment of exposure (e.g. autofocus, brightness adjustments, various settings)

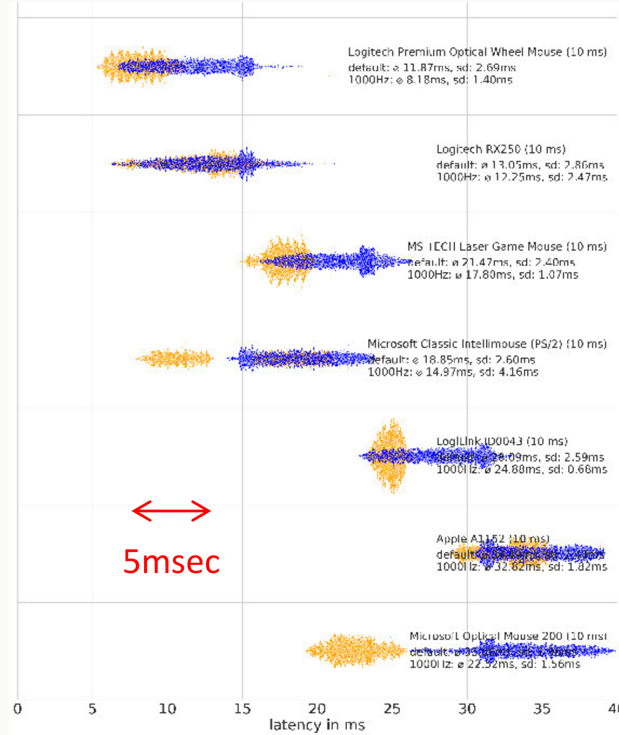
PROBLEM 1 – NO OPTION

USB CONNECTED DEVICES

- USB connected sensors without any extra sync possibilities are in general problematic



From: Raphael Wimmer, Andreas Schmid, and Florian Bockes. 2019. On the Latency of USB-Connected Input Devices. In Proceedings of CHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/3290605.3300650



Latency and jitter of button clicks in USB mice

UNIVERSITÄT BONN igg

PROBLEM 2

WHAT CLOCK TO USE FOR TIME STAMPING?

- Measuring time is based on the bbservation of a periodic process and counting the periods

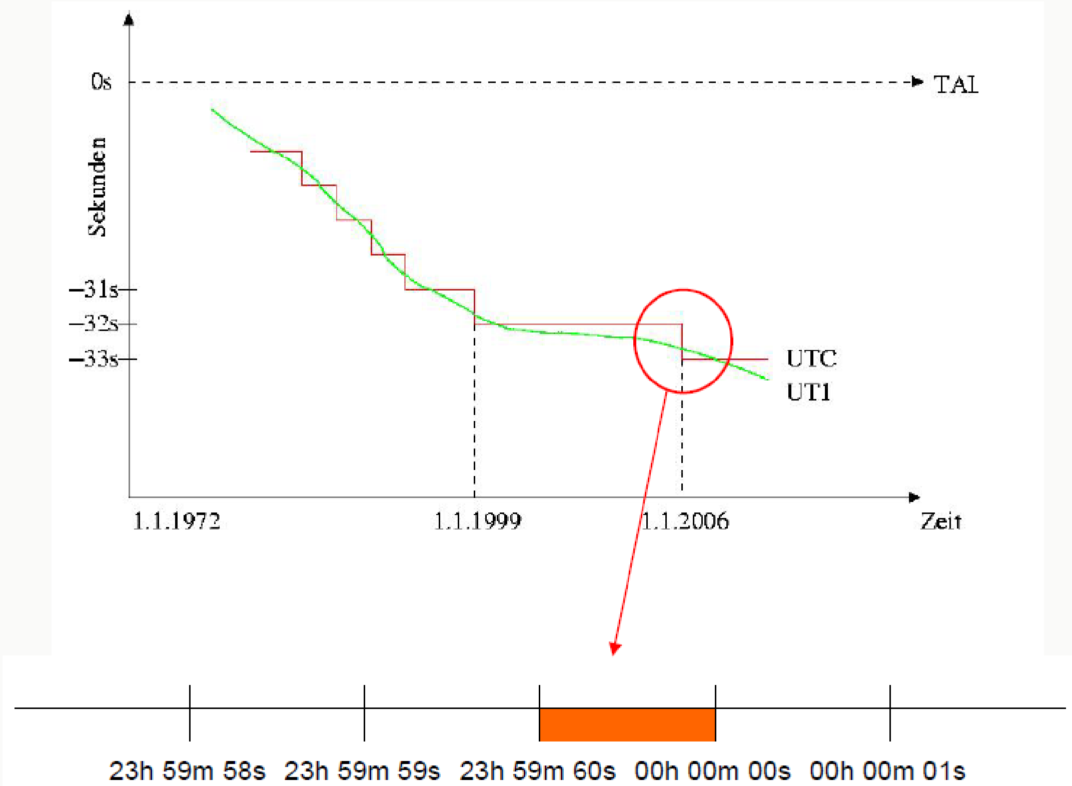
Periodic process	Representative time systems
Earth rotation	Universal time (UT)
	Greenwich sidereal time (Θ_0)
Earth revolution	Terrestrial dynamic time (TDT)
	Barycentric dynamic time (BDT)
Atomic oscillations	International atomic time (TAI)
	Coordinated UT (UTC)
	Reference time in satellite-based positioning systems

