System Developments for High-Precision Multisensor Navigation for Autonomous Driving and Flying

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RaD
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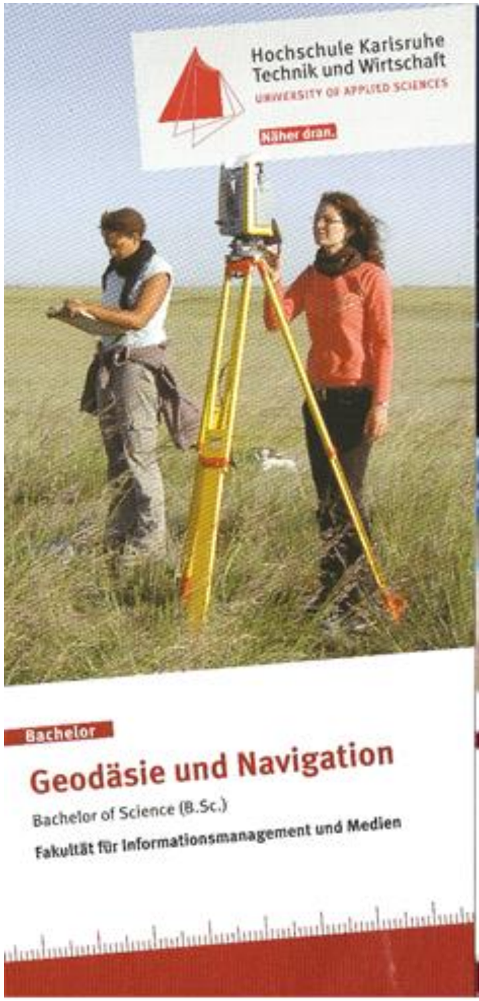
Study Programmes of the Faculty IMM with Contents related to Geodesy/Geomatics and Navigation (www.hs-karlsruhe.de/) Research Oriented (BSc – MSc – PhD)



Hochschule Karlsruhe
Technik und Wirtschaft
UNIVERSITY OF APPLIED SCIENCES
Näher dran.

Bachelor

Geodäsie und Navigation

Bachelor of Science (B.Sc.)

Fakultät für Informationsmanagement und Medien

Hochschule Karlsruhe
Technik und Wirtschaft
UNIVERSITY OF APPLIED SCIENCES
Näher dran.

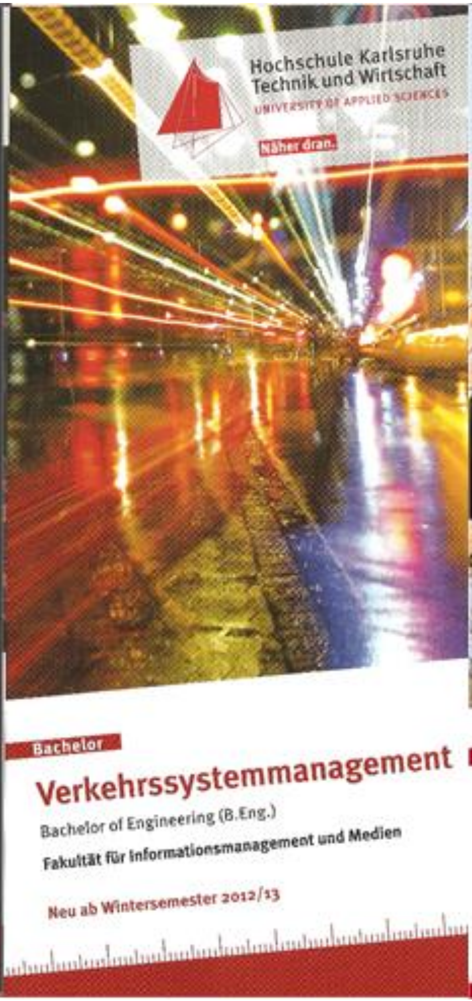
Master

Geomatics

International Degree Program /
Consecutive Degree Program

Master of Science (M.Sc.)

Faculty of Information Management and Media (IMM)



Hochschule Karlsruhe
Technik und Wirtschaft
UNIVERSITY OF APPLIED SCIENCES
Näher dran.

Bachelor

Verkehrssystemmanagement

Bachelor of Engineering (B.Eng.)

Fakultät für Informationsmanagement und Medien

Neu ab Wintersemester 2012/13

Hochschule Karlsruhe
Technik und Wirtschaft
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Näher dran.

Bachelor

Geoinformationsmanagement

mit den Vertiefungsrichtungen:
Geomarketing, Kartographie und Geomedien, Umwelt

Bachelor of Science (B.Sc.)

Fakultät für Informationsmanagement und Medien

Hochschule Karlsruhe
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RaD Project

www.navka.de

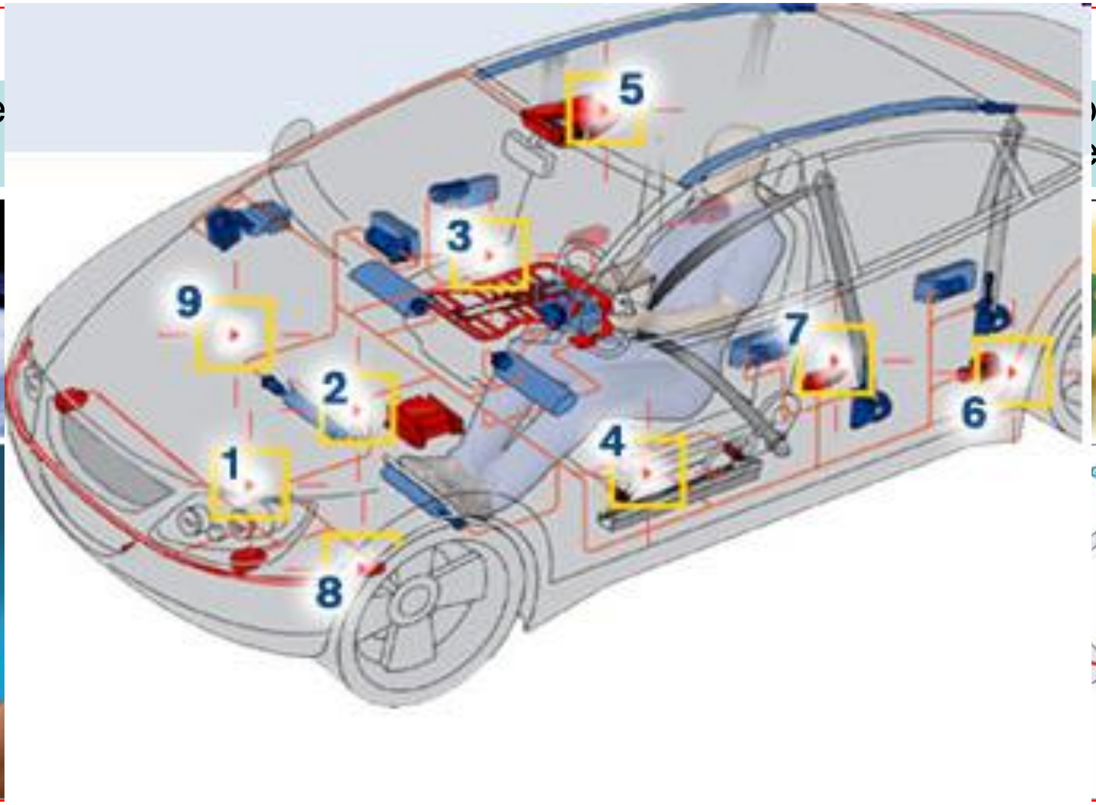
GNSS / MEMS / MOEMS Algorithms and Software for Out-/Indoor Navigation (People, Vehicles, Goods) and Georeferencing with distributed Sensors and Platforms

$$y = \lfloor x^e \; y^e \quad \cdots \quad {}_{eb,z} \,|\, \mathbf{s} \rfloor^T$$

GNSS

Deep Coupling
- Code
- Phase
- Doppler

Tight Coupling
- Position
- Velocity



MEMS
MOEMS

Deep Coupling

- Gyroscopes
- Accelerometers
- Magnetometers
- Camera
- Barometer

https://www.youtube.com/watch?v=-k--3GxrQXU

Autonomous Driving (…. and Flying)

Level 0	▶ Gesamte Kontrolle liegt ganzzeitig beim Fahrer
Level 1	▶ Unterstützung spezieller Funktionen ▶ ESP, ABS
Level 2	▶ Zwei oder mehr Funktionen werden unterstützt und können miteinander interagieren ▶ Tempomat in Verbindung mit Fahrbahnassistenz, Parkhilfe
Level 3	▶ Gesamte Kontrolle kann vom Fahrer abgegeben werden, der Fahrer muss jedoch jederzeit einsatzbereit sein und im Zweifelsfall manuell eingreifen können
Level 4	▶ Gesamte Kontrolle liegt ganzzeitig beim Fahrzeug, das Fahrzeug fährt völlig unabhängig

$$\mathbf{e}(\mathrm{t}) = \mathbf{y}(\mathrm{t})_{\text{Desired State}} - \mathbf{y}(\mathrm{t})_{\text{Navigated State}}$$

Main Topics

---

e(t) = Control Deviation (Regelabweichung)

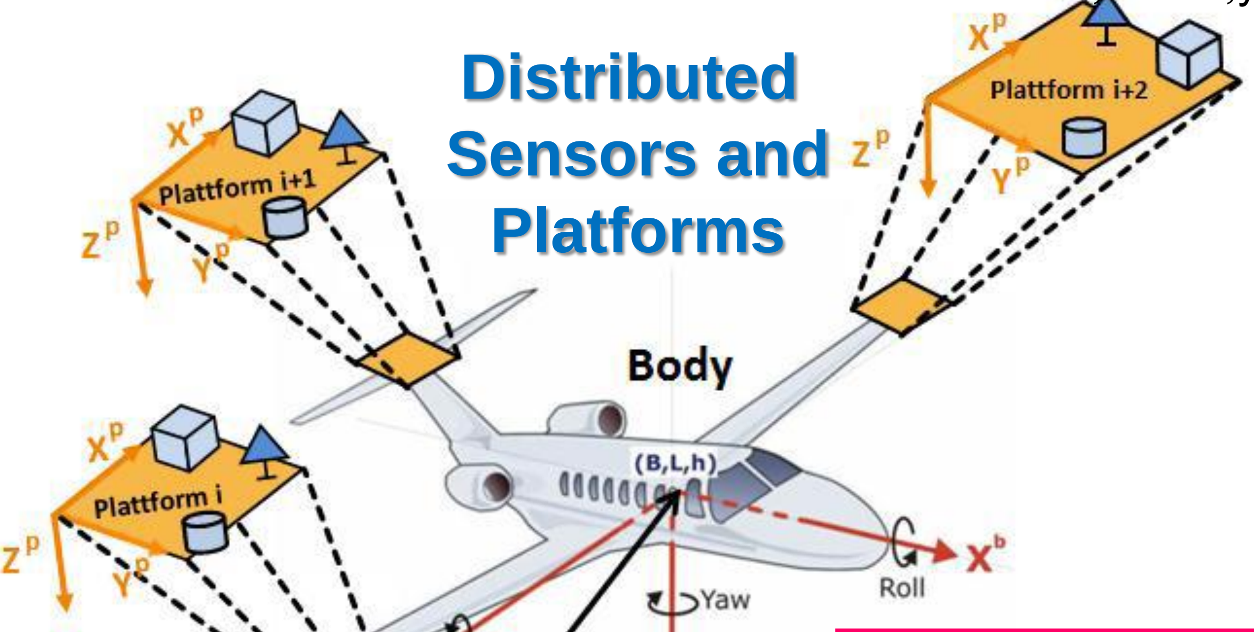
u‘(t) = Control Variables, e.g.Thrust &Torque

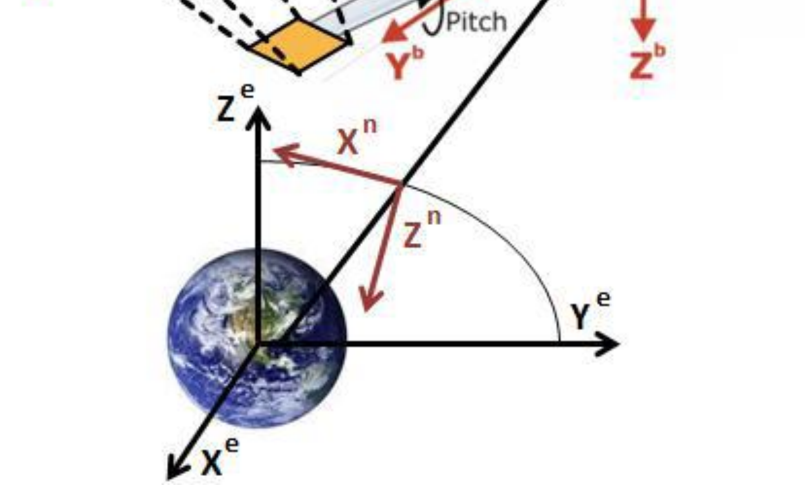
u(t) = Control , e.g. Propeller-Rotations

SLAM
- **Obstacle Detection**
- **Collision Avoidance**
- **Dynamic Path Planning**

Navigation with Distributed Sensors & Platforms (NAVKA-Concept)

$$y = \left[x^e\ y^e\ z^e \,|\, \dot{x}^e \dot{y}^e \dot{z}^e \,|\, r^e\ p^e\ y^e \,\|\, \ddot{x}^e\ \ddot{y}^e\ \ddot{z}^e \,|\, \omega^b_{eb,x}\ \omega^b_{eb,y}\ \omega^b_{eb,z} \,|\, \mathbf{s} \right]^T$$





Distributed Sensors and Platforms

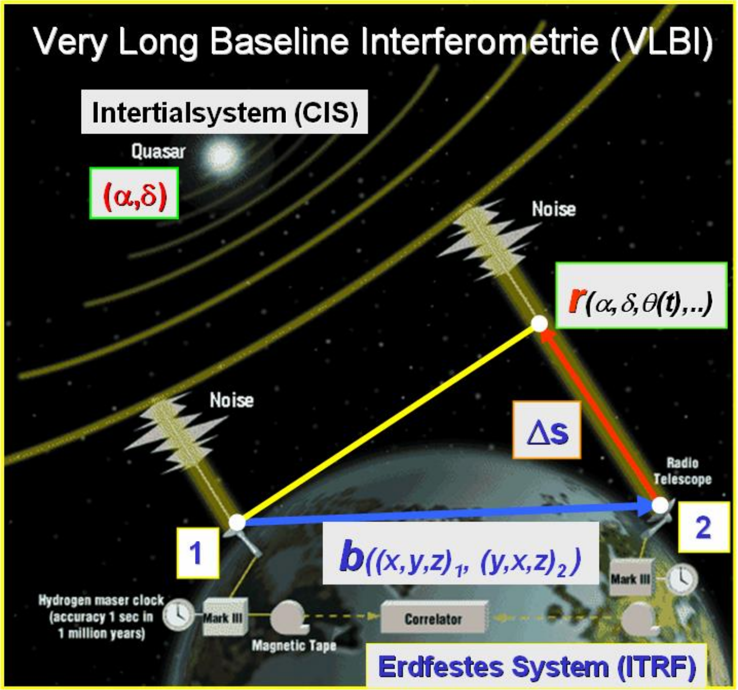
MaxPlanck München

„NAVKA Rine“FC4

Navigation Frames

Inertial Frame „(i)-Frame“ – 600 Quasars (α, δ)

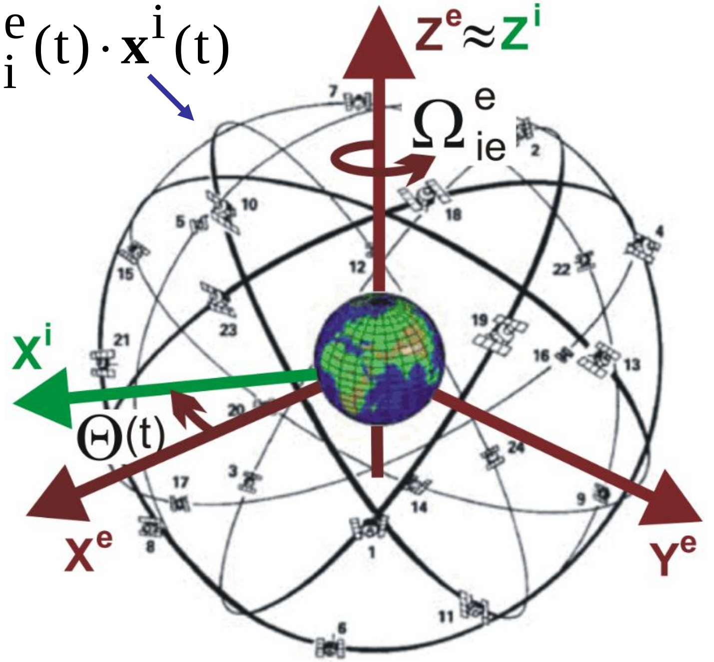
$$\mathbf{R}_i^e(t) = (\mathbf{R}_e^i(t))^T = \mathbf{R}_P \cdot \mathbf{R}_E \cdot \mathbf{R}_N \cdot \mathbf{R}_{Pr}$$



$$\mathbf{x}^e(t) = \mathbf{R}_i^e(t) \cdot \mathbf{x}^i(t)$$

$$\mathbf{r}^e(t) = \mathbf{R}_i^e(t) \cdot \mathbf{r}^i(t)$$

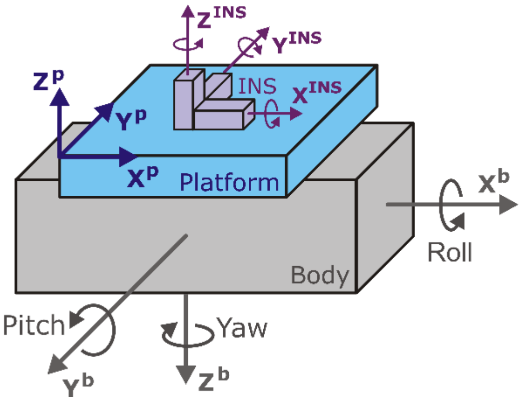
$$\mathbf{r}^i = \begin{bmatrix} \cos\delta \cdot \cos\alpha \\ \cos\delta \cdot \sin\alpha \\ \sin\delta \end{bmatrix}$$



$$\ddot{\mathbf{x}}^i(t) = \mathbf{g}^i(\mathbf{x}) + \mathbf{a}^i(\text{Sensor}, t) = \mathbf{g}^i(\mathbf{x}) + \mathbf{R}_b^i(t) \cdot \mathbf{a}^b(\text{Sensor}, t)$$

$$\mathbf{\Omega}_{ib}^b(\text{Sensor})$$

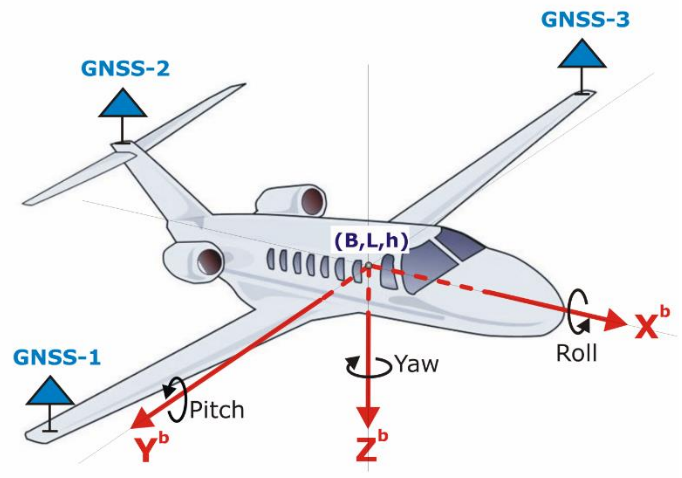
$$\dot{\mathbf{R}}_b^i(t) = \mathbf{R}_b^i(t) \cdot \mathbf{\Omega}_{ib}^b(t)$$

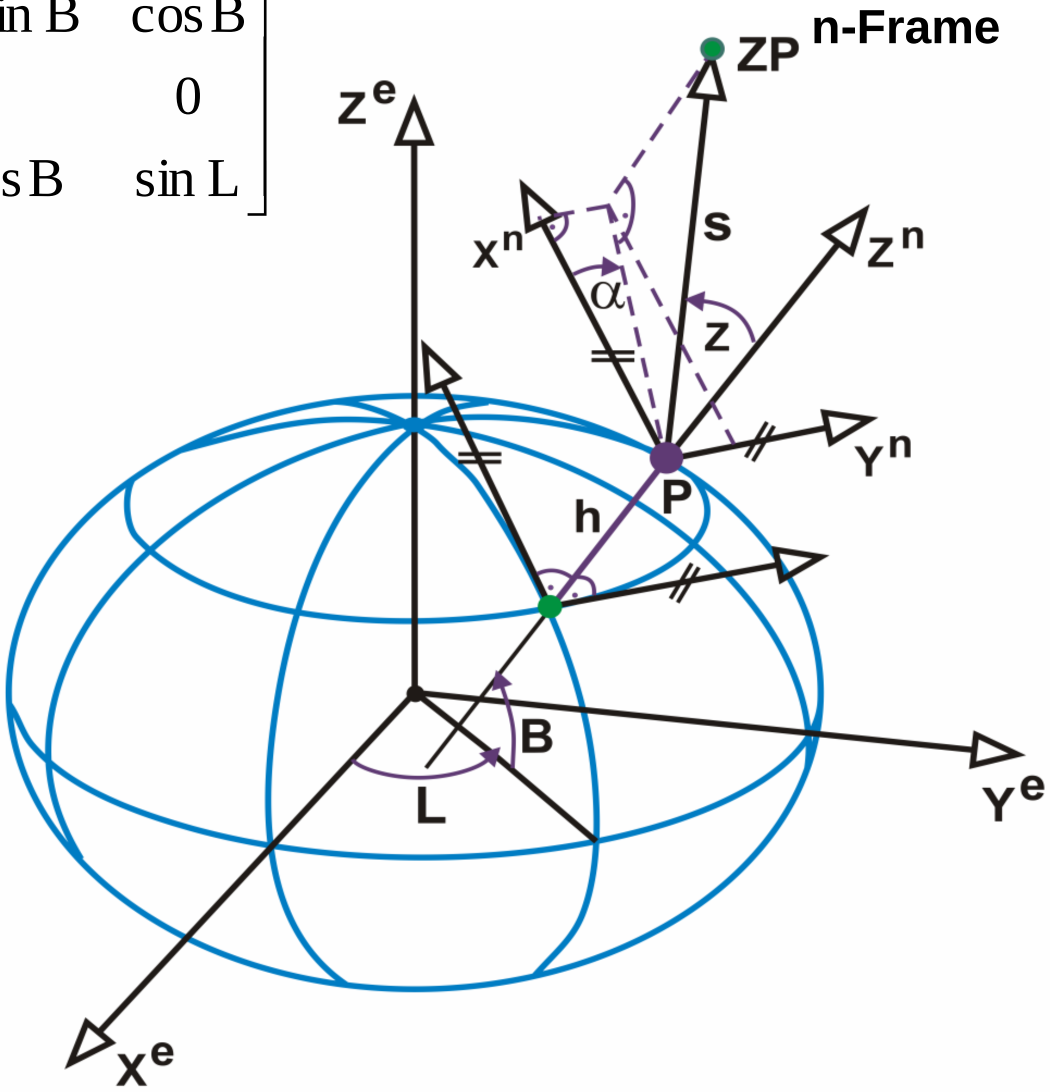


Navigationframe - „Navigation-Frame“ oder „n-Frame“

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

$$\mathbf{x}^{n,i} = \mathbf{R}_e^n(B,L) \cdot (\mathbf{x}^{e,i} - \mathbf{x}(B,L,h)^e)$$