TIME SYSTEMS

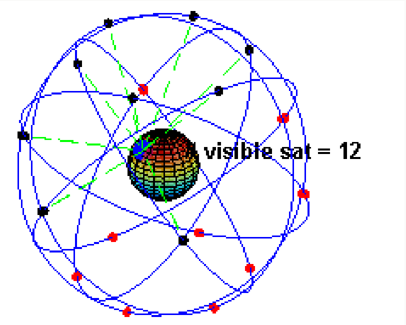
- **Universal time (UT)** is based on the Earth Rotation
  Different versions account for changing effects such as polar motion and changing rotation rates (e.g. UT1)
- **Atomic time (TAI)** is based on the duration of a state transition of the Cs_{133} atom.
- **Coordinated UT (UTC)** is using atomic time seconds, but keeping a maximum distance of 0.9sec to UT1 (needs introduction of leap seconds).
- **Unix time** is the number of seconds since UTC 01.01.1970, ignoring leap seconds
- **GPS time (GPST)** is maintained by the GPS monitoring network.
  GPST = UTC -18sec
  (leap seconds change when a UTC leap seconds change)

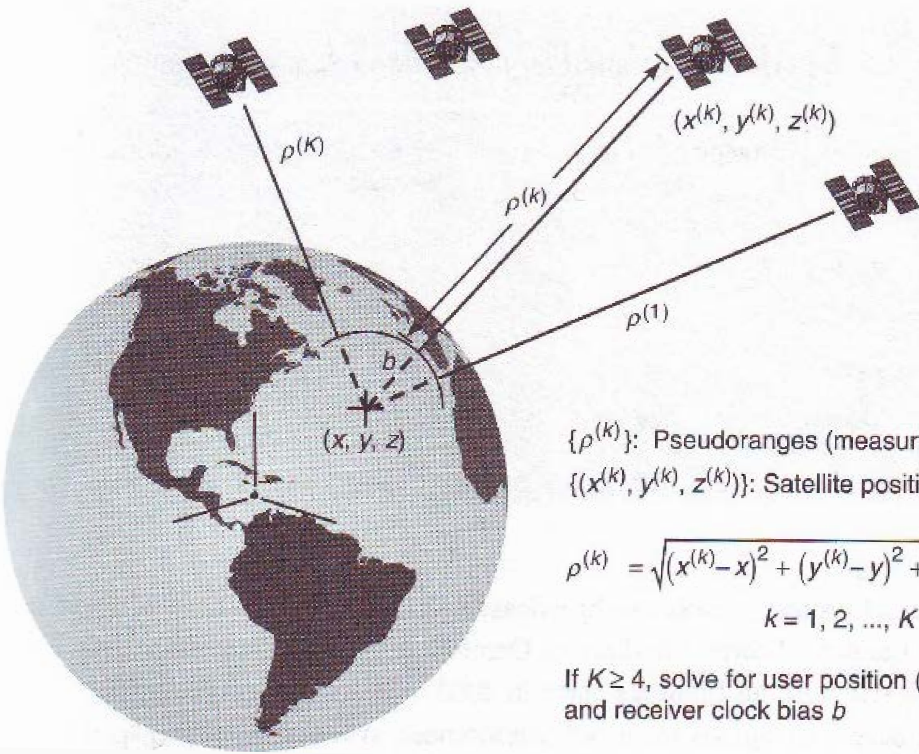
TIME SYSTEMS

LEAP SECONDS



GNSS





$\{\rho^{(k)}\}$: Pseudoranges (measurements)

$\{(x^{(k)}, y^{(k)}, z^{(k)})\}$: Satellite positions (known)

$$\rho^{(k)} = \sqrt{\left(x^{(k)}-x\right)^2 + \left(y^{(k)}-y\right)^2 + \left(z^{(k)}-z\right)^2} - b$$