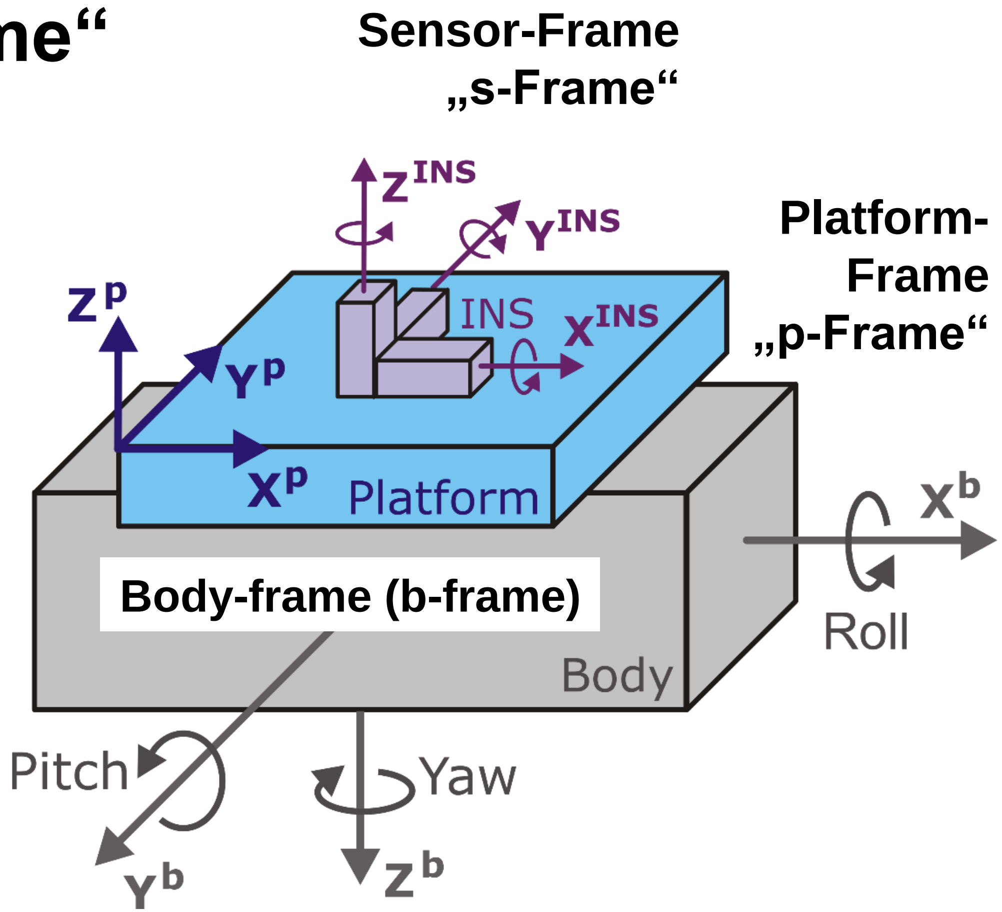




Body-Frame - „b-Frame“

$$\mathbf{x}^{b,i} = \mathbf{R}_n^b(r,p,y)\cdot\mathbf{x}^{n,i}$$

$$\begin{bmatrix} r \\ p \\ y \end{bmatrix} = \begin{bmatrix} \tan^{-1}[\mathbf{R}_b^n(3,2)/\mathbf{R}_b^n(3,3)] \\ \tan^{-1}[-\mathbf{R}_b^n(3,1)/\sqrt{\mathbf{R}_b^n(2,1)^2+\mathbf{R}_b^n(1,1)^2}\,] \\ \tan^{-1}[\mathbf{R}_b^n(2,1)/\mathbf{R}_b^n(1,1)] \end{bmatrix}$$



Sensor-Frame
„s-Frame“

Platform-Frame
„p-Frame“

Body-frame (b-frame)

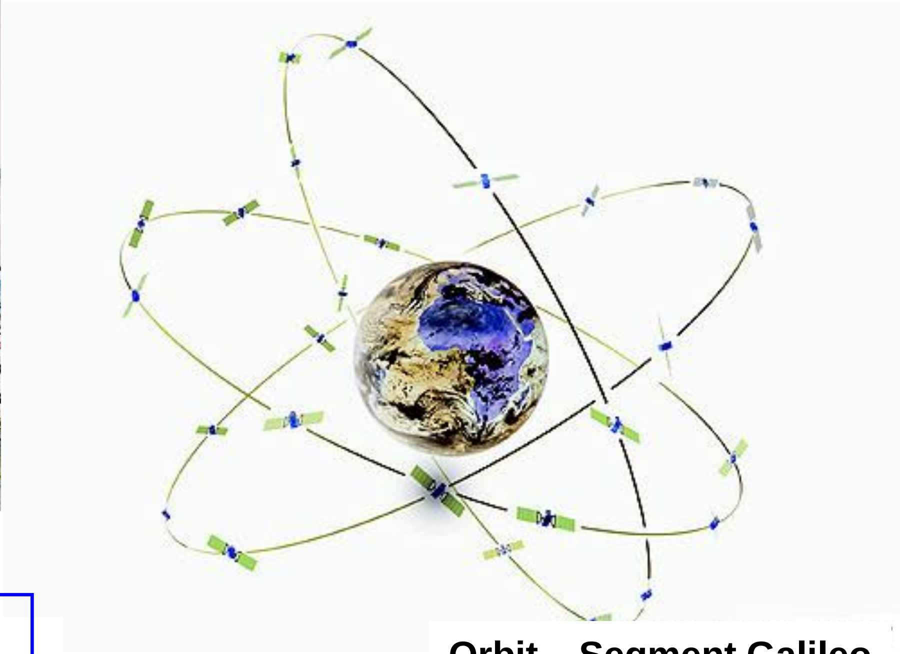
$$\mathbf{R}_n^b = \begin{pmatrix} \cos p\cos y & \cos p\sin y & -\sin p \\ \sin r\sin p\cos y-\cos r\sin y & \sin r\sin p\sin y+\cos r\cos y & \sin r\cos p \\ \cos r\sin p\cos y+\sin r\sin y & \cos r\sin p\sin y-\sin r\cos y & \cos r\cos p \end{pmatrix}$$

GNSS and Challenges

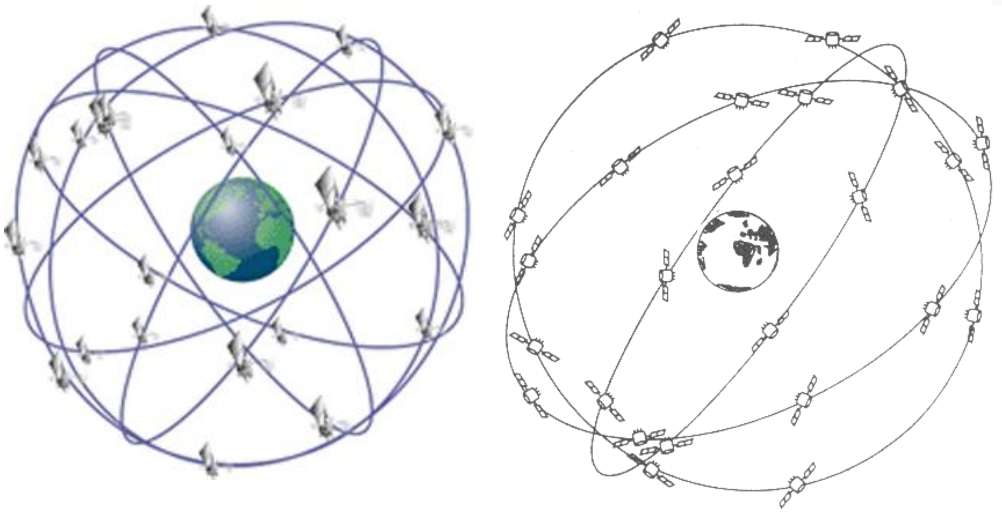
Orbit Design of the 4 GNSS (without Augmentation Systems)

28 Dec.2005 **Giove-A** lift off
05:19 UTC Baikonour,
Kazakhstan

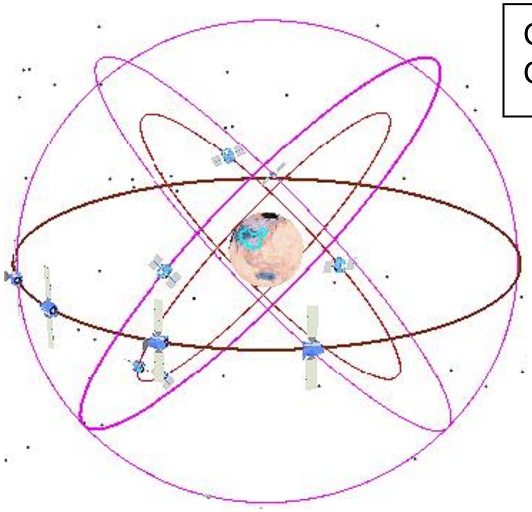
Galileo Satellite



Orbit – Segment Galileo



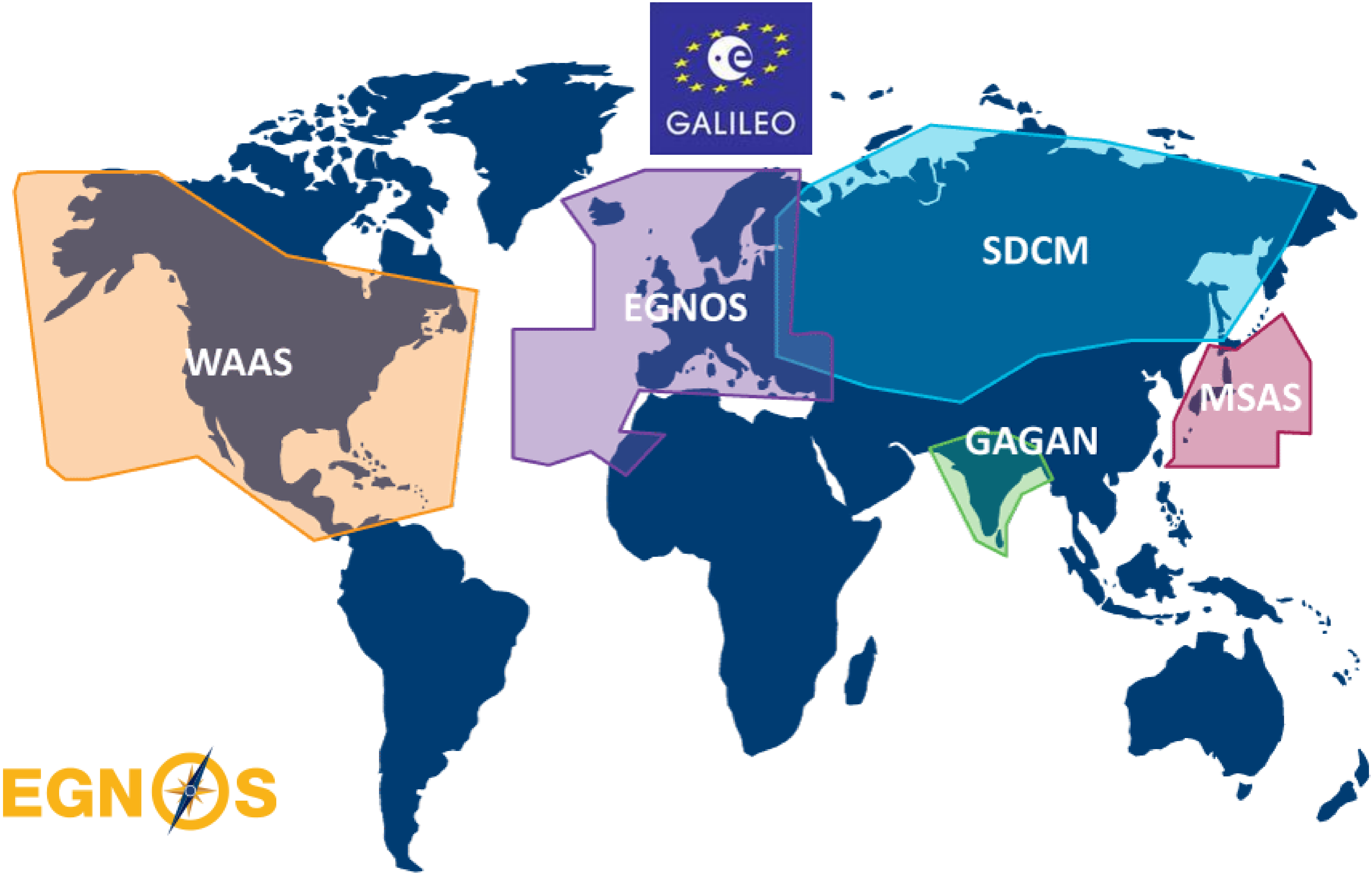
GPS Orbit and GlONASS Orbit



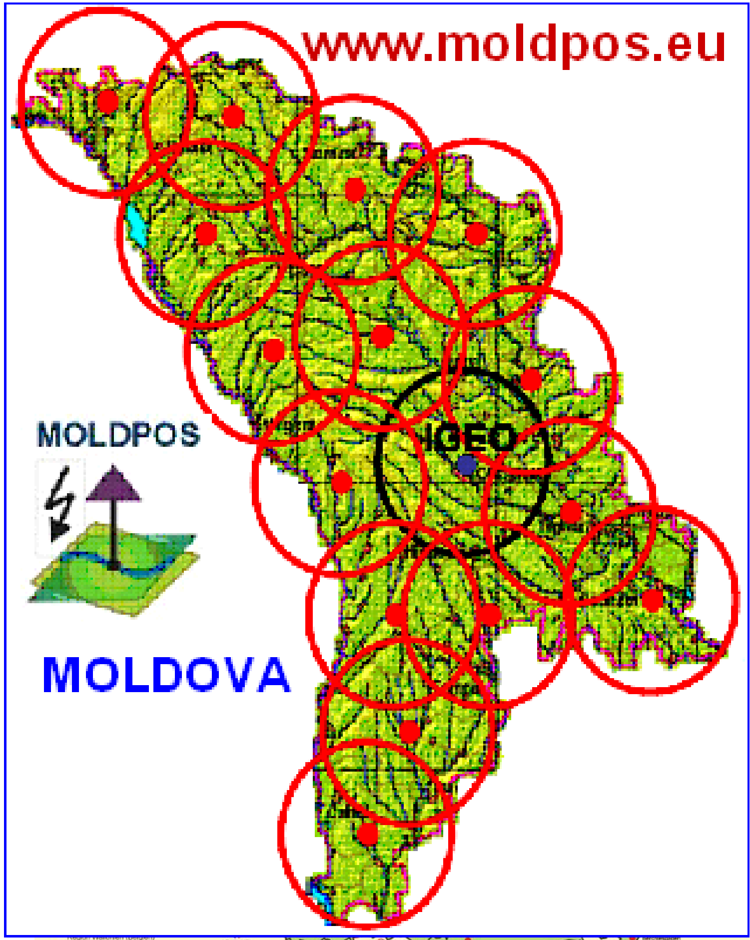
Chinese
COMPASS Orbit

Space/Satellite Based Augmentation Systems (SBAS)

….. für DGNSS-Codemessungen (DNGSS-Korrekturen. Stanard RTCM oder RTCA)



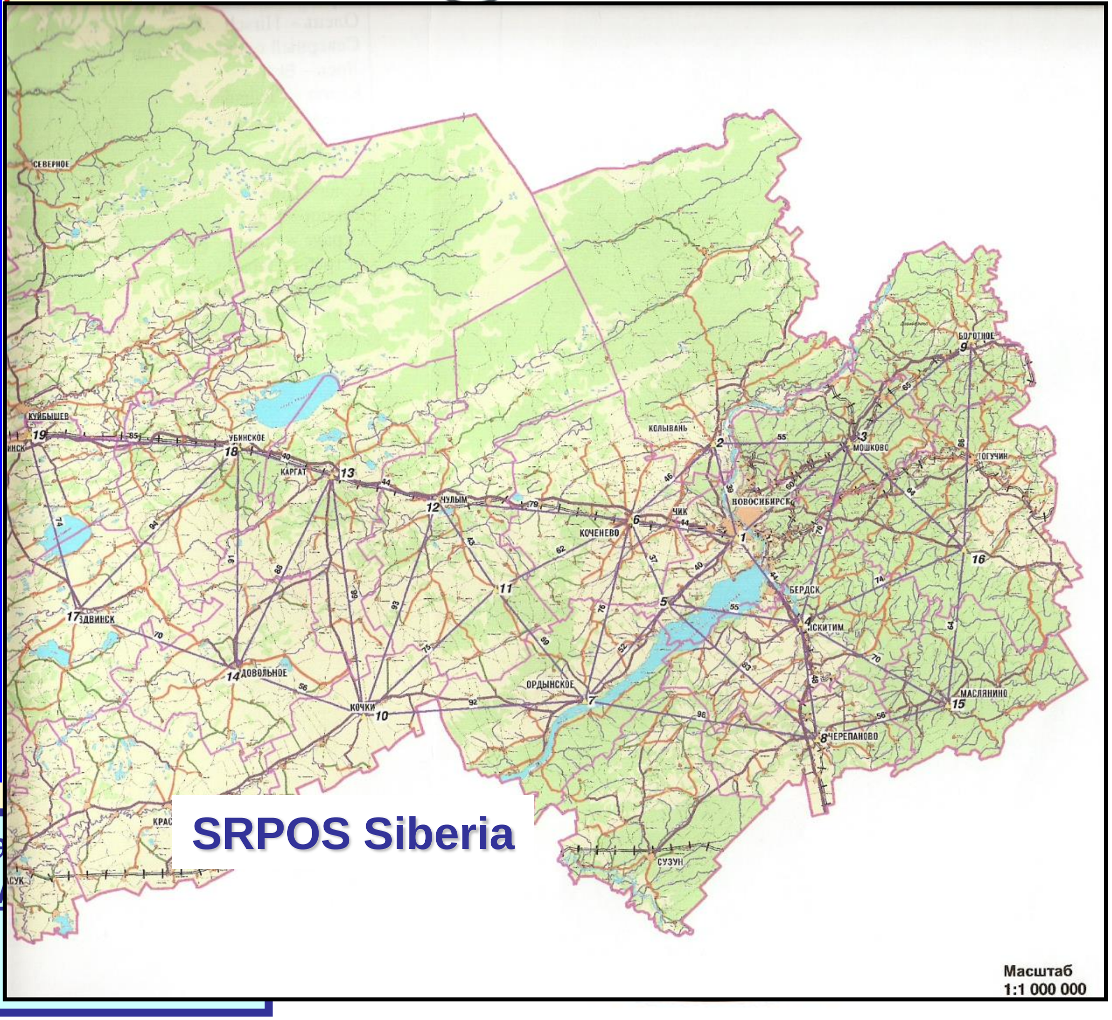
Regional Precise GNSS-Positioning Services – Worldwide
Frame in Europe: ETRF89 („Frozen Plate“). same as EUREF-IP Service



1

2

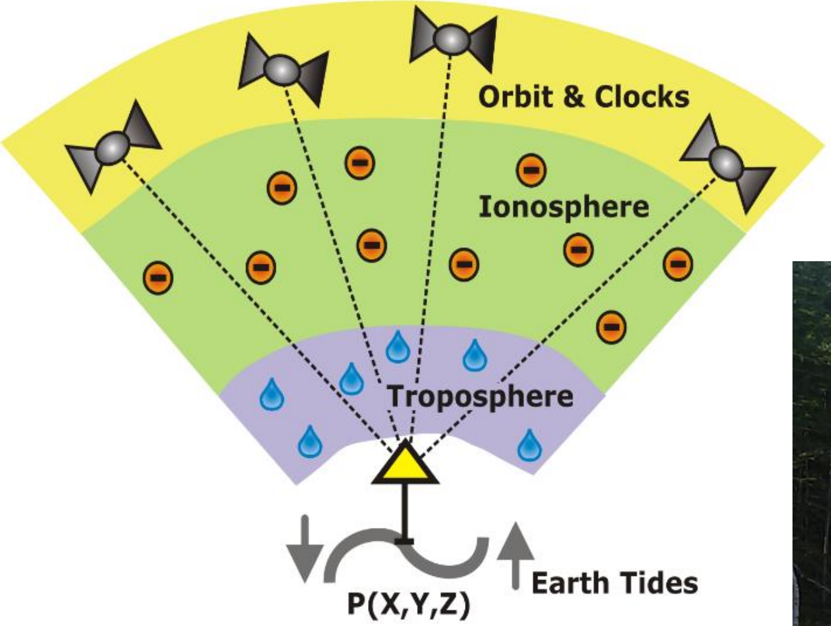
SmartNet EUROPE



4 RTCM Services: 1-3 cm Horizontal a
Geodetic Infrastructures for GNSS-Serv
www.moldpos.eu
www.geozilla.de

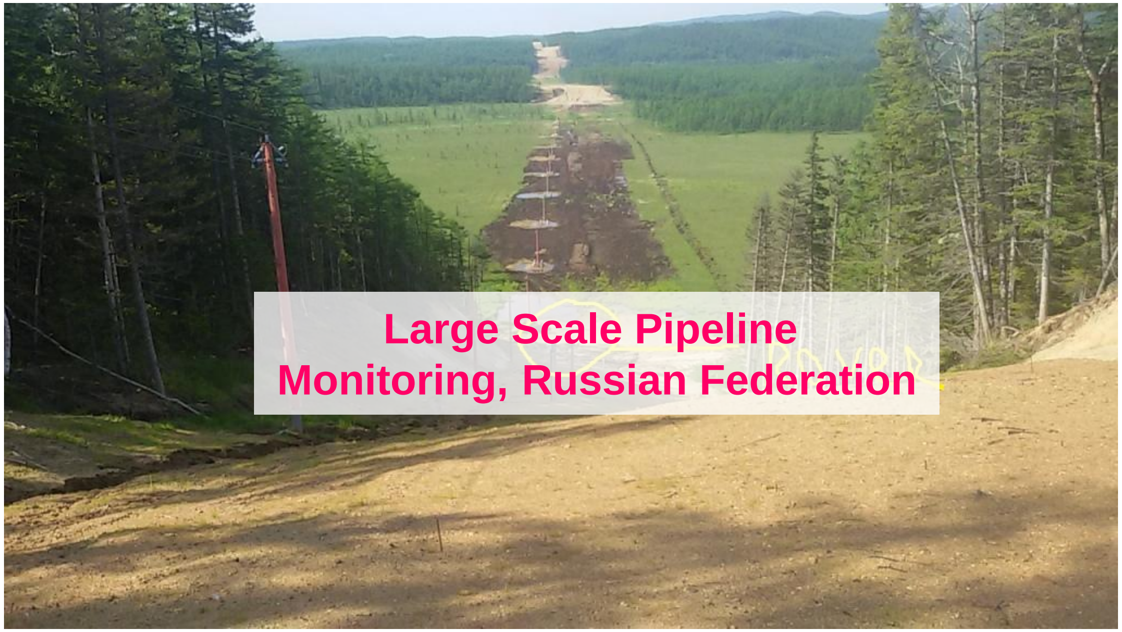
PPP-K / OPPP

GNSS-Positions – necessary to be integated in „OPPP age“ and „GNSS/MEMS sensor fusion age“.



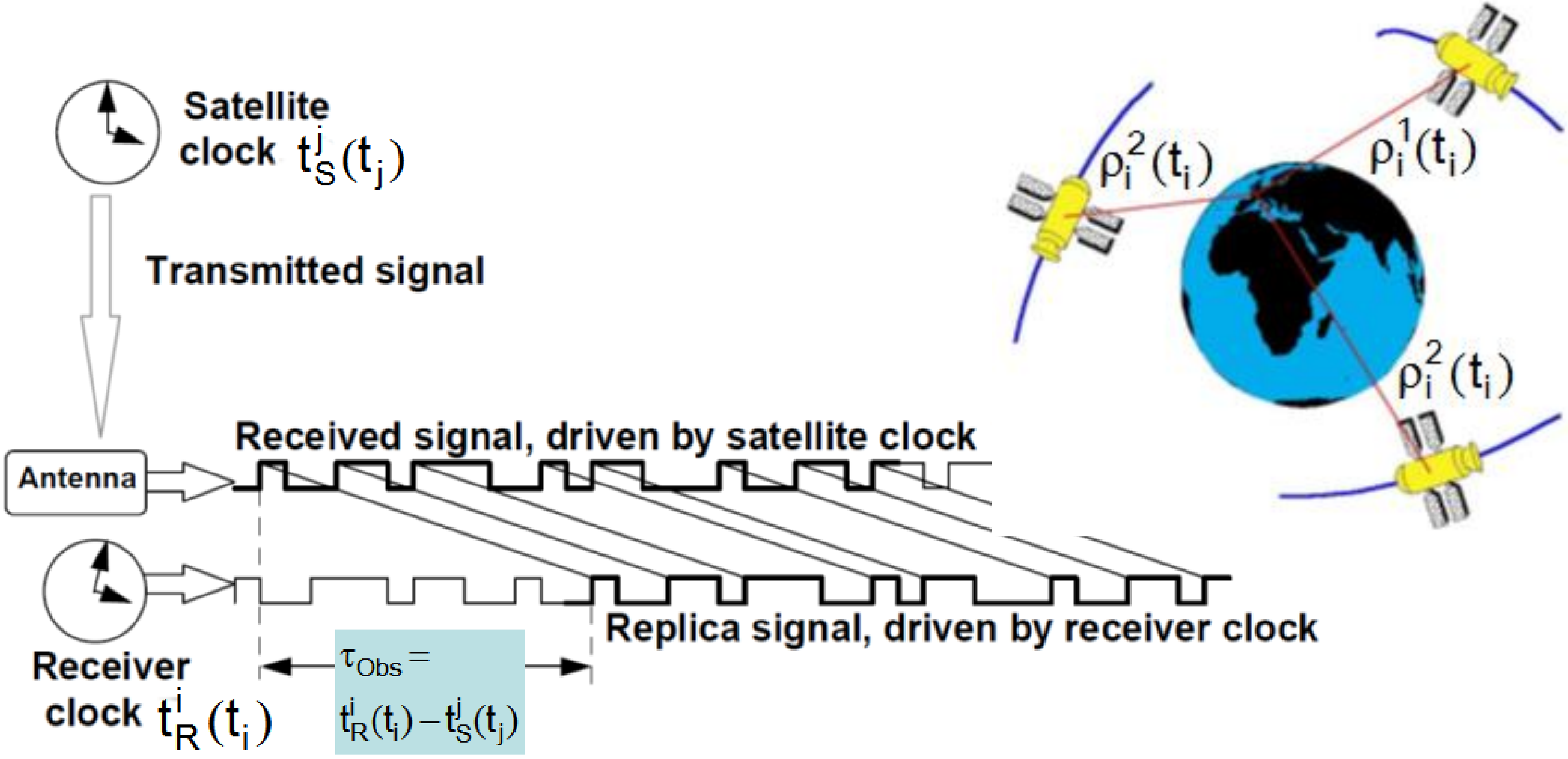
$$\mathbf{x} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

Useful for extended gemonitoring scenarios, e.g. large pipeline networks


Large Scale Pipeline Monitoring, Russian Federation

Pseudorange or Code-Observation

$$\rho_i^j(t_i)_{Obs} = c \cdot \tau_{i\,Obs}^{j} = c \cdot (t_R^i(t_i) - t_S^j(t_j)) = c \cdot ((t_i + \Delta\bar{t}_{R,i}) - (t_j + \Delta\bar{t}_{S,j}))$$



Satellite clock $t_S^j(t_j)$

Transmitted signal

Antenna

Received signal, driven by satellite clock

Replica signal, driven by receiver clock

Receiver clock $t_R^i(t_i)$

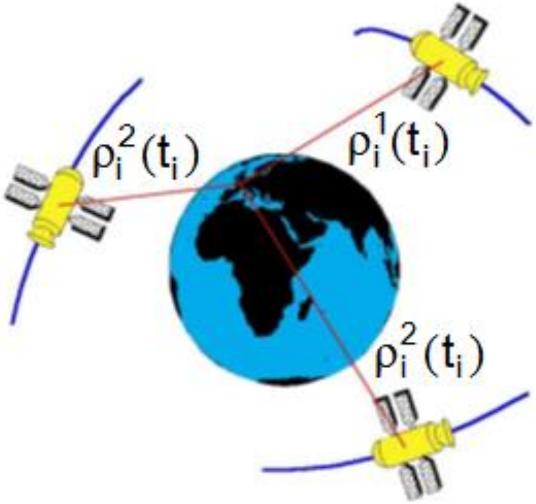
$\tau_{Obs} =$
$t_R^i(t_i) - t_S^j(t_j)$

Pseudorange Modeling in ECEF and GNSS-time

$$\rho_i^j(t_i)_{Obs} = c \cdot \tau_{iObs}^j = c \cdot (t_R^i(t_i) - t_S^j(t_j)) = c \cdot ((t_i + \Delta\bar{t}_{R,i}) - (t_j + \Delta\bar{t}_{S,j}))$$

$$\text{with} \quad \tau_{iObs}^j = t_R^i(t_i) - t_S^j(t_j)$$

1. Without Atmosphere corrections



$$\rho(t_i)_{Obs} = c \cdot (t_R^i(t_i) - t_S^j(t_j)) = c \cdot (t_i - t_j) + c \cdot \Delta\bar{t}_{R,i} - c \cdot \Delta\bar{t}_{S,j}$$

$$\rho(t_i)_{Obs} = \tilde{\rho}(t_i, t_j, \mathbf{o}^j) + c \cdot \Delta\bar{t}_{R,i} - c \cdot \Delta\bar{t}_{S,j}$$

$$\rho(t_i)_{Obs} = \left| \tilde{\mathbf{x}}_R^l(t_i) - \tilde{\mathbf{x}}_S^j(t_j, \mathbf{o}^j) \right| + c \cdot \Delta\bar{t}_{R,i} - c \cdot \Delta\bar{t}_{S,j}$$

$$\rho(t_i)_{Obs} = \left| \tilde{\mathbf{x}}_R^l(t_i) - \tilde{\mathbf{x}}_S^j(t_i - \tau_i, \mathbf{o}^j) \right| + c \cdot \Delta\bar{t}_{R,i} - c \cdot \Delta\bar{t}_{S,j}$$

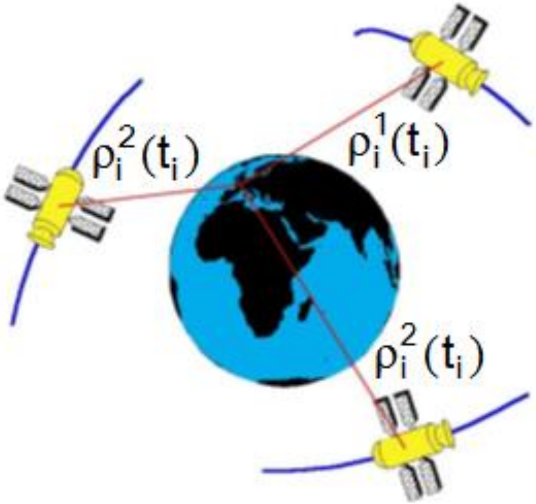
$$\rho(t_i)_{Obs} = \left| \tilde{\mathbf{x}}_R^l(t_i) - \tilde{\mathbf{x}}_S^j\left(t_i - \frac{\tilde{\rho}_i^j(t_i)}{c}, \mathbf{o}^j\right) \right| + c \cdot \Delta\bar{t}_{R,i} - c \cdot \Delta\bar{t}_{S,j} \quad \text{with} \quad \tilde{\rho}(t_i) = \left| \tilde{\mathbf{x}}_R(t_i) - \tilde{\mathbf{x}}_S\left(t_i - \frac{\tilde{\rho}_i^j(t_i)}{c}\right) \right|$$

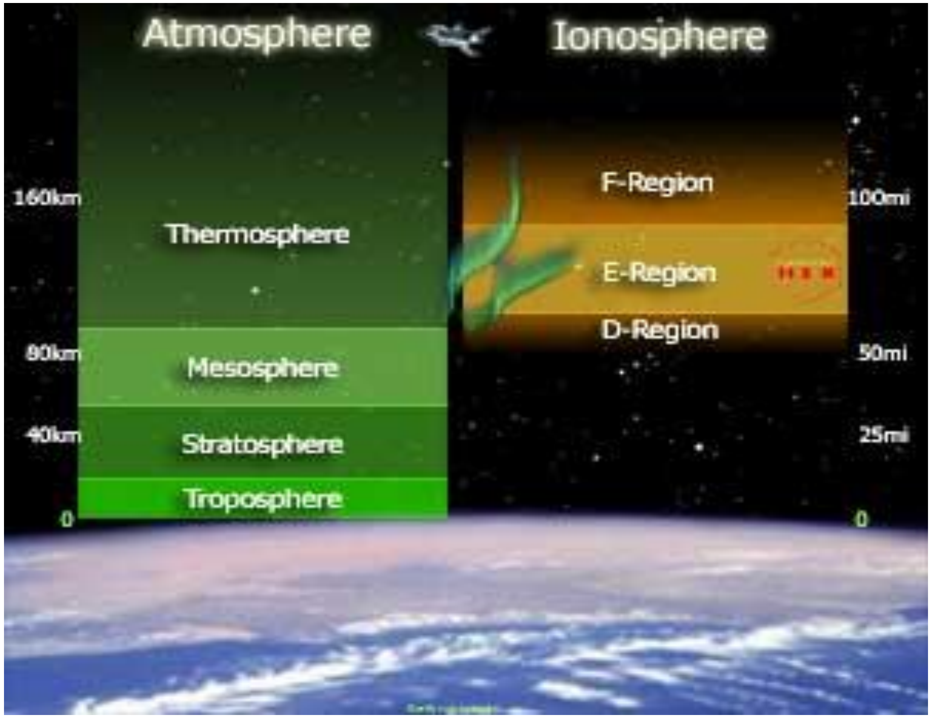
Pseudorange Modeling in ECEF and GNSS-time

2. With Atmosphere (Ionosphere and Troposphere)

$$\rho(t_i)_{Obs} = \left| \tilde{\mathbf{x}}_R(t_i) - \tilde{\mathbf{x}}_S\left(t_i - \frac{\tilde{\rho}_i^j(t_i)}{c}, \mathbf{o}^j\right) \right| + c \cdot \Delta\bar{t}_{R,i} - c \cdot \Delta\bar{t}_{S,j} + \Delta\rho^j_{i,ION} + \Delta\rho^j_{i,TROP}$$

$$\text{with } \tilde{\rho}(t_i) = \left| \tilde{\mathbf{x}}_R(t_i) - \tilde{\mathbf{x}}_S\left(t_i - \frac{\tilde{\rho}_i^j(t_i)}{c}\right) \right|$$





Light Time Equation

$$\left| \underbrace{\tilde{\mathbf{x}}_R(t_i) - \tilde{\mathbf{x}}_S\left(t_i - \frac{\tilde{\rho}_i^j(t_i)}{c}\right), \mathbf{o}^j)}_{\tilde{\rho}_i^j(t_i)\text{ - Iteration: "Light Time Equation"}} \right|$$

- Can be solved iteratively exactly based on GNSS time t(i), Orbit $\mathbf{o}^j$ and good position $\mathbf{x}_R$(t(i))
- Must be solved in repeated parameter estimation, if $\Delta t_{R,i}(t_i)$ and $\mathbf{x}_R$(t(i)) are unknown

3. Geodynamic Corrections

1. 3D-Earth Tide Corrections

$$\Delta r = \sum_{j=2}^{3} \frac{GM_j}{GM} \frac{r^4}{R_j^3} \left\{ [3l_2(\boldsymbol{R}_j * \boldsymbol{r})\boldsymbol{R}_j] + \left[3\left(\frac{h_2}{2} - l_2\right)(\boldsymbol{R}_j * \boldsymbol{r})^2 - \frac{h_2}{2}\right]\boldsymbol{r} \right\} [-0.025 sin\rho\ cos\rho\ sin(\theta_g + \lambda)]\boldsymbol{r}$$

3.2. Ocean Loading (IERS Standards, 1996)

3.3. Atmospheric Loading

3.4. Earth Orientation

$$\mathbf{R}_i^e(t) = \mathbf{R}_P \cdot \mathbf{R}_E \cdot \mathbf{R}_N \cdot \mathbf{R}_{Pr} \qquad \mathbf{x}^e(t) = \mathbf{R}_i^e(t) \cdot \mathbf{x}^i(t)$$

GNSS Code- or „Pseudorange“ Observation and Modeling

Pseudorange Modeling in ECEF and GNSS-time

$$\rho(t_i)_{Obs} = \left|\tilde{\mathbf{x}}_R(t_i) - \tilde{\mathbf{x}}_S(t_i - \frac{\tilde{\rho}_i^j(t_i)}{c}, \mathbf{o}^j)\right| + c\cdot\Delta\bar{t}_{R,i} - c\cdot\Delta\bar{t}_{S,j} + \Delta\rho^j_{i,ION} + \Delta\rho^j_{i,TROP}$$

with $\rho(t_i)_{Obs} = \left|\underbrace{\tilde{\mathbf{x}}_R(t_i) - \tilde{\mathbf{x}}_S(t_i - \frac{\tilde{\rho}_i^j(t_i)}{c}), \mathbf{o}^j)}_{\tilde{\rho}_i^j(t_i)\text{ - Iteration: "Light Time Equation"}}\right|$ and $\tau_i = \frac{\tilde{\rho}_i^j(t_i)}{c}$

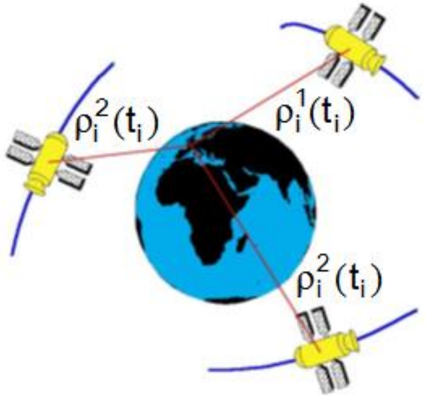
4. Additionally: Relativistic effects (Special and General Relativity)

4.1 Special and General Relativity in general

$$\frac{t'-t}{t} = \frac{\Delta t}{t} = \frac{x'-x}{x} = \frac{\Delta x}{x} = -\frac{f'-f}{f} = -\frac{\Delta f}{f} = \frac{m'-m}{m} = \frac{\Delta m}{m} = -(\frac{1}{2}\cdot\left(\frac{v}{c}\right)^2 + \frac{\Delta U}{c^2})$$

4.2 GNSS pseudorange-observation scenario

$$"t" = \tau_i = \frac{\tilde{\rho}_i^j(t_i)}{c} \quad \text{and} \quad \frac{\Delta U}{c^2} = \frac{\mu}{c^2}\cdot\left[\frac{1}{R_E + h(t_i)} - \frac{1}{R_E}\right]$$



GNSS Code- or „Pseudorange“ Observation and Modeling

Pseudorange Modeling in ECEF and GNSS-time

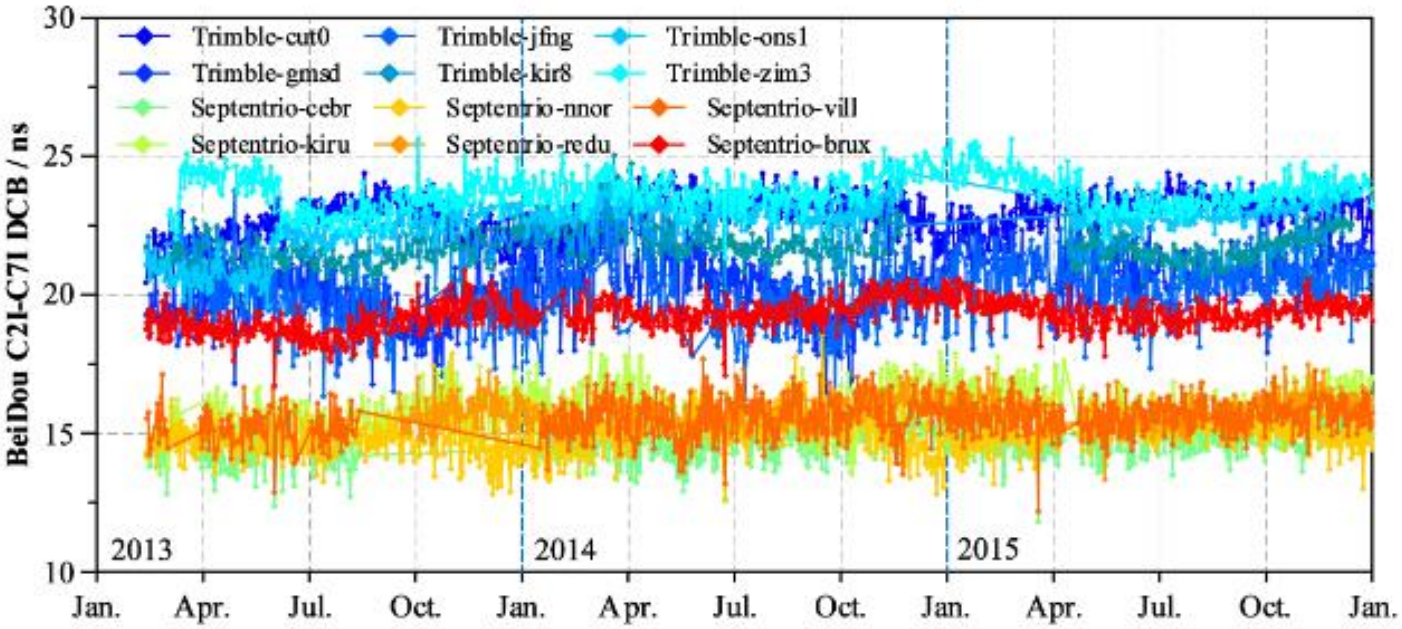
$$\rho(t_i)_{Obs} = \left| \tilde{\mathbf{x}}_R(t_i) - \tilde{\mathbf{x}}_S\left(t_i - \frac{\tilde{\rho}_i^j(t_i)}{c}, \mathbf{o}^j\right) \right| + c \cdot \Delta\bar{t}_{R,i} - c \cdot \Delta\bar{t}_{S,j} + \Delta\rho^j_{i,ION} + \Delta\rho^j_{i,TROP}$$

Further Clock/Time-Bias

Trimble NETR9 receivers: 18.0~24.0 ns

Septentrio receivers: 13.0~19.0 ns

- **GNSS differential code biases (DCB)**



Time series of BeiDou C2I-C7I DCBs for the selected receivers during the period 2013–2015

DCB products available from 01/2013

IGG – updated daily (daily interval)

DLR – updated quarterly (both weekly and daily intervals)

Pseudorange Modeling in ECEF and GNSS-time

$$\rho(t_i)_{Obs} = \left| \tilde{\mathbf{x}}_R(t_i) - \tilde{\mathbf{x}}_S\left(t_i - \frac{\tilde{\rho}_i^j(t_i)}{c}, \mathbf{o}^j\right) \right| + c \cdot \Delta\bar{t}_{R,i} - c \cdot \Delta\bar{t}_{S,j} + \Delta\rho^j_{i,ION} + \Delta\rho^j_{i,TROP}$$

5. Final Rough Pseudo-Range observation equation

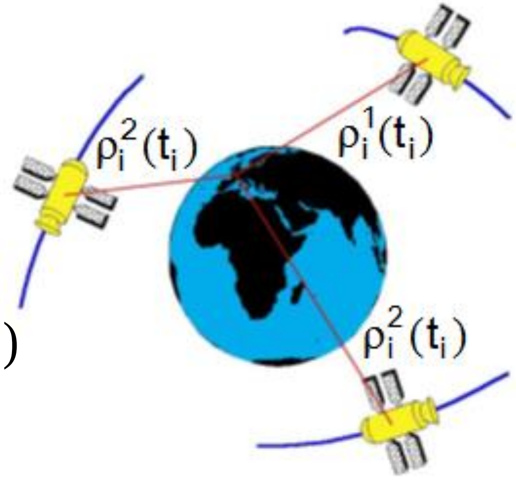
$$\rho(t_i)_{Obs} = \rho(t_i)_{Obs} = \left| \underbrace{\tilde{\mathbf{x}}_R(t_i) - \tilde{\mathbf{x}}_S\left(t_i - \frac{\tilde{\rho}_i^j(t_i)}{c}\right), \mathbf{o}^j)}_{\tilde{\rho}_i^j(t_i)\text{ - Iteration: "Light Time Equation"}} \right|$$

$$+ c \cdot \left(\Delta t_{R,i}(t_i) + \frac{1}{c^2} \cdot (\mathbf{x}_R^i(t_i) - \mathbf{x}_S^j(t_i)) \cdot (\boldsymbol{\omega}_E \times \mathbf{x}_R^i(t_i))\right)$$

$$- c \cdot \left(\Delta t_{S,j}(t_i) - \left[\frac{2}{c^2}\sqrt{\mu \cdot a} \cdot e \cdot \sin(E(t_i))\right]^j\right) + \Delta\rho^j_{i,ION}(t_i) + \Delta\rho^j_{i,TROP}(t_i)$$

Observations:

$t^i_R(t_i)$ and $\rho_i^j(t_i)_{Obs} = c \cdot \tau^j_{i\,Obs}$



Unknowns: $(x, y, z)_R(t_i), \Delta t_{R,i}(t_i)$

Corrections: Sagnac $R_{i,}$ Relativity S_j Clock S_j

Further Corrections, Add. rel. clock variations, Add. ModelsION, TROP, Earth Dynamics

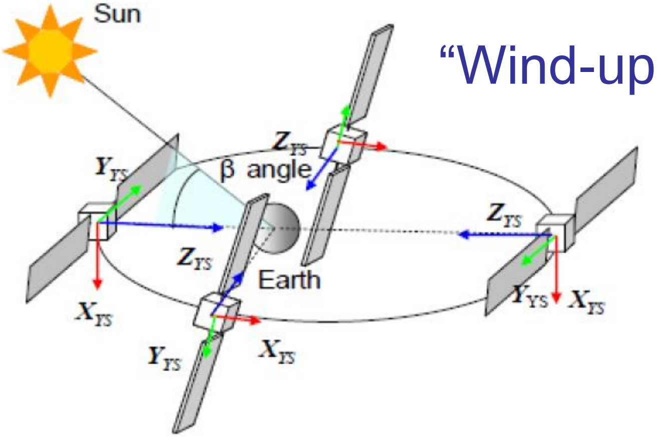
Phase Modelling in OPPP / PPP-K

$$\underbrace{\lambda_i^j(t_i)_{Obs} + D_i^j(t_i)_{Obs}}_{\text{Stored as "Phase-Observations" at } t_{i,R}} = \tilde{\rho}_i^j(t_i) + c\cdot\Delta\bar{t}_{R,i} - c\cdot\Delta\bar{t}_{S,j} + \Delta\rho^j_{i,ION} + \Delta\rho^j_{i,TROP} + \lambda\cdot(\Delta\varphi_i + \Delta\varphi_j - N_i^j)$$