$$k = 1, 2, ..., K$$

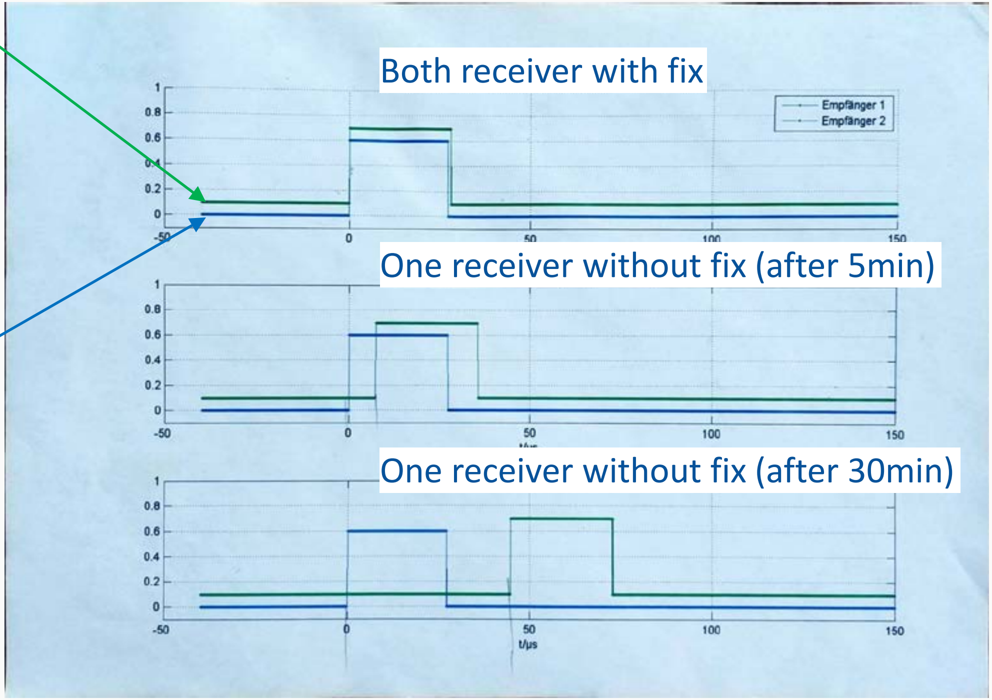
If $K \geq 4$, solve for user position (x, y, z), and receiver clock bias b

UNIVERSITÄT BONN igg

GNSS

- If a GNSS receiver has a position fix, it also has a „time fix“
- The bias between the receiver clock and the GPS time standard is freshly estimated with about 10Hz
- A good reveiver always updates its internal clock with the estimated offsets provides an electronic signal for every GPS time second (PPS)
- These information can be used to time stamp sensor data or synchronize other clocks.
- The PPS signal is stable within nanoseconds

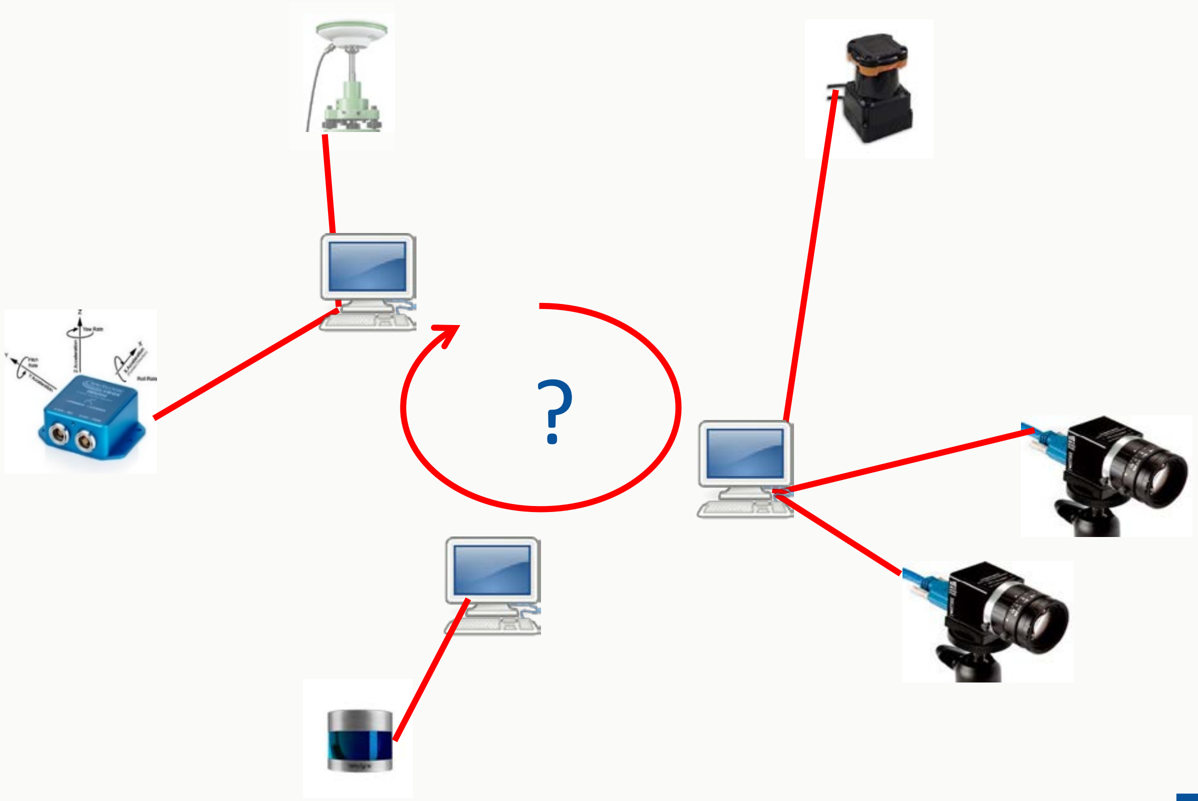
PPS



Both receiver with fix
Empfänger 1
Empfänger 2
One receiver without fix (after 5min)
One receiver without fix (after 30min)
t/µs