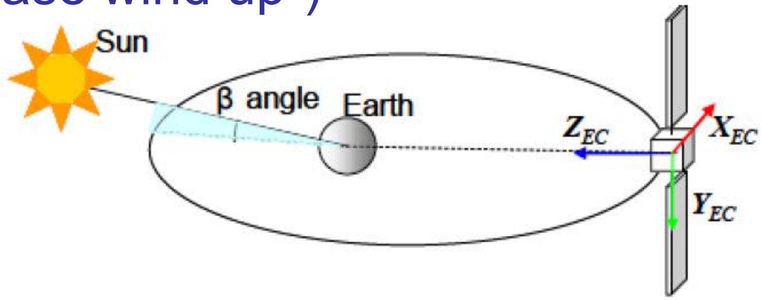
/ /

Uncalibrated phase delays (**UPD**) relevant to undifferentiated integer fixing for PPP

"Wind-up (**"**Phase wind up")



Yaw-steering Mode



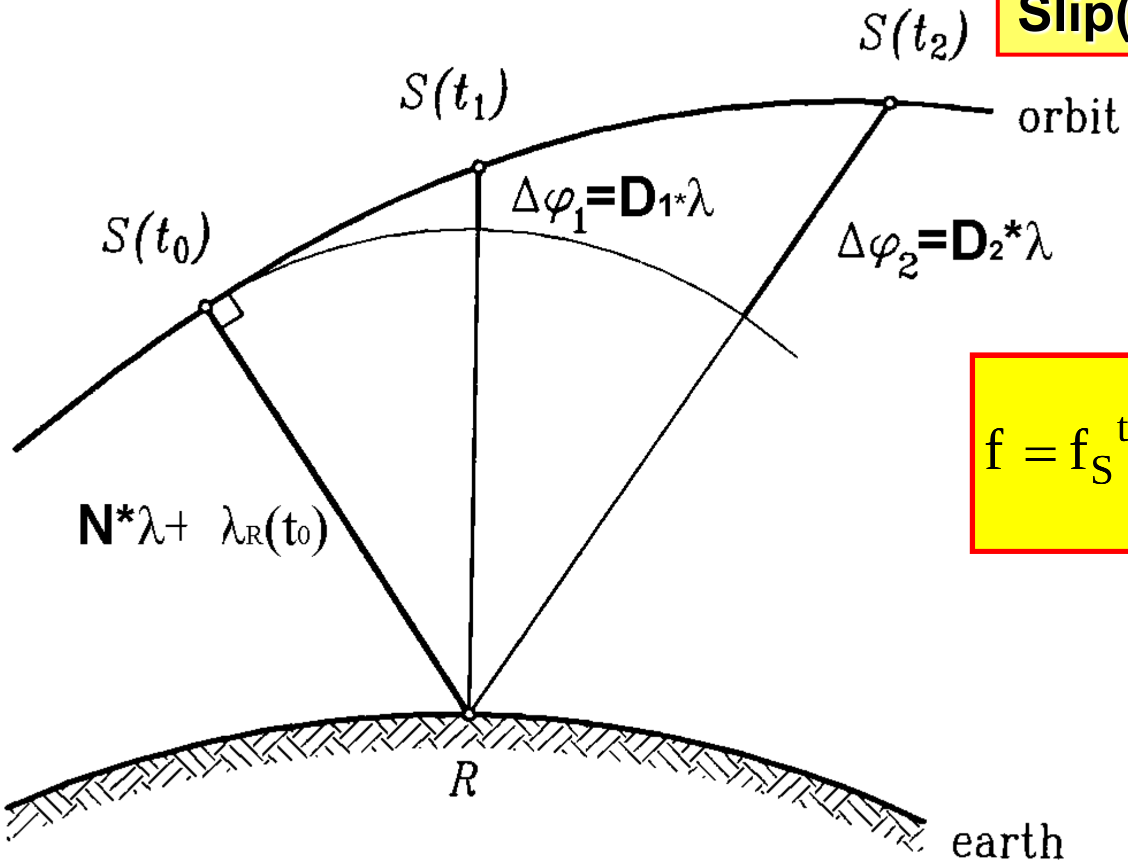
Orbit-normal („Earth-centered") Mode

Affects only carrier phase measurements (circularly polarized waves of GNSS signals).
A correction dPHi is only required for PPP absolute positioning.
DPhI depends on relative orientation of satellite and receiver antennas, and the direction of the line of sight. While moving in the orbit the satellites perform a rotation to keep its solar panels pointing to the sun direction in order to obtain the maximum energy, while the satellite antenna keeps pointing to the earth's centre. This rotation causes the a phase variation dPHi.

http://www.navipedia.net/index.php/Carrier_Phase_Wind-up_Effect

Doppler-Frequency Measurement Types

$$D_i = \mathrm{int}(\Delta\varphi'_i\,[\mathrm{cyc}]) = \mathrm{int}\left(\int_{t_0}^{t_i}(f_R - f_S)^t\,dt\right)$$



1.) Add. Measurement for Positioning by Phase-Measurements

Cycles D_i at Phase-Measurements. Error: „Cycle-Slip(s)“

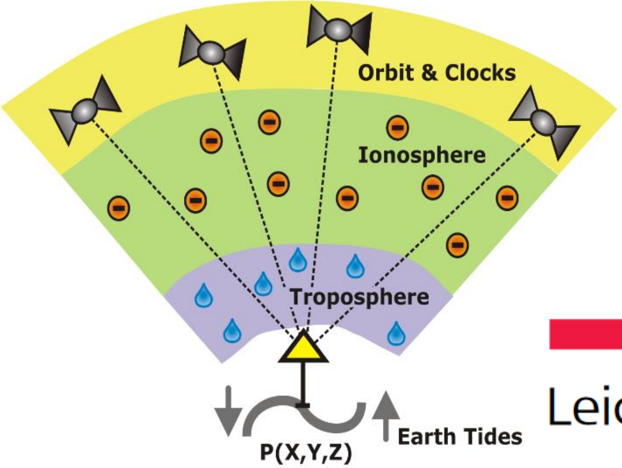
2.) General Measurment for Positioning and Navigation

$$f = f_S{}^t - f_R{}^t = \frac{f_S{}^t}{c}\cdot\frac{\mathbf{r}_S - \mathbf{r}_R}{\left|\mathbf{r}_S - \mathbf{r}_R\right|}\cdot(\dot{\mathbf{r}}_S - \dot{\mathbf{r}}_R)$$

$$\Delta f = f\cdot\left(\frac{1}{2}\cdot\left(\frac{v}{c}\right)^2 + \frac{\Delta U}{c^2}\right)$$

„Global G(lobal“)NSS Precise Positioning Services - Worldwide

1



- **SSR-based: Abs. Prec. OPPP**
- **Starfire™GPS-Corrections**
- **Starfire Receiver (left)**
- **Global Accuracy: „dm“**

NAVCOM
A John Deere Company

Leica SteerDirect
steering solutions

Abs. GNSS = „Non-DGNSS“
No Reference-Stations
But: NAVCOM Roverclients!

2

„RTX“

OmniSTAR.
The Global Positioning System

Trimble.

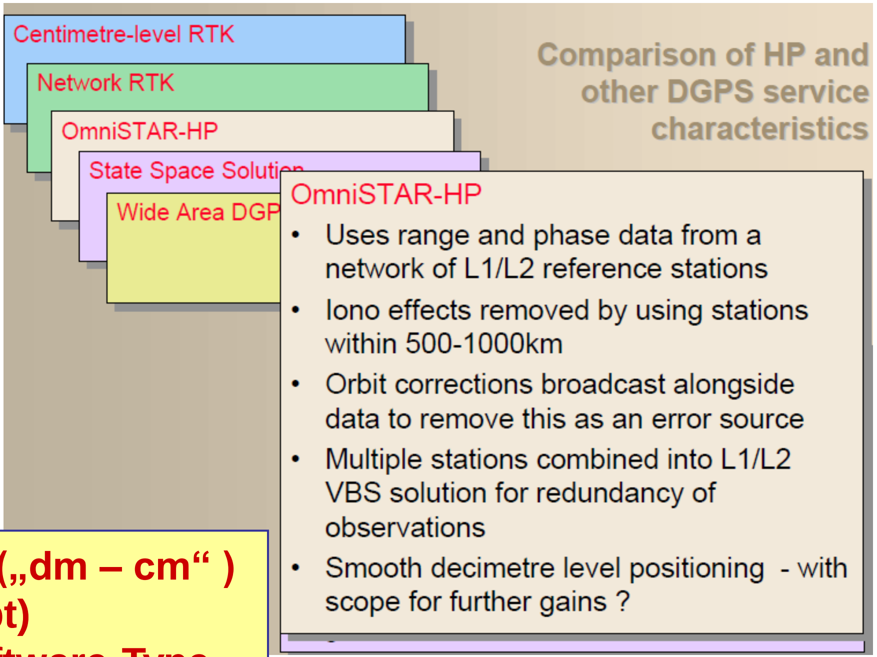
16 March 2011

Check out the Latest News!

Read Press Release

Continue to an OmniSTAR website:

- North and South America
- Europe, North Africa, Middle East, India
- Asia Pacific
- South Africa



Comparison of HP and other DGPS service characteristics

Centimetre-level RTK
Network RTK
OmniSTAR-HP
State Space Solution
Wide Area DGP

OmniSTAR-HP

- Uses range and phase data from a network of L1/L2 reference stations
- Iono effects removed by using stations within 500-1000km
- Orbit corrections broadcast alongside data to remove this as an error source
- Multiple stations combined into L1/L2 VBS solution for redundancy of observations
- Smooth decimetre level positioning - with scope for further gains ?

OSR (= Observation-)related: Networked, scalabe („dm – cm“)
DGNSS RTCM Correction (VRS-Concept)
• RTCM-Standard =>Open for any Rover- and Software-Type

Commericial OPPP / PPP-K Services

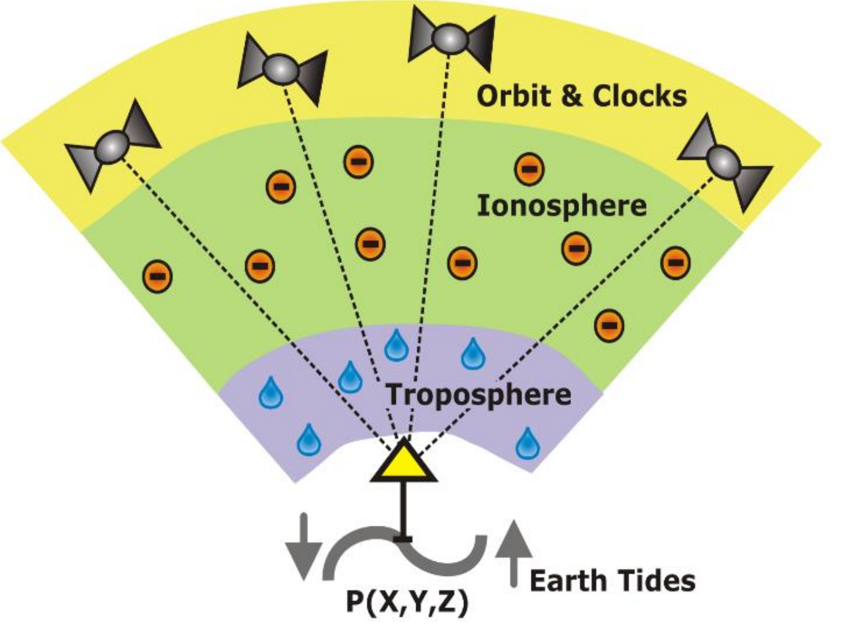
NAME	Service	Accuracy performance	Supported constellations	Method	Provider
OmniStar	G2	<10cm	GPS+GLONASS	PPP	Trimble
RTX	CenterPoint	<4cm	GPS+GLONASS+BDS	PPP	Trimble
StarFix	G2+	3cm	GPS+GLONASS	PPP	Fugro
	G4	5-10cm	GPS+GLONASS+BDS+Galileo	PPP	
StarFire	SF2	5cm	GPS+GLONASS	PPP	John Deere
	SF3	3cm	GPS+GLONASS Future(BDS+Galileo)	PPP	
Veripos	C2	5cm	GPS+GLONASS	PPP	Hexagon AB
	Apex²	5cm	GPS+GLONASS	PPP	
TerraStar	TerraStar C	2-3cm	GPS+GLONASS	PPP	Hexagon AB

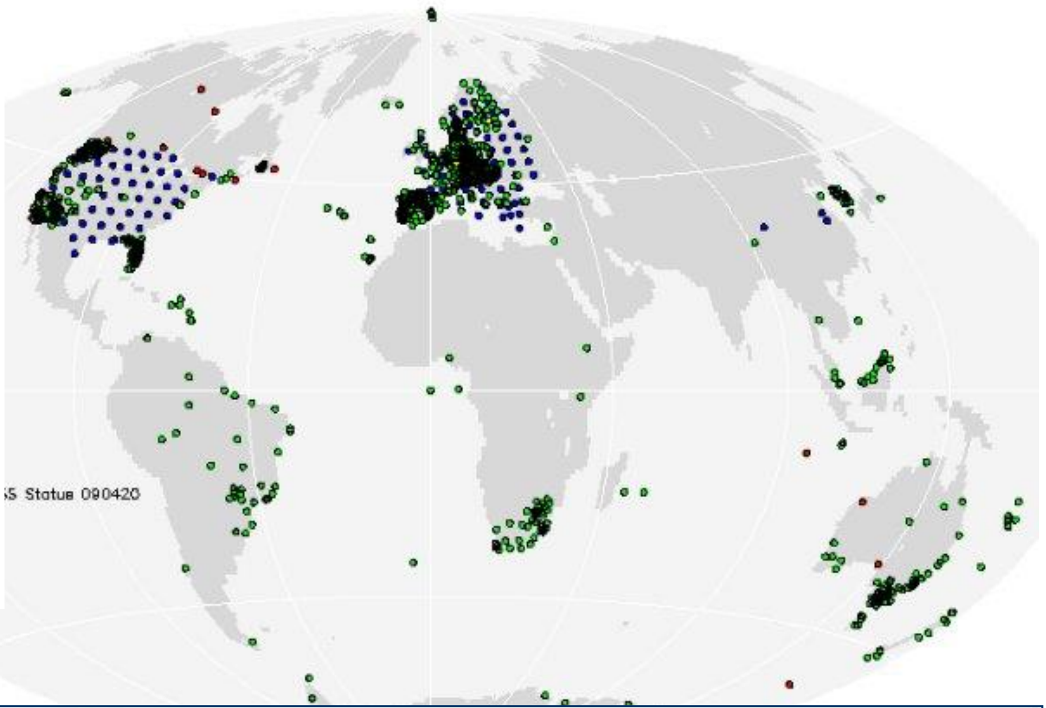
August 2017: Joint Venture „Sapcorda Services“ (Bosch, Geo++, Mitsubishi, ublox)

Public OPPP / PPP-K Service

International GNSS-Service (IGS

„RTS“: http://rts.igs.org/



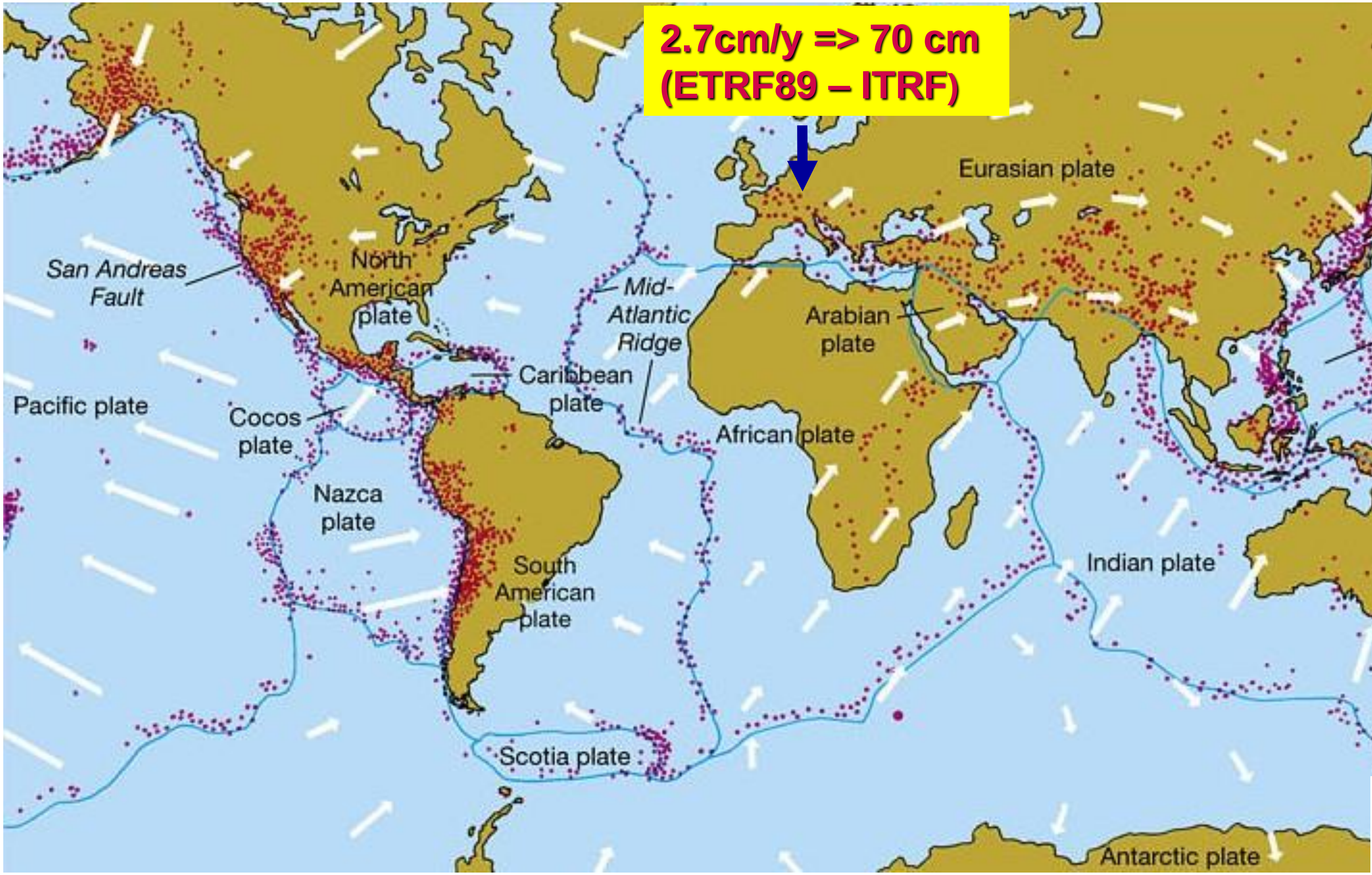


International GNSS Service

Formerly the International GPS Service

Real-time Service

GNSS Positioning – Medium Term Geodynamical Modeling

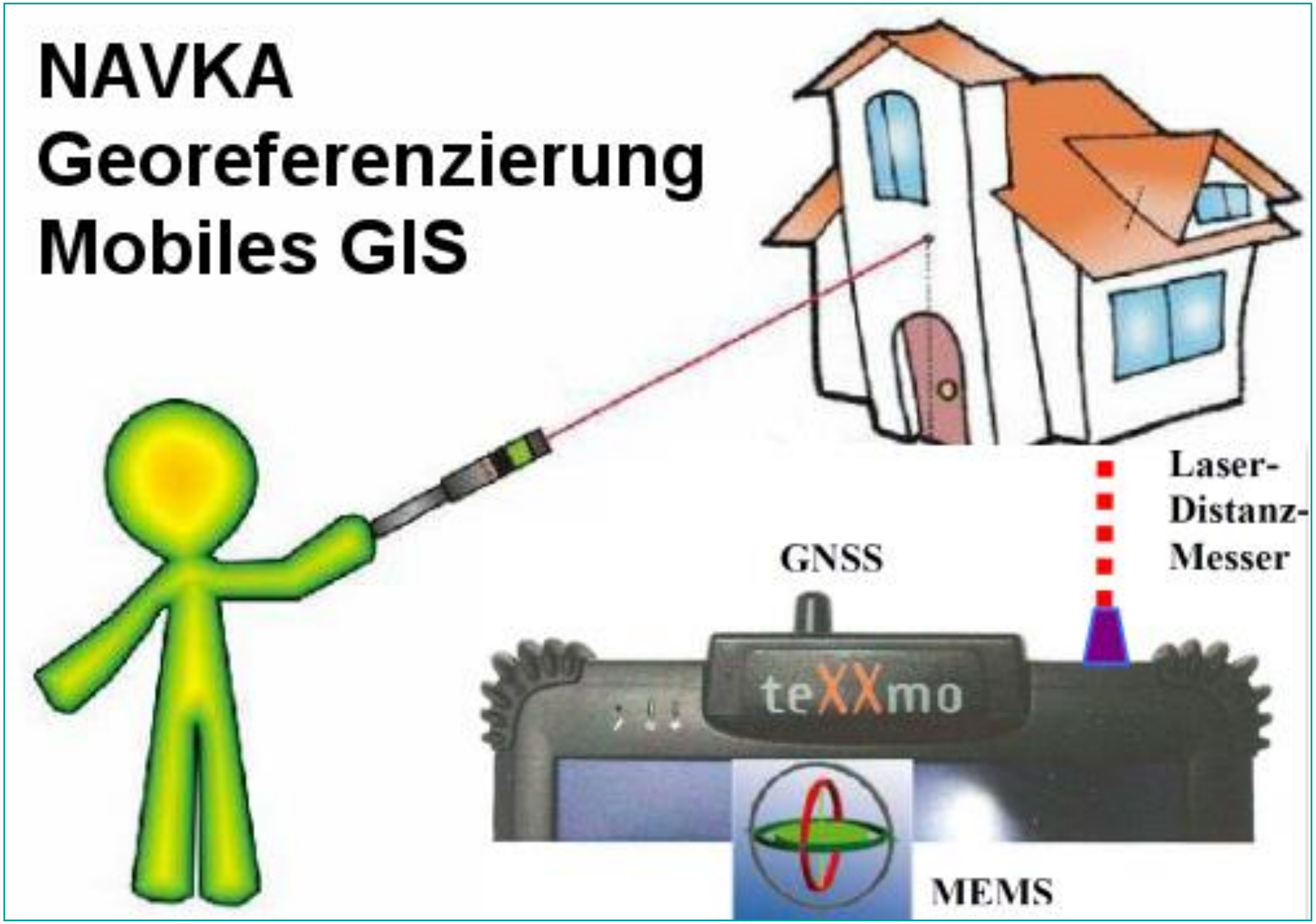


2.7cm/y => 70 cm
(ETRF89 – ITRF)

$$x(t_1)_{ITRF_{zz},t_1} = (1+\Delta m)\cdot \mathbf{R}(\varepsilon_x,\varepsilon_y,\varepsilon_z)\cdot \mathbf{x}(t_1)_{ITRFyy,t_1} + \mathbf{t}$$

$$\mathbf{x}(t_2)_{ITRFzzt_2} = \mathbf{x}(t_1)_{ITRFzzt_1} + \left(\left((\dot{\mathbf{R}}+\Delta\dot{m})\cdot\mathbf{x}(t_1)_{ITRFzzt_1}+\dot{\mathbf{t}}\right)+\left(\dot{\mathbf{R}}_{P(j)}\cdot\mathbf{x}(t_1)_{ITRFzzt_1}\right)\right)\cdot(t_2-t_1)$$

GNSS / MEMS / Laser Sensorfusion (ZIM-Projekt bis 3/2019)

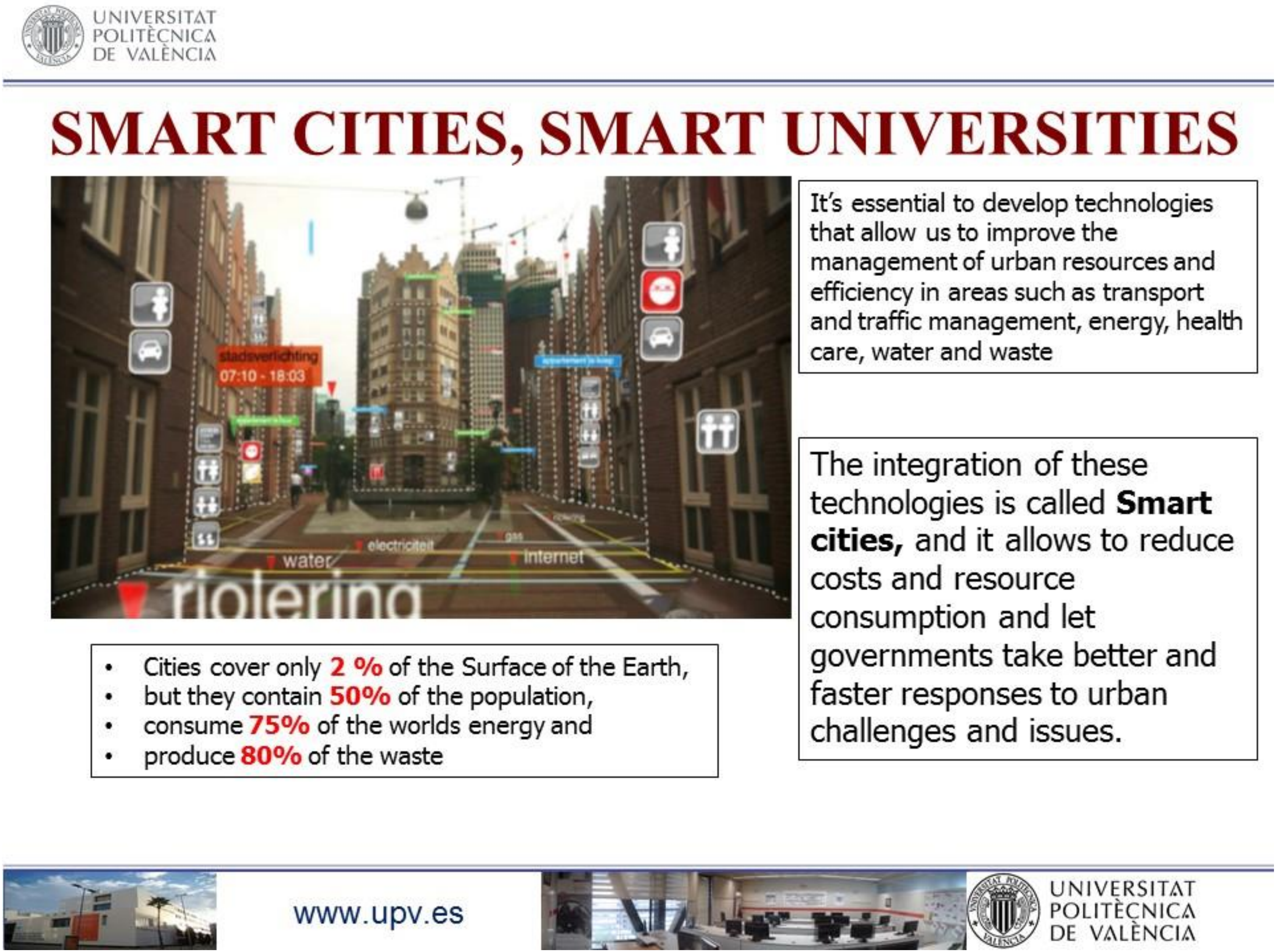


PREGON-X RaD at HSKA:

http://www.navka.de/index.php/de/weitere-projekte/fue-projekte-produkte-2b

INSPIRE

NAVKA Indoor-Navigation – General Aspects



UNIVERSITAT POLITÈCNICA DE VALÈNCIA

SMART CITIES, SMART UNIVERSITIES

It's essential to develop technologies that allow us to improve the management of urban resources and efficiency in areas such as transport and traffic management, energy, health care, water and waste

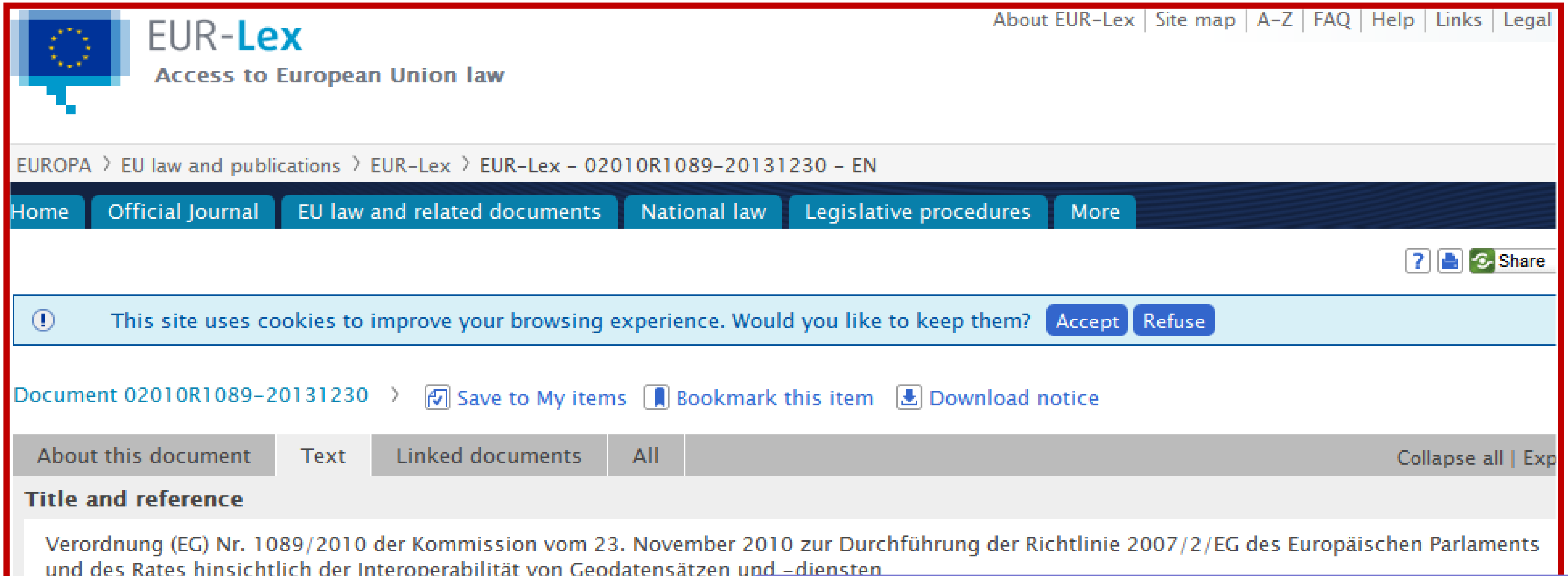
The integration of these technologies is called **Smart cities,** and it allows to reduce costs and resource consumption and let governments take better and faster responses to urban challenges and issues.

- Cities cover only 2 % of the Surface of the Earth,
- but they contain 50% of the population,
- consume 75% of the worlds energy and
- produce 80% of the waste

www.upv.es

UNIVERSITAT POLITÈCNICA DE VALÈNCIA

NAVKA Indoor-Navigation – European Infrastructure INSPIRE



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Title and reference

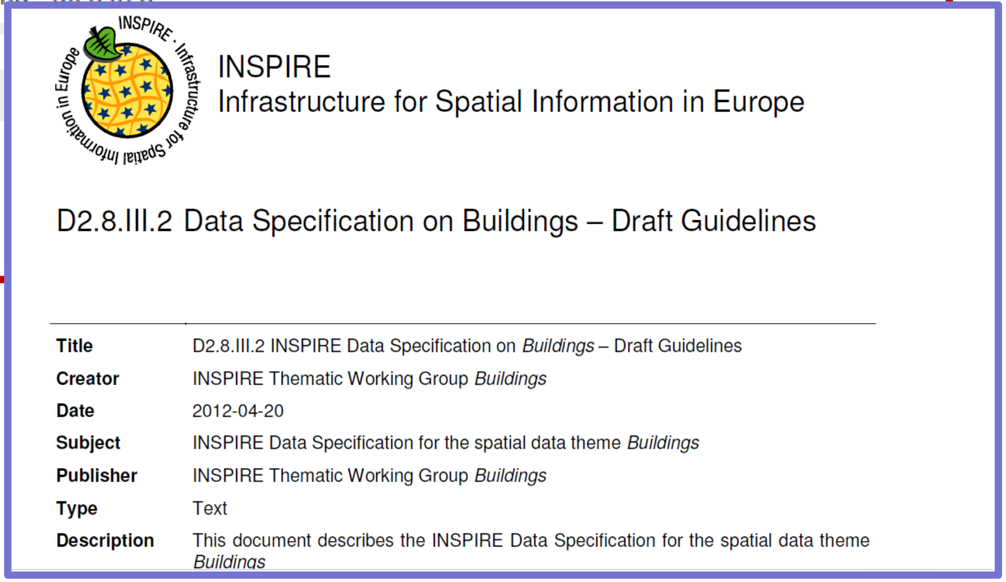
Verordnung (EG) Nr. 1089/2010 der Kommission vom 23. November 2010 zur Durchführung der Richtlinie 2007/2/EG des Europäischen Parlaments und des Rates hinsichtlich der Interoperabilität von Geodatensätzen und -diensten

Languages and formats available

	BG	ES	CS	DA	DE	ET	EL	EN	FR	GA
HTML										
PI										

Georeferencing and Interoperability ITRF/ETRF89

http://inspire.ec.europa.eu/index.cfm/pageid/3



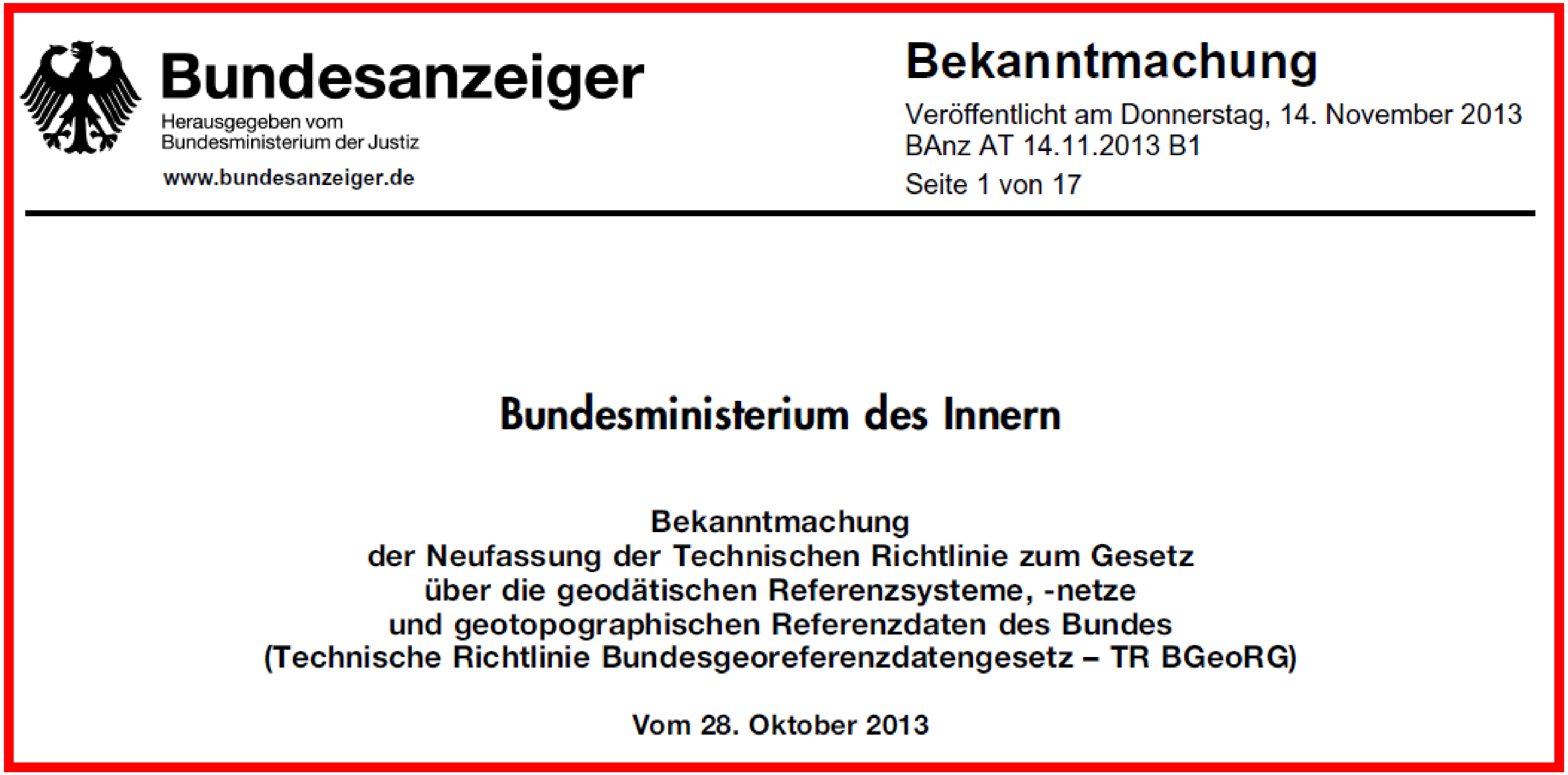
INSPIRE

Infrastructure for Spatial Information in Europe

D2.8.III.2 Data Specification on Buildings – Draft Guidelines

Title	D2.8.III.2 INSPIRE Data Specification on *Buildings* – Draft Guidelines
Creator	INSPIRE Thematic Working Group *Buildings*
Date	2012-04-20
Subject	INSPIRE Data Specification for the spatial data theme *Buildings*
Publisher	INSPIRE Thematic Working Group *Buildings*
Type	Text
Description	This document describes the INSPIRE Data Specification for the spatial data theme *Buildings*

NAVKA Indoor-Navigation – INSPIRE realization in Germany



Bundesanzeiger
Herausgegeben vom
Bundesministerium der Justiz
www.bundesanzeiger.de

Bekanntmachung
Veröffentlicht am Donnerstag, 14. November 2013
BAnz AT 14.11.2013 B1
Seite 1 von 17

Bundesministerium des Innern

Bekanntmachung
der Neufassung der Technischen Richtlinie zum Gesetz
über die geodätischen Referenzsysteme, -netze
und geotopographischen Referenzdaten des Bundes
(Technische Richtlinie Bundesgeoreferenzdatengesetz – TR BGeoRG)

Vom 28. Oktober 2013

http://inspire-geoportal.ec.europa.eu/

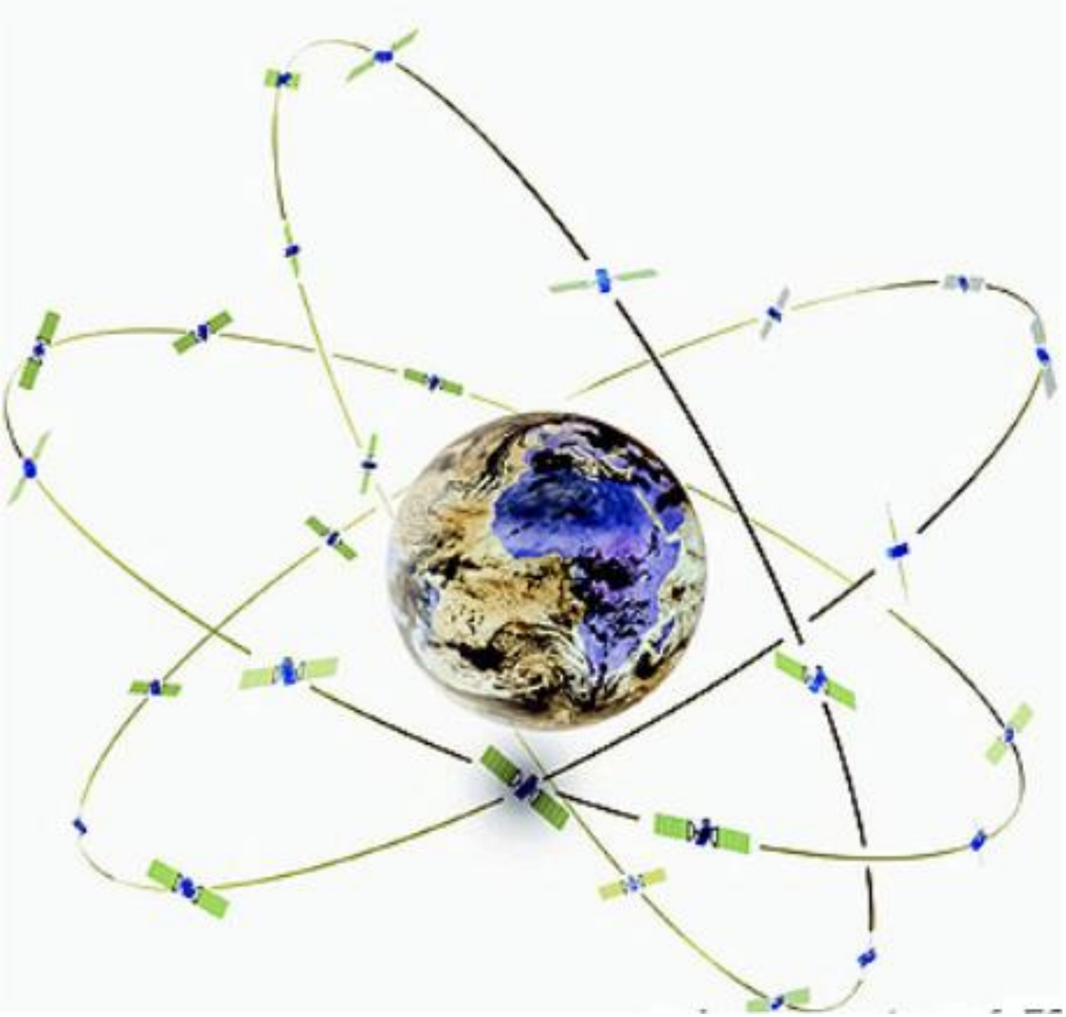
Seamless Out-/Indoor Georeferencing and Interoperability based on ITRF/ETRF89