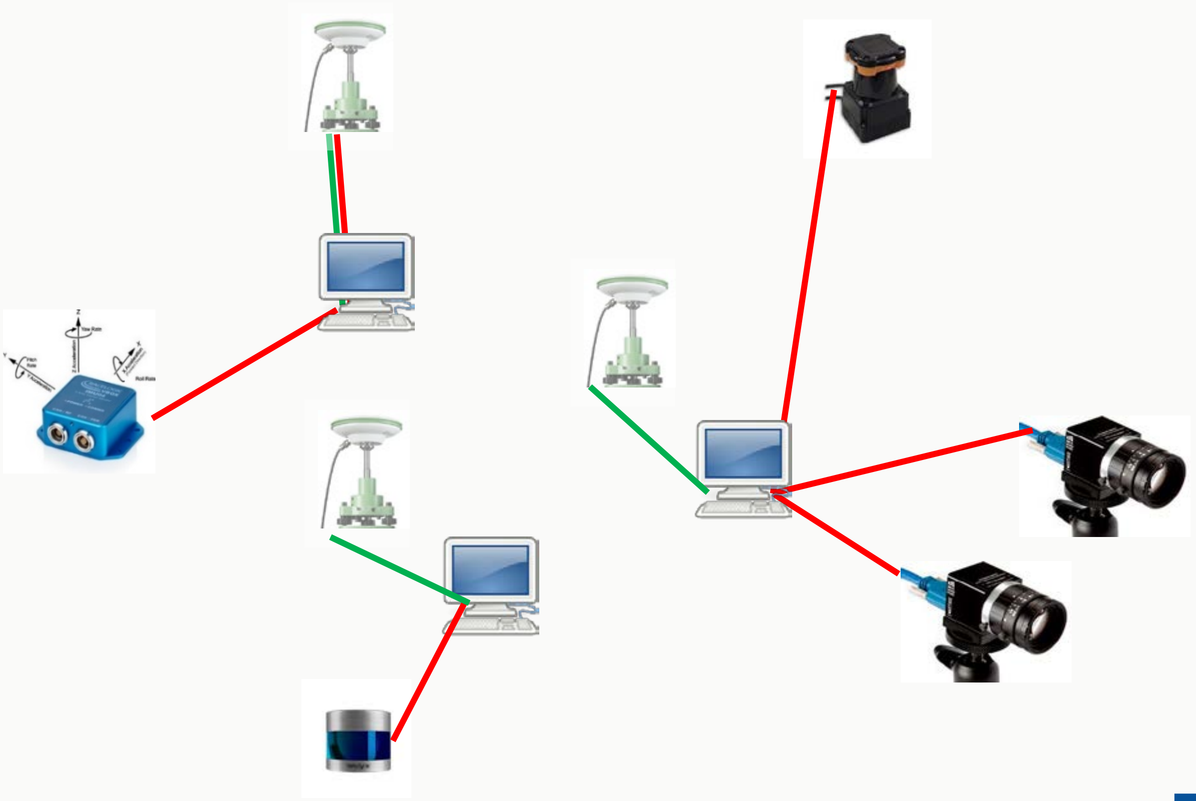
PROBLEM 3

HOW TO SYNCHRONIZE MULTIPLE CLOCKS?