Paradigma-Changes GALILEO - Aspects

GALILEO

In Orbit Placement of GALILEO Satellites
with Ariane 8 Satellites

Galileo-Satellites



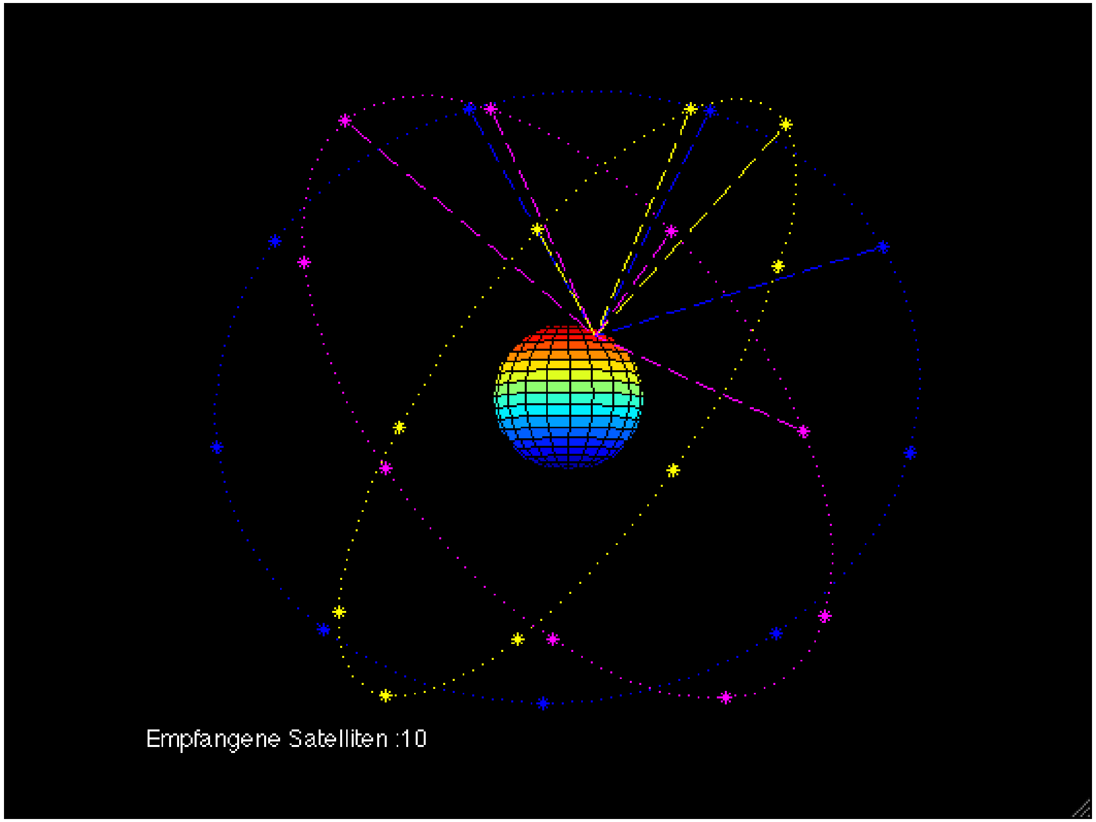
GALILEO and GPS Satellites

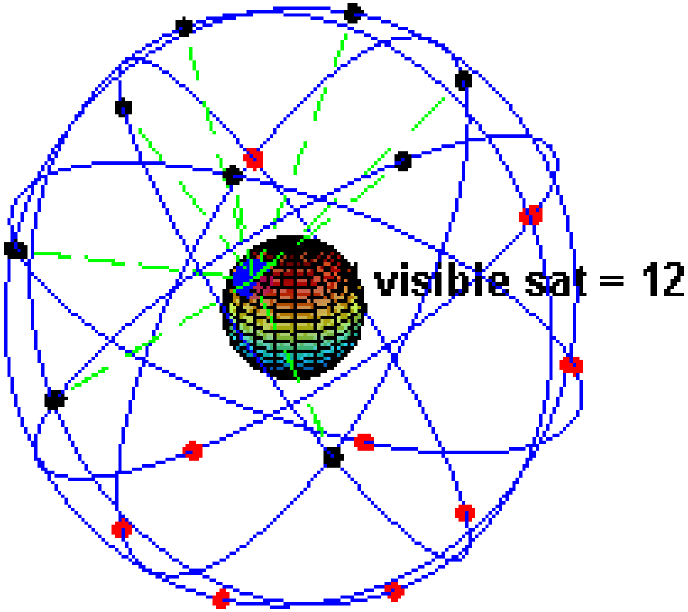
GALILEO Satelliten

https://en.wikipedia.org/wiki/List_of_Galileo_satellites

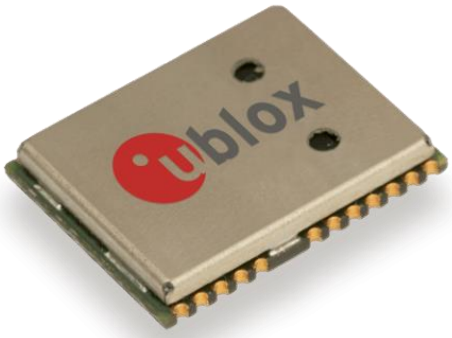
GPS Satelliten

https://de.wikipedia.org/wiki/Global_Positioning_System

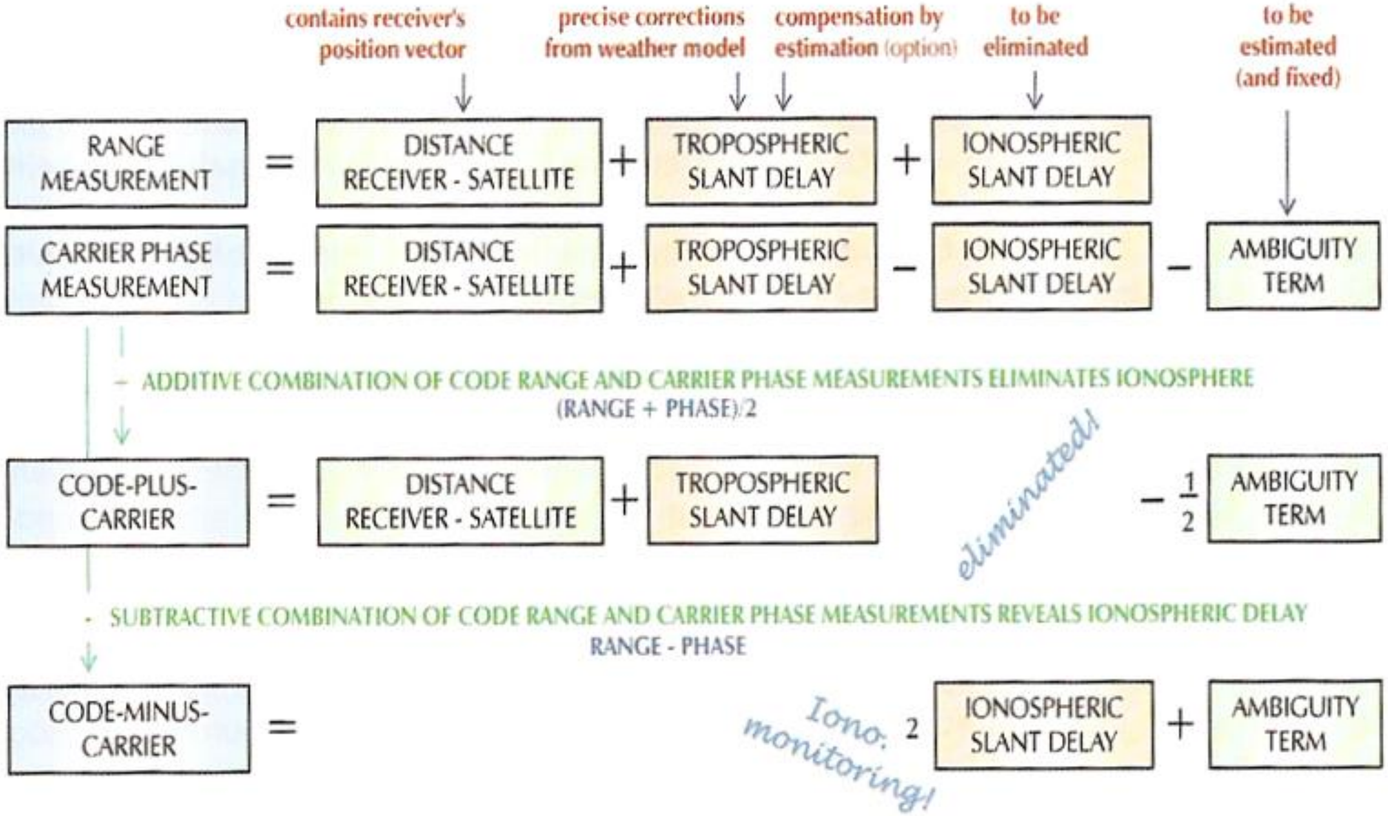




GALILEO - E1 Code/Phase Linear-Combination



Ublox NEO 8MN
29.- EUR



contains receiver's position vector
precise corrections from weather model
compensation by estimation (option)
to be eliminated
to be estimated (and fixed)

RANGE MEASUREMENT = DISTANCE RECEIVER - SATELLITE + TROPOSPHERIC SLANT DELAY + IONOSPHERIC SLANT DELAY

CARRIER PHASE MEASUREMENT = DISTANCE RECEIVER - SATELLITE + TROPOSPHERIC SLANT DELAY − IONOSPHERIC SLANT DELAY − AMBIGUITY TERM

ADDITIVE COMBINATION OF CODE RANGE AND CARRIER PHASE MEASUREMENTS ELIMINATES IONOSPHERE
(RANGE + PHASE)/2

CODE-PLUS-CARRIER = DISTANCE RECEIVER - SATELLITE + TROPOSPHERIC SLANT DELAY − $\frac{1}{2}$ AMBIGUITY TERM

eliminated!

SUBTRACTIVE COMBINATION OF CODE RANGE AND CARRIER PHASE MEASUREMENTS REVEALS IONOSPHERIC DELAY
RANGE - PHASE

CODE-MINUS-CARRIER = 2 IONOSPHERIC SLANT DELAY + AMBIGUITY TERM

Iono: monitoring!

Vereinfachte Beobachtungsgleichung „Code-plus-Carrier“:

$$\frac{PR+\phi}{2} = \rho - \frac{\lambda}{2}\cdot N + \left(\frac{c_2}{4\cdot f^3} + \frac{c_3}{3\cdot f^4}\right) + SPD$$

kombinierte Beobachtung

Entfernung

Mehrdeutigkeit

Ionosphärenfehler höherer Ordnung

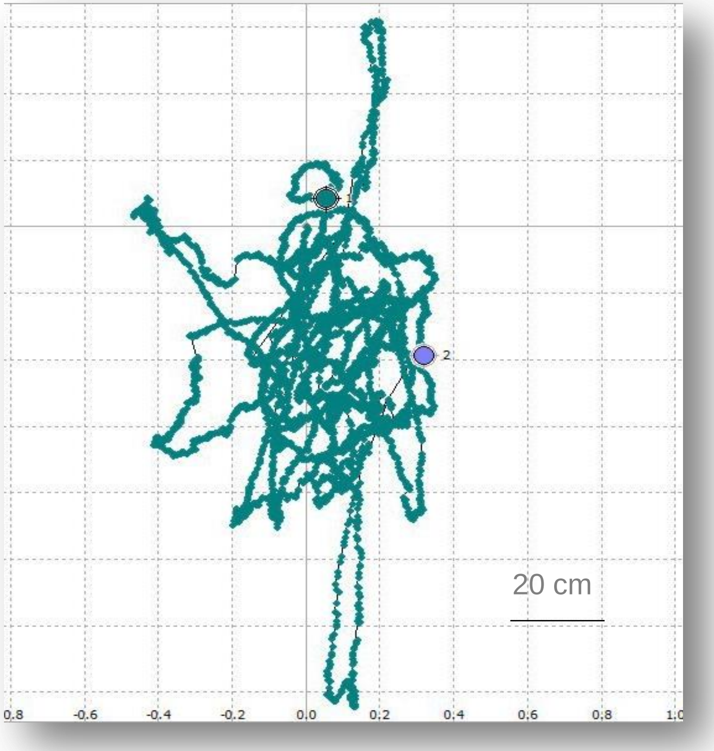
troposphärische Laufzeitverzögerung (Slant Path Delay)

OPPP – L1-Pseudorange and –Phasemeasurements

RTS/IGS - Realtime Data Stream of IGS SSR-Products

- Rover Motion: Over Point 2
- Rover Motion: Around Point 2

L1, PPP-K



Key:

⊕ : Computed Position

● : Station’s True Position found in “ITRF 2008” Frame

3D IGS/RTS OPPP Kinematic Positioning Error at 1 Hz in ITRF2008.09.2015

Positioning Error, Point 2: 0.25m

OPPP – E1/E5 and L1/L5 Phasemeasurements – 21. Sept. 2017

Broadcom launches dual-frequency GNSS receiver for mass market

September 21, 2017 - By Tracy Cozzens

GNSS receiver „BCM47755“

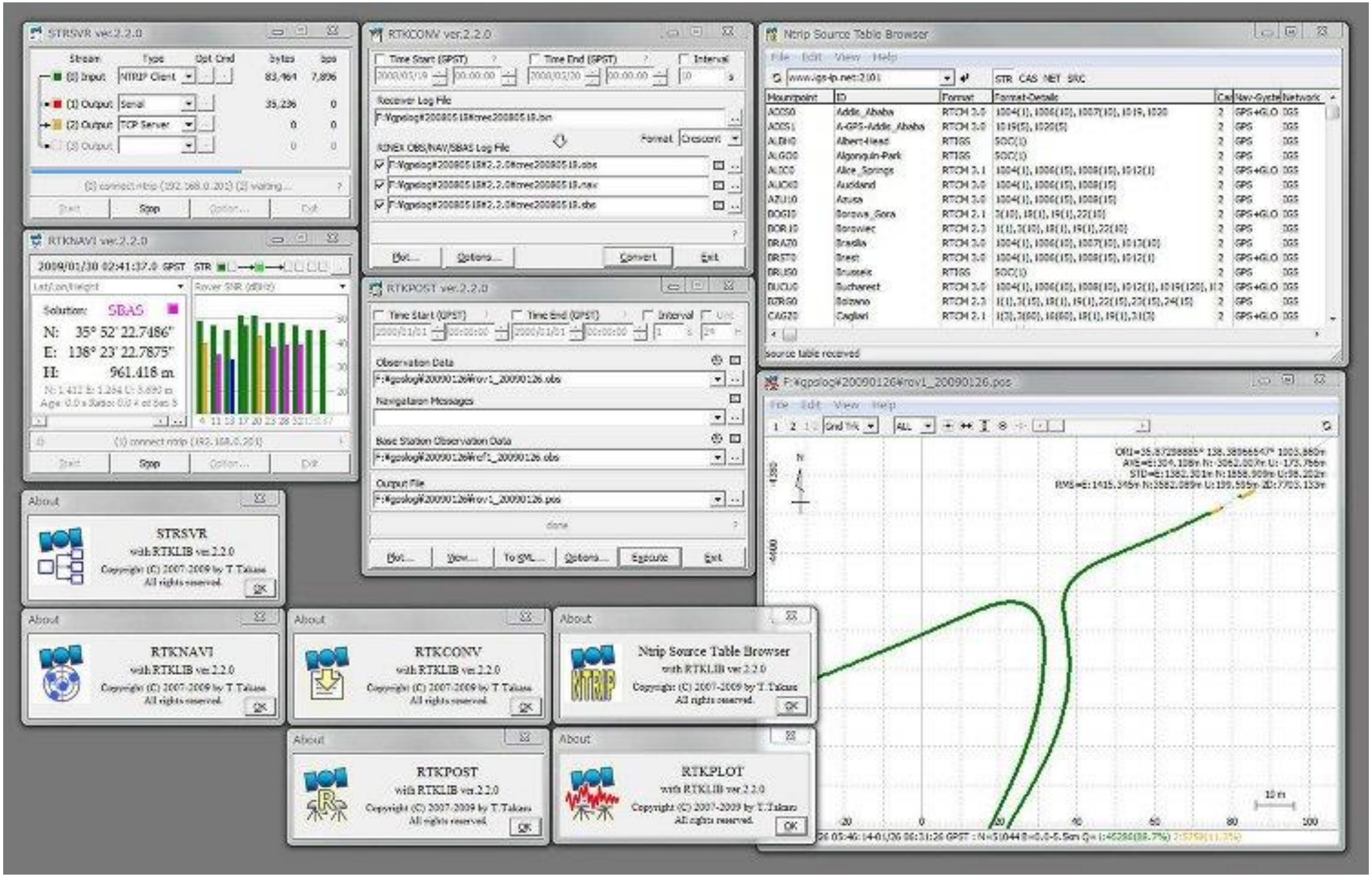
1 cm

OPP-K global Positioning

- **GNSS-Receivers**
- **Smartphones**

Open Source – DGNSS, PPP-K

RTKLIB - Open Source Software (DGNSS/RTK, GNSS-PPP, Postprocessing



STRSVR ver.2.2.0

Stream	Type	Opt Cmd	bytes	bps
(0) Input	NTRIP Client		83,461	7,896
(1) Output	Serial		35,236	0
(2) Output	TCP Server		0	0
(3) Output			0	0

(0) connect ntrip (192.168.0.201) (2) waiting...

RTKNAVI ver.2.2.0

2009/01/30 02:41:37.0 GPST STR

Solution: SBAS

N: 35° 52' 22.7486"

E: 138° 23' 22.7875"

H: 961.418 m

(1) connect ntrip (192.168.0.201)

RTKCONV ver.2.2.0

☐ Time Start (GPST) 2008/05/19 00:00:00 ☐ Time End (GPST) 2008/05/20 00:00:00 ☐ Interval 10 s

Receiver Log File: F:¥gpslog¥20080519¥crec20080519.bin

Format: Crescent

RINEX OBS/NAV/SBAS Log File

☑ F:¥gpslog¥20080519¥2.2.0¥crec20080519.obs

☑ F:¥gpslog¥20080519¥2.2.0¥crec20080519.nav

☑ F:¥gpslog¥20080519¥2.2.0¥crec20080519.sbs

RTKPOST ver.2.2.0

☐ Time Start (GPST) 2000/01/01 00:00:00 ☐ Time End (GPST) 2000/01/01 00:00:00 ☐ Interval 1 s ☐ Unit 24 H

Observation Data: F:¥gpslog¥20090126¥rov1_20090126.obs

Navigation Messages:

Base Station Observation Data: F:¥gpslog¥20090126¥ref1_20090126.obs

Output File: F:¥gpslog¥20090126¥rov1_20090126.pos

done

Ntrip Source Table Browser

www.igs-ip.net:2101

Mountpoint	ID	Format	Format-Details	Car	Nav-System	Network
ADIS0	Addis_Ababa	RTCM 3.0	1004(1), 1006(10), 1007(10), 1019, 1020	2	GPS+GLO	IGS
ADIS1	A-GPS-Addis_Ababa	RTCM 3.0	1019(5), 1020(5)	2	GPS	IGS
ALBH0	Albert-Head	RTIGS	SOC(1)	2	GPS	IGS
ALGO0	Algonquin-Park	RTIGS	SOC(1)	2	GPS	IGS
ALIC0	Alice_Springs	RTCM 3.1	1004(1), 1006(15), 1008(15), 1012(1)	2	GPS+GLO	IGS
AUCK0	Auckland	RTCM 3.0	1004(1), 1006(15), 1008(15)	2	GPS	IGS
AZU10	Azusa	RTCM 3.0	1004(1), 1006(15), 1008(15)	2	GPS	IGS
BOGI0	Borowa_Gora	RTCM 2.1	3(10), 18(1), 19(1), 22(10)	2	GPS+GLO	IGS
BOR10	Borowiec	RTCM 2.3	1(1), 3(10), 18(1), 19(1), 22(10)	2	GPS	IGS
BRAZ0	Brasilia	RTCM 3.0	1004(1), 1006(10), 1007(10), 1013(10)	2	GPS	IGS
BRST0	Brest	RTCM 3.0	1004(1), 1006(15), 1008(15), 1012(1)	2	GPS+GLO	IGS
BRUS0	Brussels	RTIGS	SOC(1)	2	GPS	IGS
BUCU0	Bucharest	RTCM 3.0	1004(1), 1006(10), 1008(10), 1012(1), 1019(120), 1	2	GPS+GLO	IGS
BZRG0	Bolzano	RTCM 2.3	1(1), 3(15), 18(1), 19(1), 22(15), 23(15), 24(15)	2	GPS	IGS
CAGZ0	Cagliari	RTCM 2.1	1(3), 3(60), 16(60), 18(1), 19(1), 31(3)	2	GPS+GLO	IGS

source table received

F:¥gpslog¥20090126¥rov1_20090126.pos

ORI=35.87298885° 138.38966547° 1003.860m

AVE=E:304.108m N:-3062.007m U:-173.766m

STD=E:1382.301m N:1858.909m U:98.202m

RMS=E:1415.346m N:3582.089m U:199.585m 2D:7703.153m

26 05:46:14-01/26 06:31:26 GPST : N=51044 B=0.0-5.5km Q=1:46286(88.7%) 2:5759(11.3%)

STRSVR
with RTKLIB ver.2.2.0
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RTKPLOT
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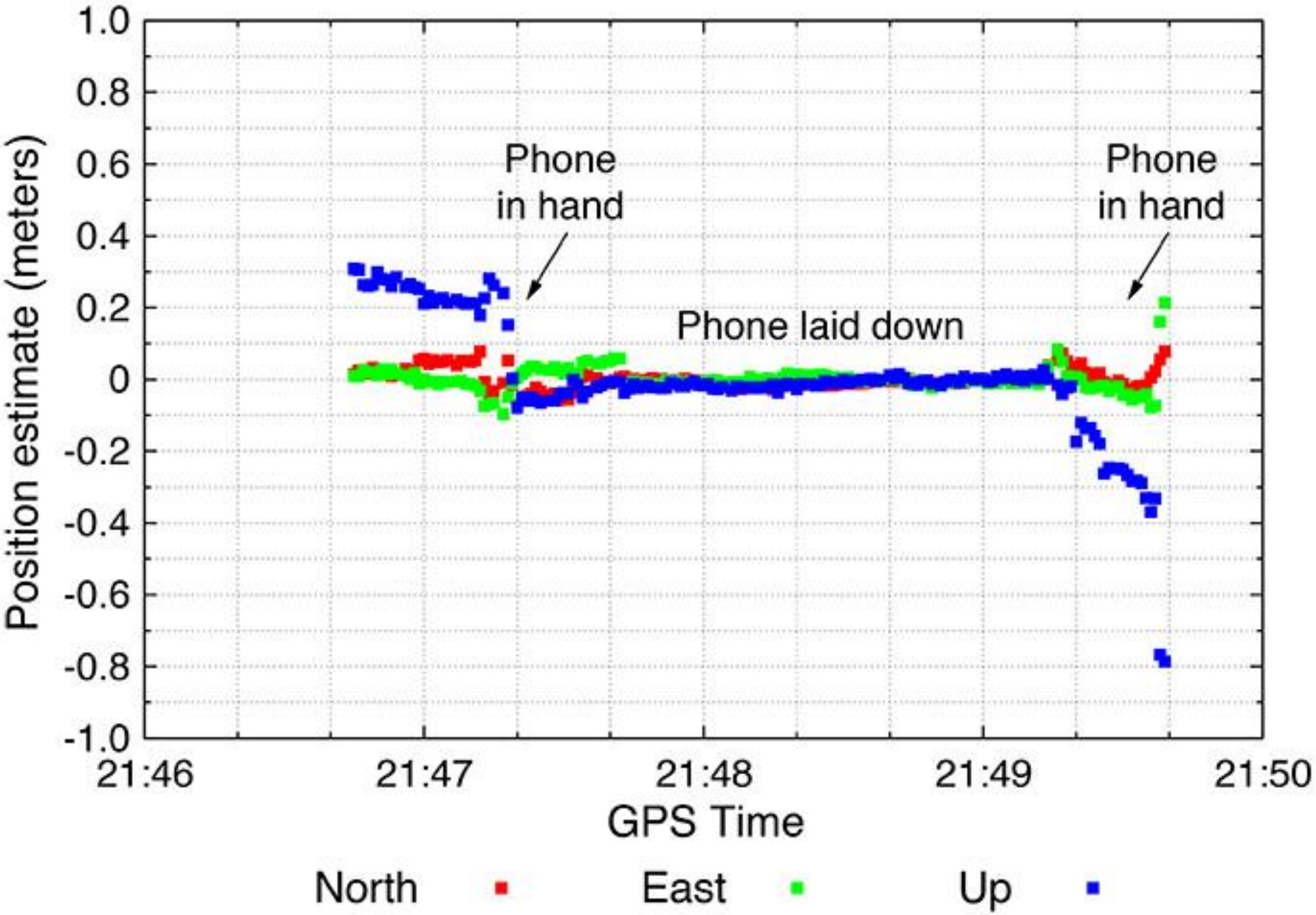
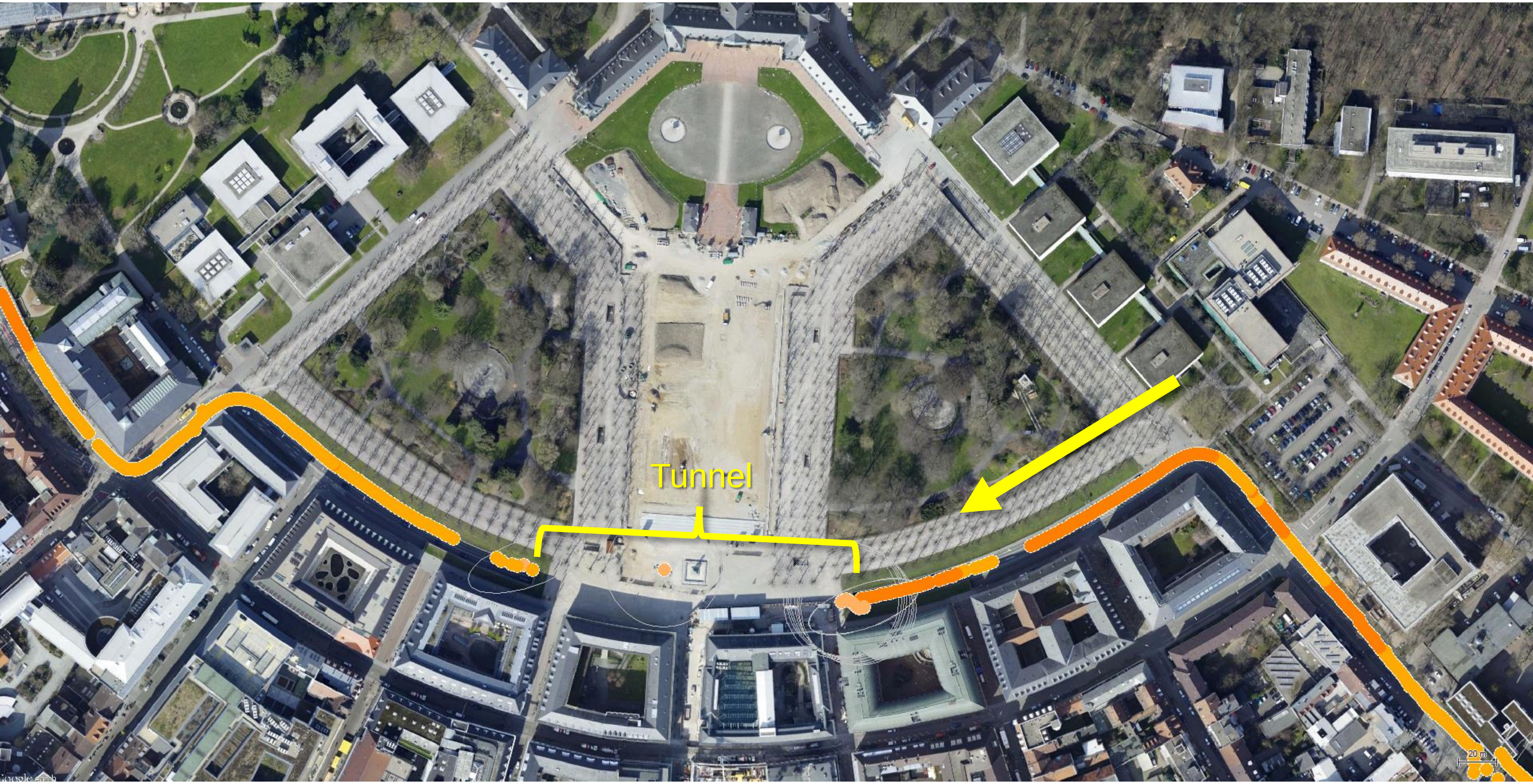
GNSS Rawdata on Smartphones (since Sept. 2016)