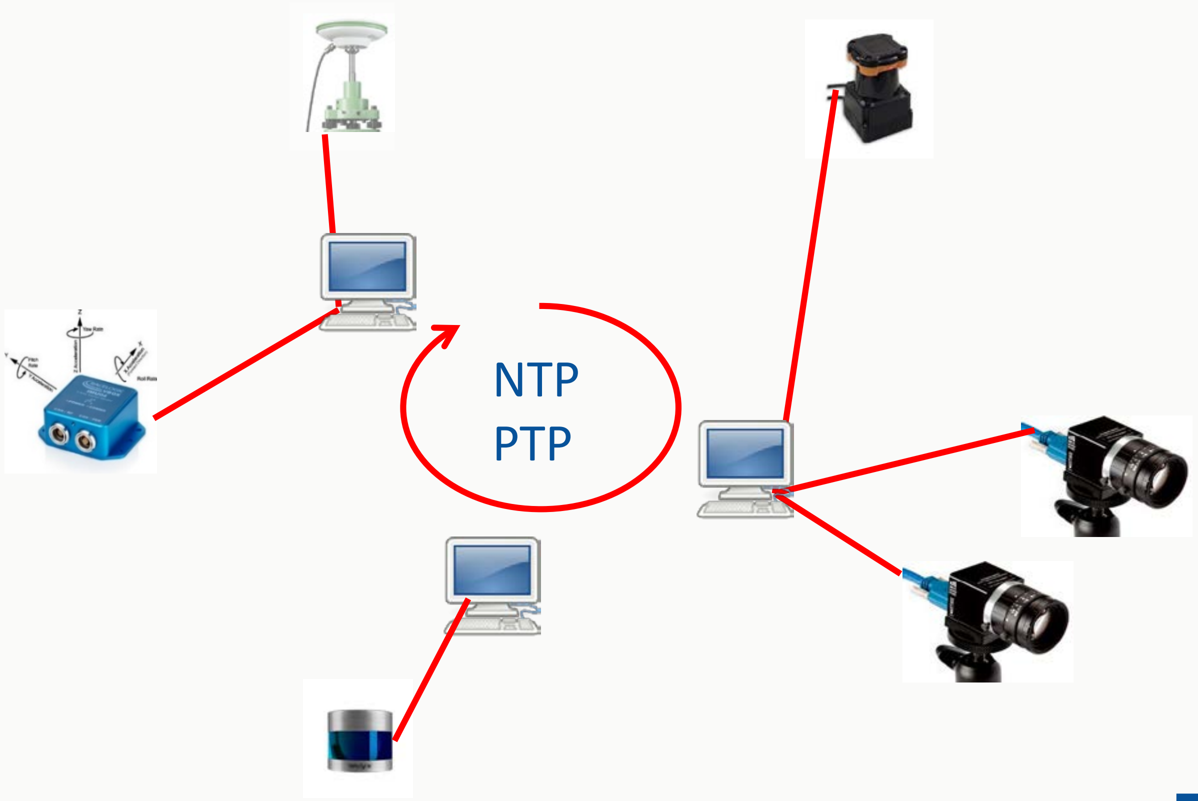
PROBLEM 3 – CLOCK SYNC

OPTION 1: SYNC ALL CLOCKS WITH GNSS

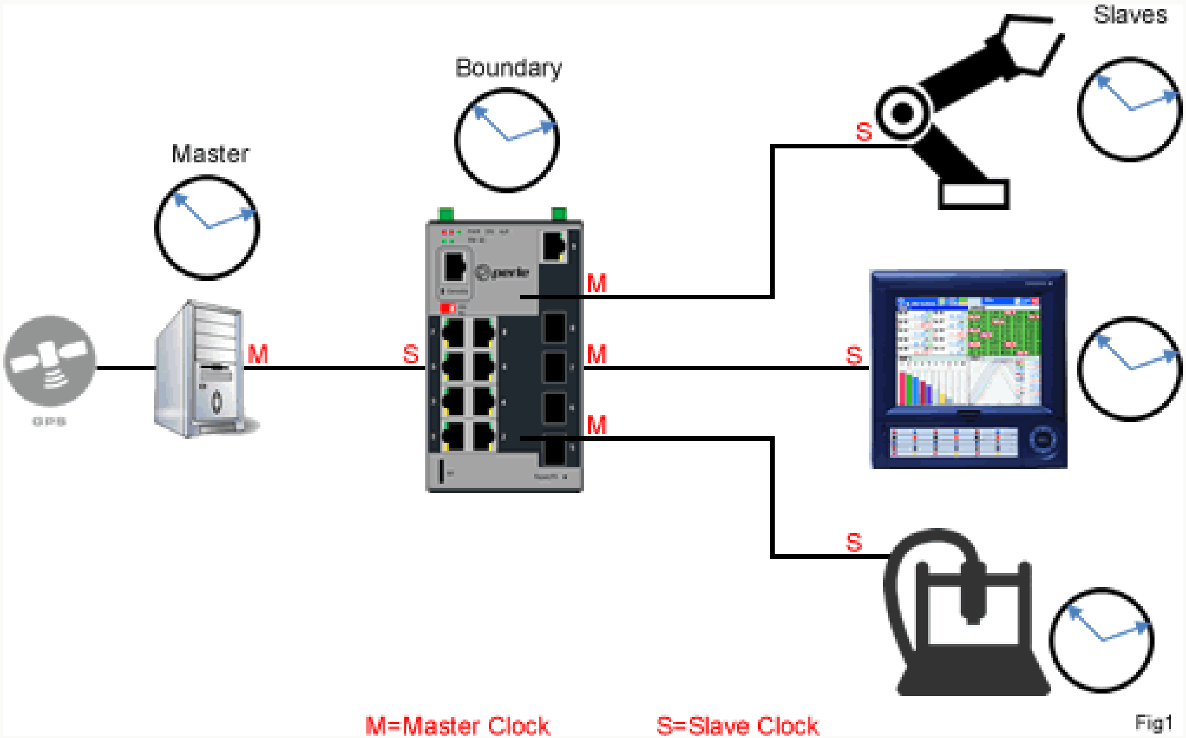


PROBLEM 3 – CLOCK SYNC