New Way (NAVKA): Algorithms for Multiplatform-, Multisensor-, Leverarm-Design

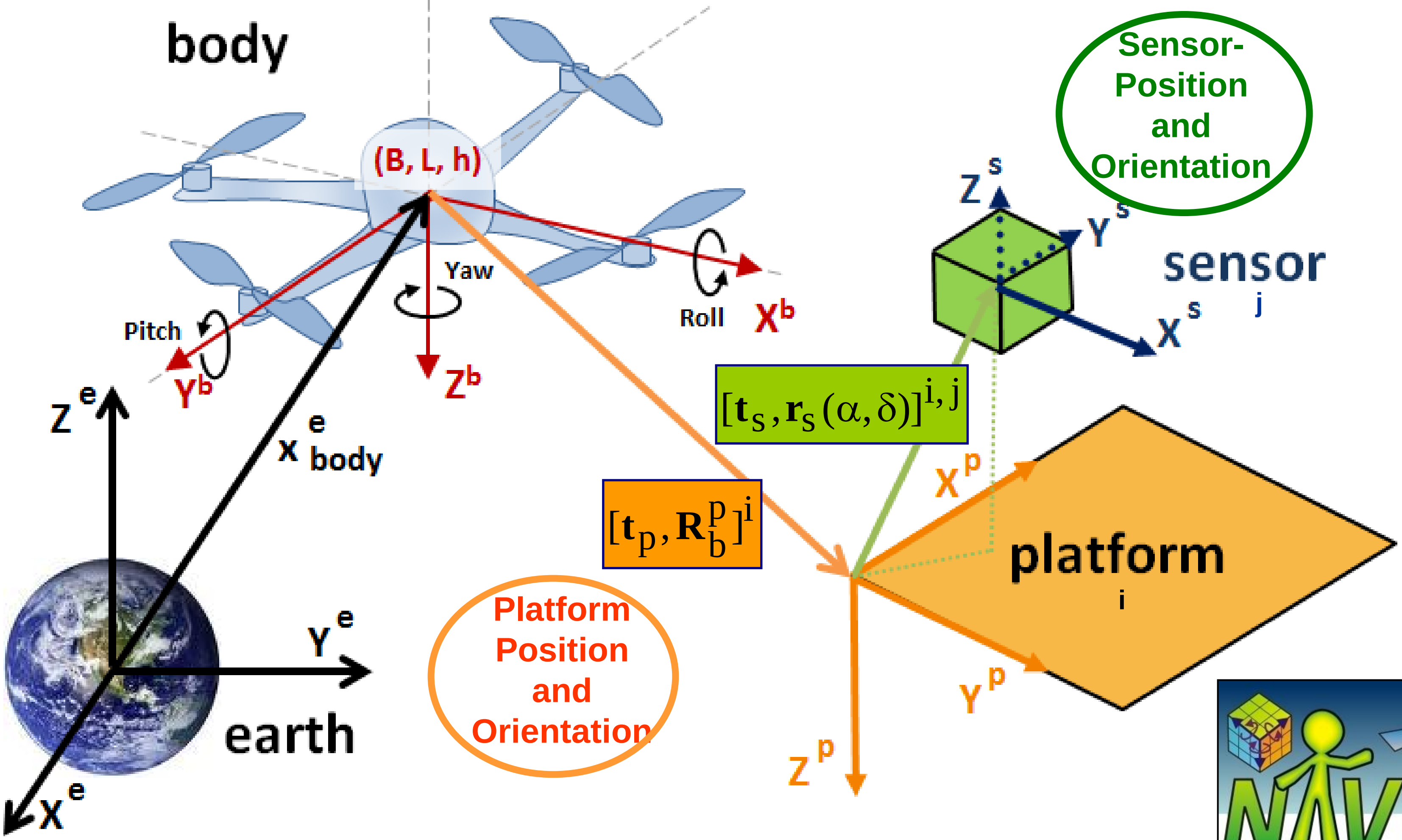


- GNSS Positioning Single L1 Receiver

Paradigma-Changes
MULTISENSOR-INTEGRATION

$$\mathbf{y} = \left[x^e \; y^e \; z^e \,|\, \dot{x}^e \dot{y}^e \dot{z}^e \;|\, r^e \; p^e \; y^e \,\|\, \ddot{x}^e \; \ddot{y}^e \; \ddot{z}^e \,|\, \omega^b_{eb,x} \; \omega^b_{eb,y} \; \omega^b_{eb,z} \,|\, \mathbf{s} \right]^T$$

3.) „Multisensor-Multiplatform Leverarm“ Concept



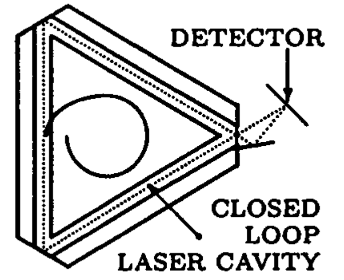
Sensor-Position and Orientation

Platform Position and Orientation

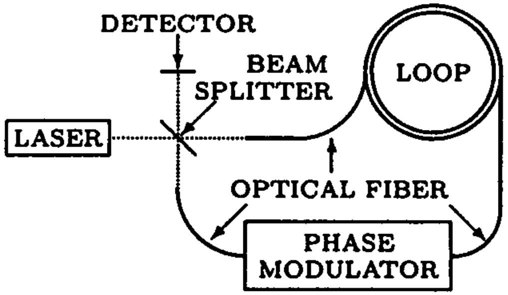
Autonomous MEMS-Sensors + New Algorithms „Deep-Coupling“

2. Autonomous

1.) MEMS-Gyro

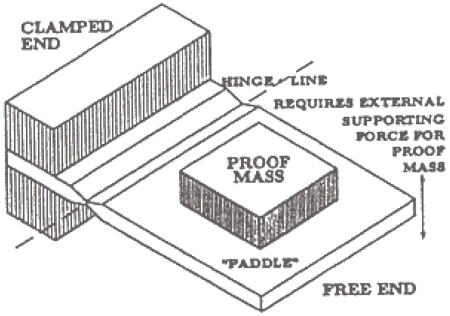


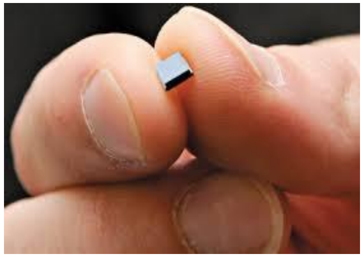
(a) Ring Laser Gyro (RLG)



(b) Fiber Optic Gryo (FOG)

2.) MEMS-Accelerometers





Observation I: $\boldsymbol{\omega}_{ip}^{p}$

$$\boldsymbol{\omega}_{ep}^{p} = \boldsymbol{\omega}_{ip}^{p} - \mathbf{R}_{e}^{p}(r,p,y)\cdot\boldsymbol{\omega}_{ie}^{e}$$

Observation I: $\mathbf{a}^{p}$

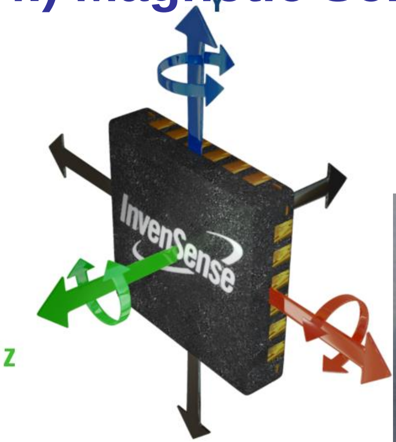
$$\ddot{\mathbf{x}}^{i}(t) = \mathbf{g}^{i}(\mathbf{x}) + \mathbf{R}_{p}^{i}(t)\cdot\mathbf{a}^{p}$$

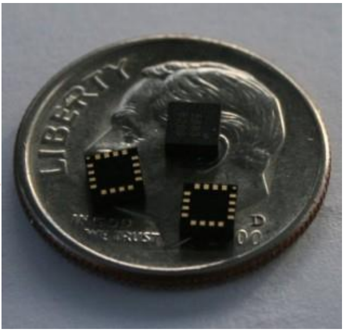
References: Inertial Space (i) and Gravity Field

Autonomous MEMS-Sensors + New Algorithms „Deep-Coupling“

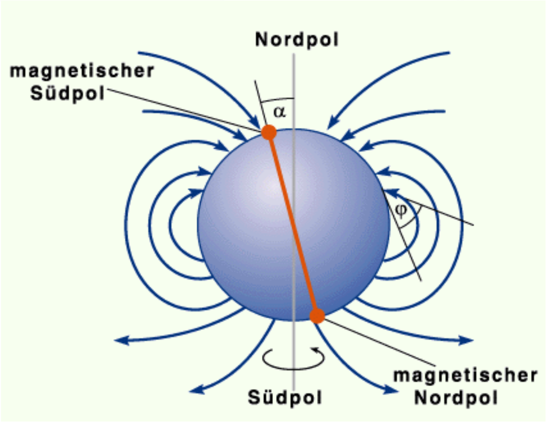
2. Autonomous

4.) Magnetic Sensors





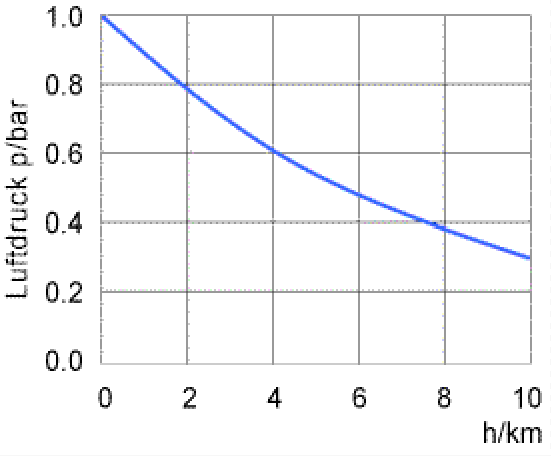
Reference: Earthmagnetic Field M



5.) Barometric Sensors (Height)

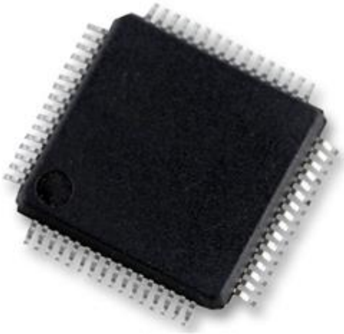
Auxiliary Sensor

Reference: Earth Atmosphere



CPU and GNSS/MEMS Sensors e.g. in FlightControl FC4

microcontroller
Cortex M4 (ARMv7-M)
ST Microelectronics F4 family



9 DOF
accelerometer
gyroscope
magnetometer

InvenSense MPU-9150

barometer

Measurement Specialities MS5611

telemetry

LAIRD RM-024

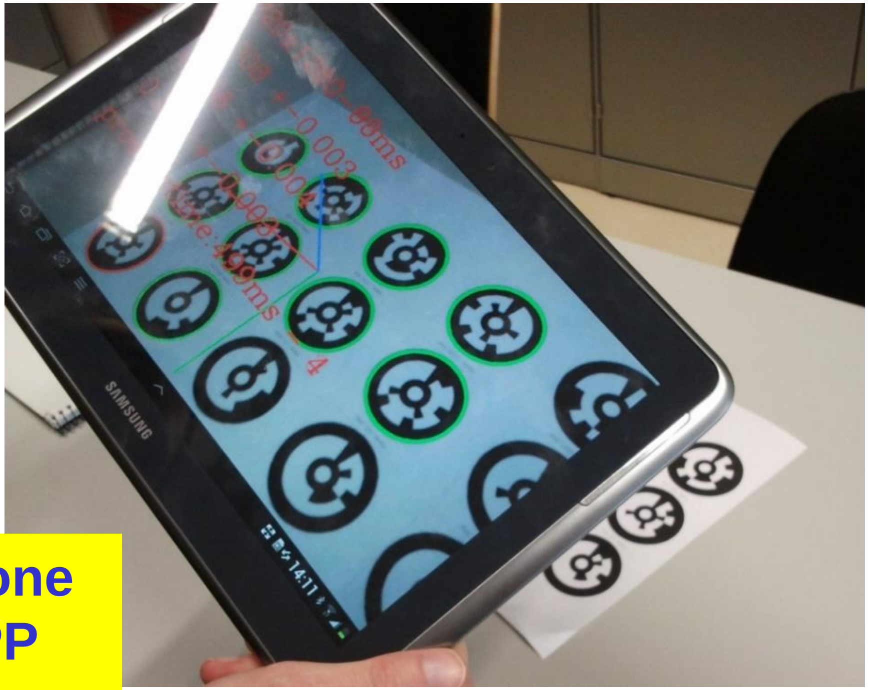
GPS

u-blox NEO-M8N

accelerometer
(thermal MEMS)

MEMSIC MXR-9500

NAVKA Camera based Indoor-Navigation-Concepts

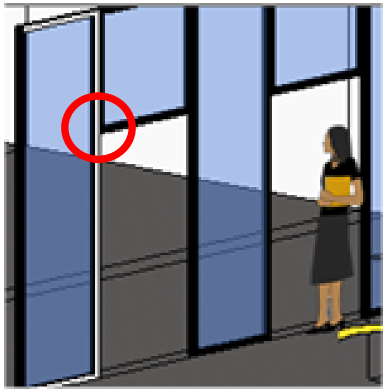


SMART-Phone Marker APP (Optical Markers, LED, Infrared)

$$u_i = cx + \left(\frac{r_{11} * (X_i - X0) + r_{12} * (Yi - Y0) + r_{13} * (Z_i - Z0)}{r_{31} * (X_i - X0) + r_{32} * (Yi - Y0) + r_{33} * (Z_i - Z0)}\right) * f$$

$$v_i = cy + \left(\frac{r_{21} * (X_i - X0) + r_{22} * (Yi - Y0) + r_{23} * (Z_i - Z0)}{r_{31} * (X_i - X0) + r_{32} * (Yi - Y0) + r_{33} * (Z_i - Z0)}\right) * f$$

NAVKA - Infrastructe-based Indoor-Navigation for Smartphones/Tablets



Cameras of Digital Smartphones / Tablet PC
Infrastructure-based (“Virtual Markers”)

$$u_i = cx + \left(\frac{r_{11} * (X_i - X0) + r_{12} * (Yi - Y0) + r_{13} * (Z_i - Z0)}{r_{31} * (X_i - X0) + r_{32} * (Yi - Y0) + r_{33} * (Z_i - Z0)}\right) * f$$

$$v_i = cy + \left(\frac{r_{21} * (X_i - X0) + r_{22} * (Yi - Y0) + r_{23} * (Z_i - Z0)}{r_{31} * (X_i - X0) + r_{32} * (Yi - Y0) + r_{33} * (Z_i - Z0)}\right) * f$$

“Virtual Landmarks (VLM)”

NAVKA Smartphone- and Tablet Indoor Navigation with Virtual Markers identified by Camera
&
Deep Coupling with all other MEMS-Smartphone Sensors
&
Infrastructure Position-Information (e.g. RFID and other)
&
Indoor Mapmatching
& …

SMART-Phone Marker APP (Optical Markers, LED, Infrared)

NAVKA Indoor-Navigation-Concepts - Visual Odometry

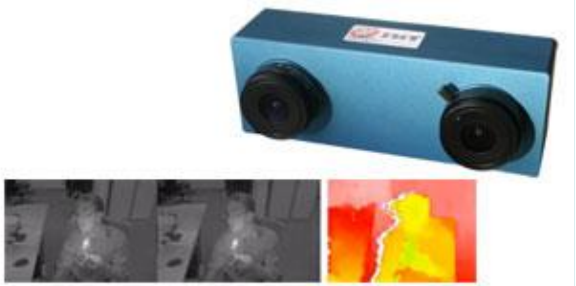
1.)

Velocity - Observation from the differentation of subsequent VO-based position-differences

$$\mathbf{v}^{\mathrm{VO}}(\mathrm{t})$$

General leverarm-situation for Stereo-Camera

$$\mathbf{t}_{\mathrm{VO}}^{\mathrm{b}} \quad \mathbf{R}(\mathrm{r_x}, \mathrm{r_y}, \mathrm{r_z})_{\mathrm{b}}^{\mathrm{VO}}$$



Final Observation Equation in Tight Coupling

$$\mathbf{v}^{\mathrm{VO}}(\mathrm{t}) = \mathbf{R}_{\mathrm{b}}^{\mathrm{VO}} \cdot \mathbf{R}(\mathrm{r}, \mathrm{p}, \mathrm{y})_{\mathrm{e}}^{\mathrm{b}} \cdot (\dot{\mathbf{x}}(\mathrm{t})^{\mathbf{e}} + \mathbf{R}(\mathrm{r}, \mathrm{p}, \mathrm{y})_{\mathbf{b}}^{\mathbf{e}} \cdot (\boldsymbol{\omega}_{\mathbf{eb}}^{\mathbf{b}} \times \mathbf{t}_{\mathrm{VO}}^{\mathrm{b}}))$$

NAVKA Indoor-Navigation-Concepts - Visual Odometry

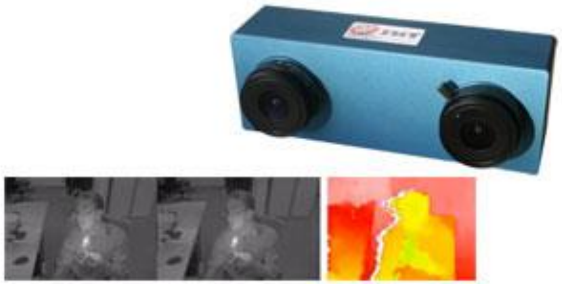
2.)

Orientation-rate observation from the subsequent VO-based orientation change

$$\boxed{\mathbf{\Omega}_{e,VO}^{VO}(t)}$$

General leverarm-situation for Stereo-Camera

$$\mathbf{t}_{VO}^{b} \quad \mathbf{R}(r_x, r_y, r_z)_b^{VO}$$

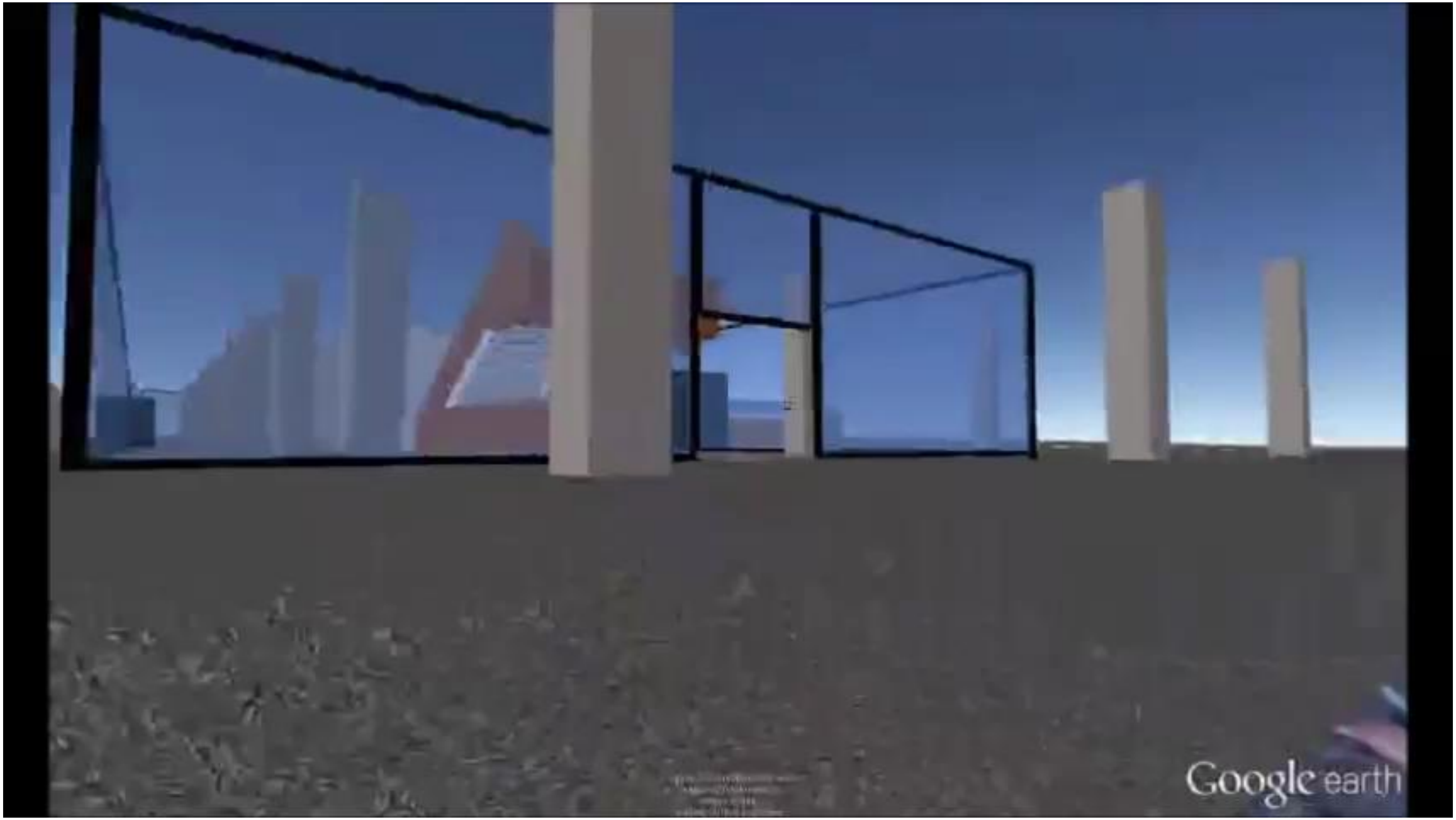


Final Observation Equation in Tight Coupling

$$\mathbf{\Omega}_{"Object-Frame",VO}^{VO}(t) = \mathbf{R}_b^{VO} \cdot (\mathbf{\Omega}_{Object-Frame,VO}^{b}(t)) \cdot (\mathbf{R}_b^{VO})^T$$

$$= \mathbf{R}_b^{VO} \cdot (\mathbf{\Omega}_{Object-Frame,e}^{b}(t) + \mathbf{\Omega}_{e,b}^{b}(t) + \mathbf{\Omega}_{b,VO}^{b}(t)) \cdot (\mathbf{R}_b^{VO})^T$$