OPTION 2: SYNCHRONIZE CLOCKS VIA CLOCK SYNC PROTOCOL

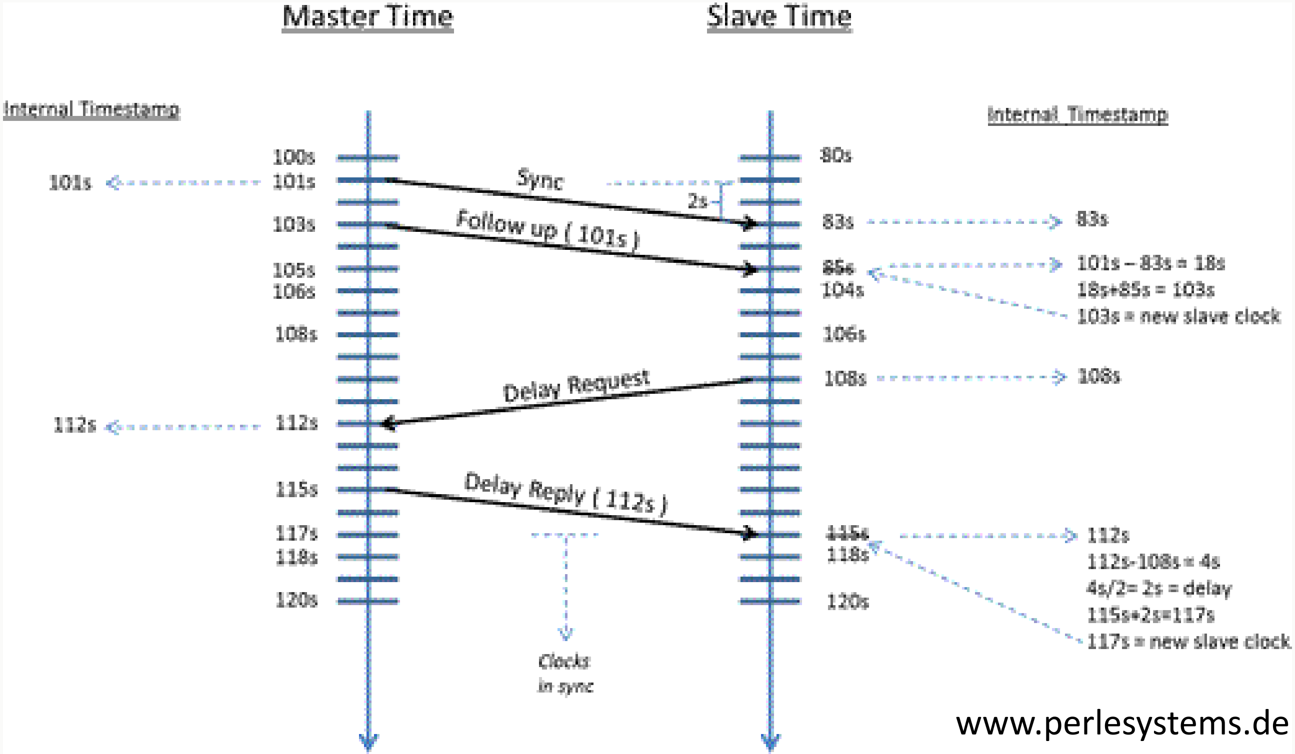


PRECISE TIME PROTOCOL (PTP)



www.perlesystems.de

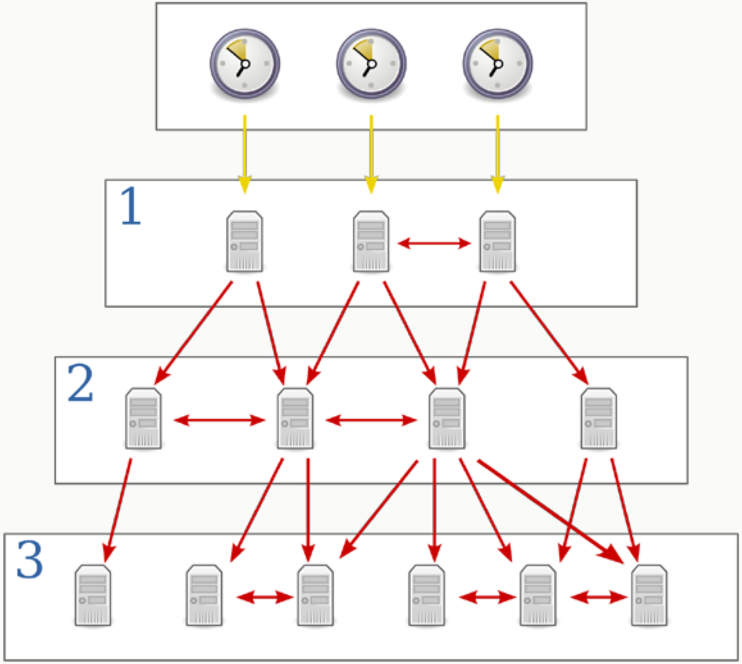
PRECISE TIME PROTOCOL (PTP)



~ microseconds accuracy

NETWORK TIME PROTOCOL (NTP)

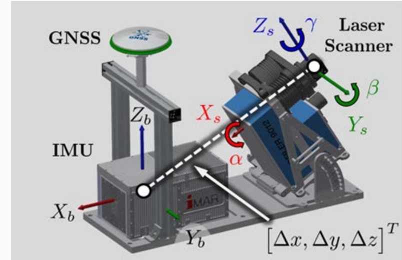
- A client measures round trip times to one or more servers of a higher hierachy level (stratum)
- Based on different algorithms the offset is calculated
- Synchronization is accurate in the order of 10s of milliseconds
- Works well for server networks
- Control loops for time synchromization need some time to converge, not ideal for sensors

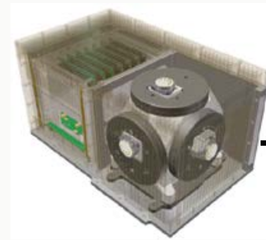


wikipedia

TIME SYNC EXAMPLE

IGG MOBILE MAPPING SYSTEM





PPS

NMEA (GGA message contains UTC time)

~10^3 kHz

Data file

timestamp (UTC) x y z
timestamp (UTC) x y z
timestamp (UTC) x y z
...

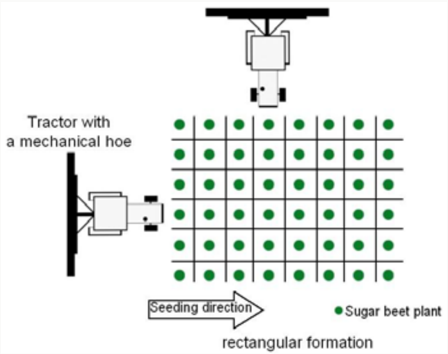
Interpolate

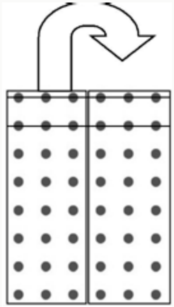
~1 kHz

Data file

timestamp (UTC) acc_x acc_y acc_z ...
timestamp (UTC) acc_x acc_y acc_z ...
timestamp (UTC) acc_x acc_y acc_z ...
...

TIME SYNC EXAMPLE: PRECISE SEEDING OF SUGARBEET

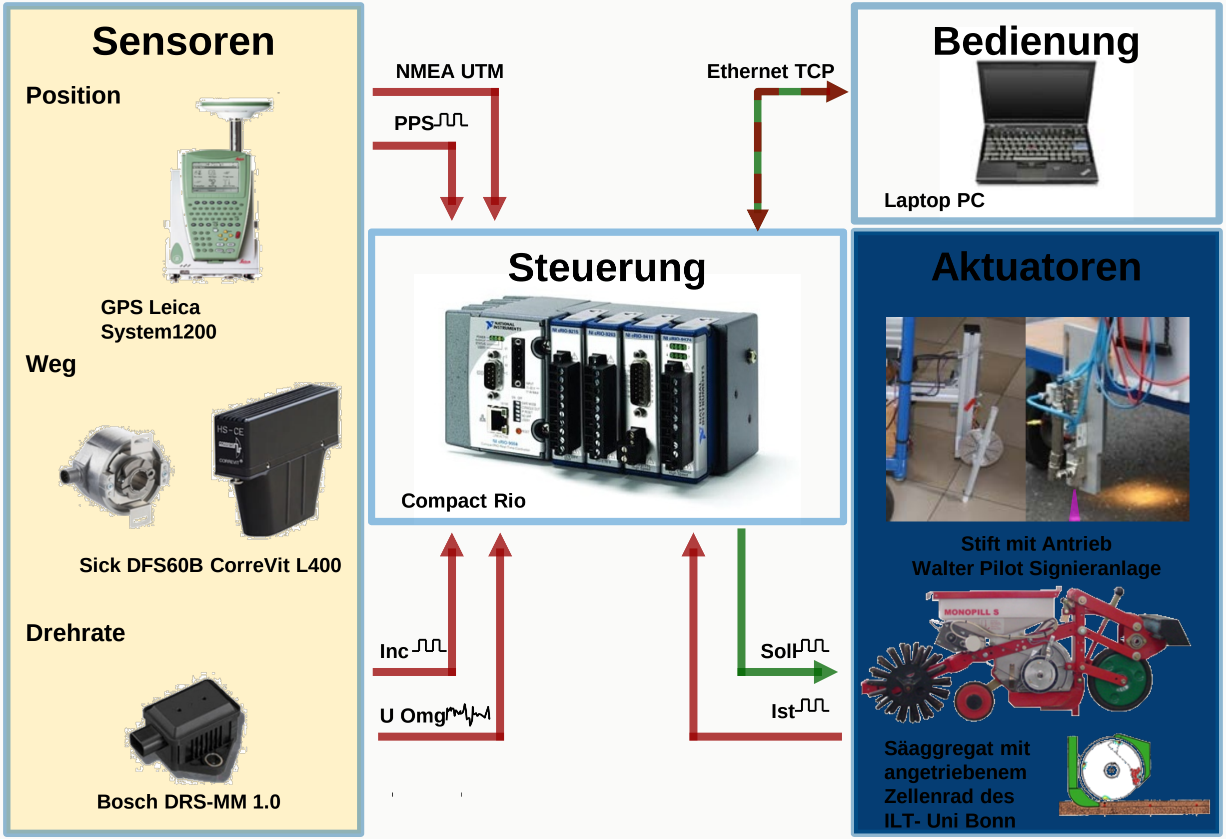




- RTK GPS
- Gyroscope
- Odometer
- Kalman Filter
- Realtime Processing

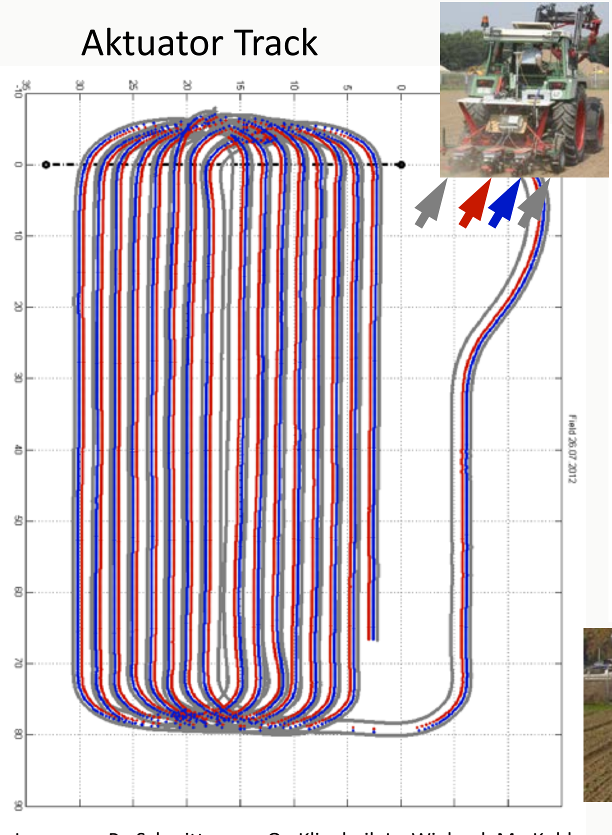
Controlled seeding wheel

TIME SYNC EXAMPLE:
PRECISE SEEDING OF SUGARBEET

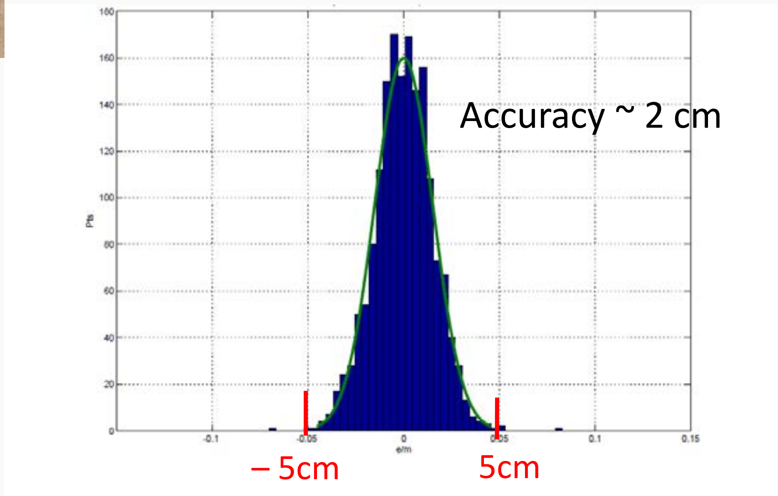


TIME SYNC EXAMPLE: PRECISE SEEDING OF SUGARBEET

Aktuator Track



Deviation of measured plant positions from nominal position



Lammers, P.; Schmittmann, O.; Klingbeil, L.; Wieland, M.; Kuhlmann, H. (2017): Coordinate controlled placement of sugar beet seeds. Proceedings of the 45th International Symposium on Agricultural Engineering, Actual Tasks on Agricultural Engineering, 21-24 February 2017, Opatija, Croatia, 293-301.

WHAT YOU HAVE LEARNED TODAY

- Why is synchronization between sensors important?
- What synchronization accuracy is needed?
- What are the critical points in synchronization?
- How can GNSS receivers be used for synchronization?
- How can clocks in computer networks be synchronized?
- How is sensor synchronization realized in the IGG mobile mapping system?

THANKS