NAVKA Seamless Out-/Indoor-Navigation-Concepts



https://www.youtube.com/watch?v=FvesMeAF3HY

Autonomuous Out-/Indoor Navigation – „NAVKArine G1MC“

Hochschule Karlsruhe
Technik und Wirtschaft
UNIVERSITY OF APPLIED SCIENCES

NAVKA
www.navka.de

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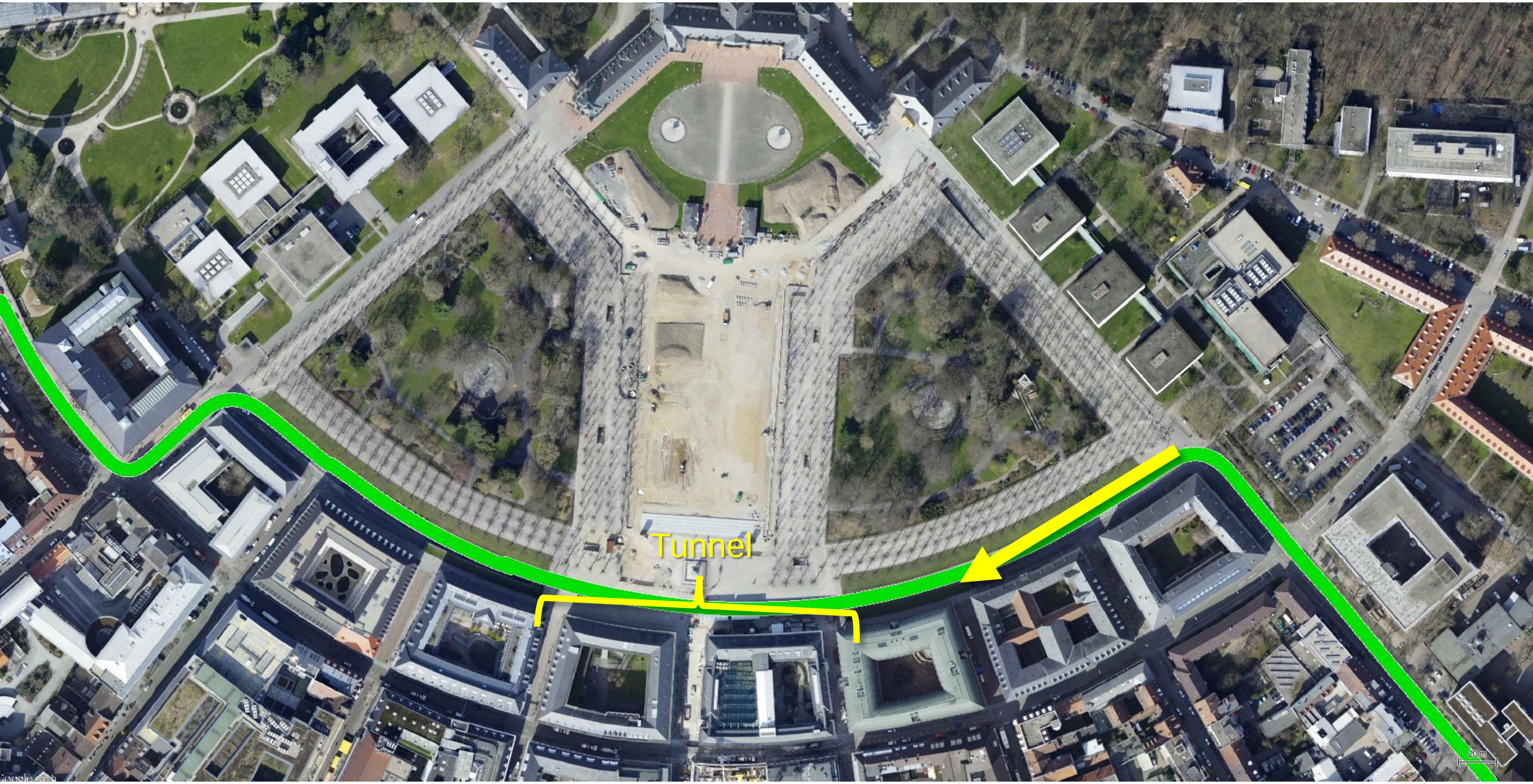
Bundesministerium
für Wirtschaft
und Energie
aufgrund eines Beschlusses
des Deutschen Bundestages

New Way (NAVKA): Algorithms for Multiplatform-, Multisensor-, Leverarm-Design



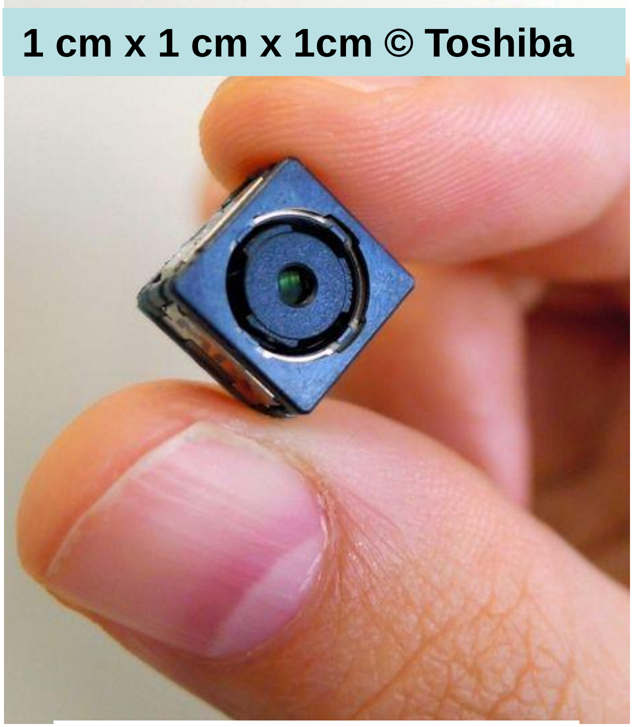
- NAVKA-Sensorfusion (GNSS/MEMS/MOMS) - Full 3D Navigation State-Information

(Position,Velocity, Accleration, Attitude, Rotationrate-Rate) Information

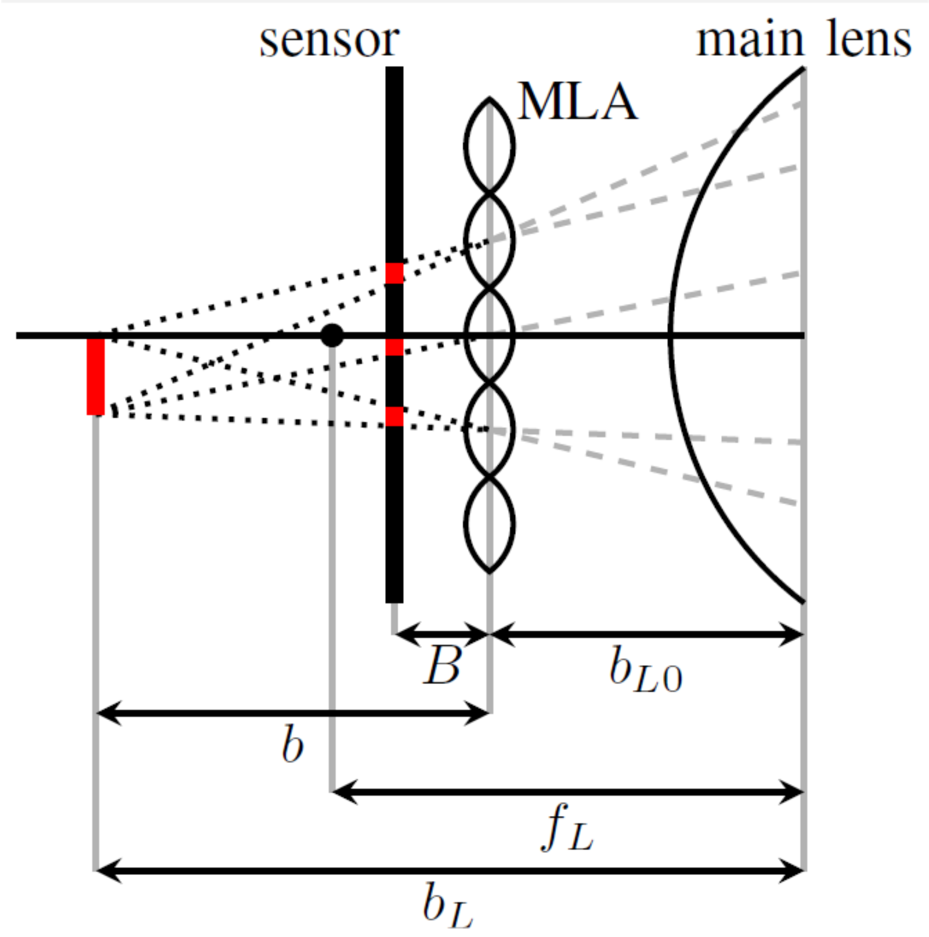
https://www.youtube.com/watch?v=ymuhJ6pt52o

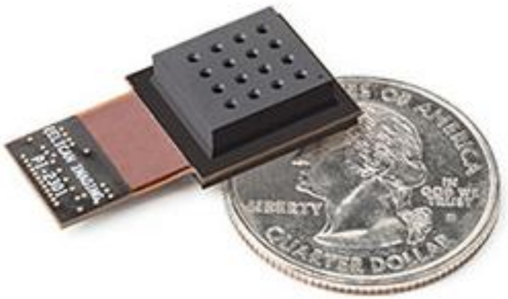
NAVKA Seamless Out-/Indoor-Navigation-Concepts

MOEMS – Plenoptic Cameras



1 cm x 1 cm x 1cm © Toshiba





Pelican Imaging 3D-Viewer

Principle: Main Lense and MLA

GNSS/MEMS/MOEMS based State Estimation

State Estimation

$$\mathrm{bel}(\mathbf{y}_t) = p(\mathbf{y}_t \,|\, \mathbf{y}_0, \mathbf{l}_{0:t}, \mathbf{u}_{0:t})$$

1.) Stepwise Prediction and Control, Error **s**, arbitrary density p_s

$$\mathbf{y}_t + \mathbf{s} = \mathbf{T}(\mathbf{y}_{t-1}, \mathbf{u}_t)$$

2.) Stepwise Measurements $\mathbf{l}_t$ concernimg the statevektor $\mathbf{y}_t$ with measurement error **e**, arbitrary density p_e

$$\mathbf{l}_t + \mathbf{e} = \mathbf{l}(\mathbf{y}_t)$$

3.) Arbitrary starting statevector $\mathbf{y}_{t=0}$ and density $\mathbf{p}_{yo}$

General Concept: Recursive Bayes-Estimation and 1. Order Markov

$$\underbrace{p(\mathbf{y}_t \,|\, \mathbf{y}_0, \mathbf{l}_{0:t}, \mathbf{u}_{0:t})}_{\text{A-posteriori Density}} = \eta \cdot \underbrace{p(\mathbf{l}_t \,|\, \mathbf{y}_t)}_{\text{Sensor Measurements Density}} \cdot \int_{-\infty}^{+\infty} \underbrace{p(\mathbf{y}_t \,|\, \mathbf{y}_{t-1}, \mathbf{u}_t)}_{\text{Prediction-Density } \mathbf{t}_t} \cdot \underbrace{p(\mathbf{y}_{t-1} \,|\, \mathbf{l}_{0:t-1}, \mathbf{u}_{0:t-1})}_{\text{A-priori Density}} \cdot d\mathbf{y}_{t-1}$$

Chapman-Kolmogorov-Equation for Prediction of State from t-1 to t

$$p(\mathbf{y}_t \,|\, \mathbf{y}_0, \mathbf{l}_{0:t-1}, \mathbf{l}_t, \mathbf{u}_{0:t-1}, \mathbf{u}_t, \mathbf{y}_{t-1}) = \int_{-\infty}^{+\infty} p(\mathbf{y}_t \,|\, \mathbf{y}_{t-1}, \mathbf{u}_t) \cdot p(\mathbf{y}_{t-1} \,|\, \mathbf{l}_{0:t-1}, \mathbf{u}_{0:t-1}) \cdot d\mathbf{y}_{t-1}$$

GNSS/MEMS/MOEMS based State Estimation

1. Component: State Transition of the Body (b) in regard

$$y = \left\lfloor x^e \; y^e \; z^e \,|\, \dot{x}^e \dot{y}^e \dot{z}^e \;|\, r^e \; p^e \; y^e \,\|\, \ddot{x}^e \; \ddot{y}^e \; \ddot{z}^e \,|\, \omega^b_{eb,x} \; \omega^b_{eb,y} \; \omega^b_{eb,z} \,|\, \mathbf{s} \right\rfloor^T$$

1.) State Transition-Equations for the body (b) in the e-frame

Space Curve of the body (b) in the e-frame

$$\begin{bmatrix} \mathbf{x}(t) \\ \dot{\mathbf{x}}(t) \\ \ddot{\mathbf{x}}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{I} & [\Delta t] & \left[\frac{1}{2}\Delta t^2\right] \\ \mathbf{0} & \mathbf{I} & [\Delta t] \\ \mathbf{0} & \mathbf{0} & \mathbf{I} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{x}(t-\Delta t) \\ \dot{\mathbf{x}}(t-\Delta t) \\ \ddot{\mathbf{x}}(t-\Delta t) \end{bmatrix}$$

Rotation Rates of the Body (b) with respect to the e-frame

$$\mathbf{\Omega}^b_{eb}(t) = \mathbf{\Omega}^b_{eb}(t-\Delta t)$$

Orientation / Attitude

$$\mathbf{R}^b_e(t) = \mathbf{R}^b_e(t-\Delta t) \cdot [I + \mathbf{\Omega}^b_{eb} \cdot \Delta t + \frac{1}{2!} \cdot (\mathbf{\Omega}^b_{eb})^2 \cdot \Delta t^2 + \ldots.] \text{ with } \mathbf{\Omega}^b_{eb} = \mathbf{\Omega}^b_{ib}(\text{Sensor}) - \mathbf{\Omega}^b_{ie}$$

Modifcation of the State Parameters and Equations

by

Considering Special Conditions Detected in Multithreading Computing

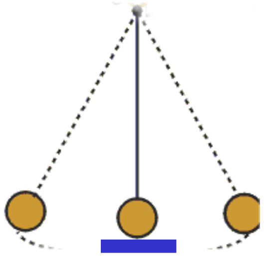
Further NAVKA-Key-Characteristics

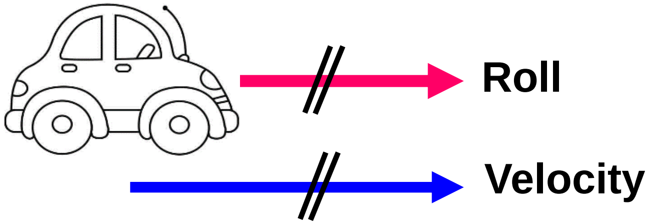
$$\mathbf{x} = \left\lfloor x^e \; y^e \; z^e \mid v^e_x \; v^e_y \; v^e_z \mid r^e \; p^e \; y^e \parallel \ddot{x}^e \; \ddot{y}^e \; \ddot{z}^e \mid \omega^b_{eb,x} \; \omega^b_{eb,y} \; \omega^b_{eb,z} \right\rfloor^T$$

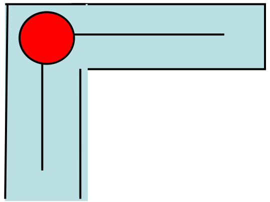
2.) General M-Estimation & Additional State Information

2.1) Parallel Processing Algorithms

$$\mathbf{F}(\mathbf{x}) = \mathbf{0}$$







Zero-Updates („ZUPT“)

„Automotive Mode“

„Indoor-Map-Matching“

2.2) Condition In/-Equations

$$\mathbf{u} \leq \mathbf{F}(\mathbf{x}) \leq \mathbf{o}$$

SIMPLEX Algorithms Providing also Robustness via L1-Norm based M-Estimation

2.3) Sensorintegration

GNSS/MEMS/MOEMS based State Estimation

Sensors providing Space / Parameter Relation

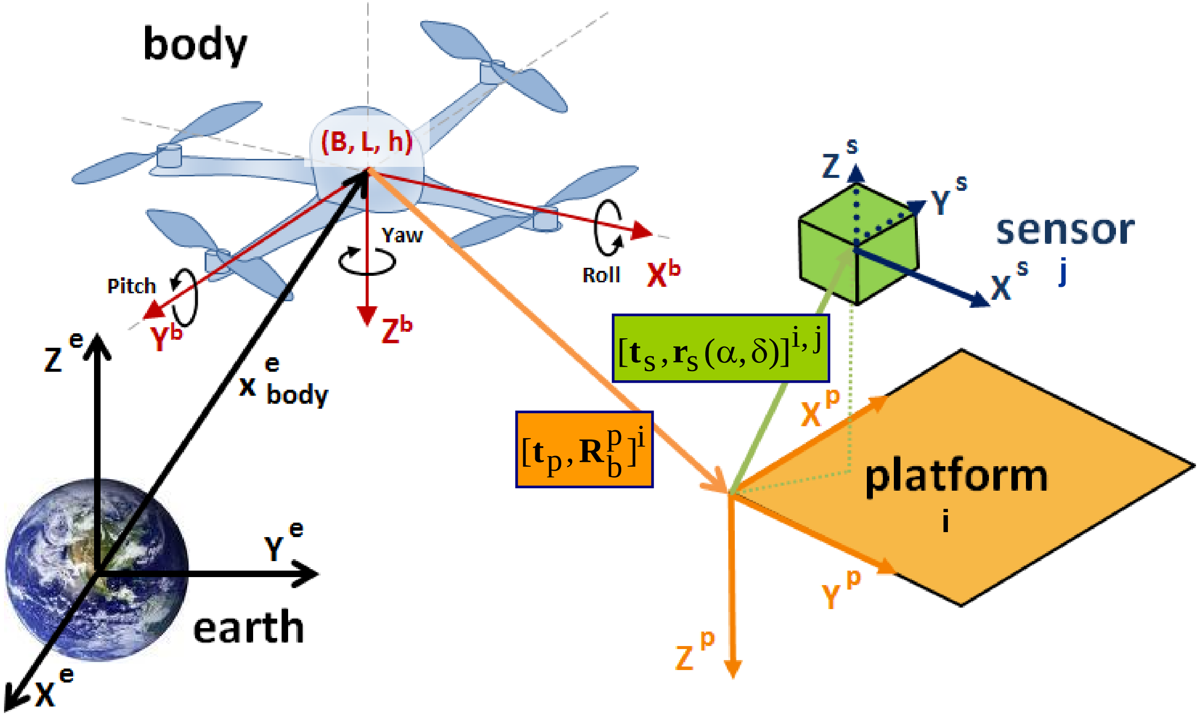
NAVKA: Algorithms, Software & Systems for Multiplatform-, Multisensor-, Leverarm-Design

Accelerometer- Sensorobservation j (Rawdata, on i-th Platform (p) – one-dimensional!)

$$a_{s_{i,j}} = \mathbf{r}^{p_i}_{s_{i,j}} \cdot \mathbf{a}^{p_i}_{s_{i,j}} \quad \Rightarrow \quad \mathbf{a}^{p_i}_{s_{i,j}} = \mathbf{R}^{p,i}_{b} \cdot \mathbf{R}^{b}_{e}(r,p,y) \cdot \mathbf{a}^{e,i}_{s_{i,j}}$$

$$a_{s_{i,j}} = \mathbf{r}^{p_i}_{s_{ij}} \cdot \mathbf{R}^{p,i}_{b} \cdot \mathbf{R}^{b}_{e}(r,p,y) \cdot [\ddot{\mathbf{x}}(t)^e - \mathbf{g}^e(\mathbf{x}) + 2 \cdot \mathbf{\Omega}^e_{ie} \cdot \dot{\mathbf{x}}(t)^e + \mathbf{\Omega}^e_{ie} \cdot \mathbf{\Omega}^e_{ie} \cdot \mathbf{x}(t)^e]_{s_{i,j}}$$

Observation-Equation for Sensor j on Platform i



$$\mathbf{r}^{pi}_{si,j} = \begin{bmatrix} \cos\delta \cdot \cos\alpha \\ \cos\delta \cdot \sin\alpha \\ \sin\delta \end{bmatrix}^{i,j}$$

Orientation j-th Sensor (s) on i-th Platform (p)

NAVKA: Algorithms, Software & Systems for Multiplatform-, Multisensor-, Leverarm-Design

$$y = \lfloor x^e \ y^e \ z^e \mid \dot{x}^e \dot{y}^e \dot{z}^e \mid r^e \ p^e \ y^e \parallel \ddot{x}^e \ \ddot{y}^e \ \ddot{z}^e \mid \omega^b_{eb,x} \ \omega^b_{eb,y} \ \omega^b_{eb,z} \mid \mathbf{s} \rfloor^T$$

(1) $a_{s_{i,j}} = \mathbf{r}^{p_i}_{s_{ij}} \cdot \mathbf{R}^{p,i}_b \cdot \mathbf{R}^b_e(r,p,y)$

„l(i,j)“

Observation-Equation for Sensor j on Platform i

$$\cdot[\ddot{\mathbf{x}}(t)^e - \mathbf{g}^e(\mathbf{x}) + 2 \cdot \mathbf{\Omega}^e_{ie} \cdot \dot{\mathbf{x}}(t)^e + \mathbf{\Omega}^e_{ie} \cdot \mathbf{\Omega}^e_{ie} \cdot \mathbf{x}(t)^e]_{s_{i,j}}$$

Referencing : Platform p(i) on Body (b) and Sensor s(i,j) on Platform (i) – „Leverarms“

(2)

$$\mathbf{x}^e_{s_{i,j}} = \mathbf{x}^e_b + \mathbf{R}^e_b(r,p,y) \cdot [\mathbf{t}^b_{b,p_i} + \mathbf{R}^b_{p_i} \cdot \mathbf{t}^{p_i}_{p_i,s_{i,j}}]$$

Classical Kalman-Filtering as Least Squares or (robust) M-estimation In caes of Gauß densities

Procedure of Kalmanfiltering:

1.) Prediction of **x** by the system equations (1) reading:

$$\mathbf{x}(i)_{i-1} = \mathbf{T}(\mathbf{x}(i-1), \mathbf{s}) \tag{3}$$

2.) Covariance matrix of the prediction:

$$\partial \mathbf{x}(i)_{i-1} = \underbrace{\begin{bmatrix} \cdots\cdots \dfrac{\partial \mathbf{T}_k}{\partial x_j} \cdots\cdots \end{bmatrix}}_{\bar{\mathbf{T}}} \cdot \partial \mathbf{x}(i-1) + \underbrace{\begin{bmatrix} \cdots\cdots \dfrac{\partial \mathbf{T}_k}{\partial s_l} \cdots\cdots \end{bmatrix}}_{\bar{\mathbf{S}}} \cdot \partial \mathbf{s} \tag{4}$$

$$\Rightarrow \mathbf{C}_{x(i)_{i-1}} = \bar{\mathbf{T}} \cdot \mathbf{C}_{x(i-1)} \cdot \bar{\mathbf{T}}^{T} + \bar{\mathbf{S}} \cdot \mathbf{C}_{ss} \cdot \bar{\mathbf{S}}^{T} \tag{5}$$

3.) Filtering (Least Squares Adjustment, L2-Norm):
(Approximate state vector, filtering step i : $\mathbf{x}_0$)

$$\mathbf{x}(i)_{i-1} + \mathbf{v}_x = \mathbf{I} \cdot d\hat{\mathbf{x}} + \mathbf{x}_0 \quad ; \quad \mathbf{C}_{x(i)_{i-1}} \tag{6}$$

$$\mathbf{l}(i) + \mathbf{v}_l = \mathbf{A}(\mathbf{x}_0) \cdot d\hat{\mathbf{x}} + \mathbf{l}(\mathbf{x}_0) \quad ; \quad \mathbf{C}_l \tag{7}$$

$$d\hat{\mathbf{x}} = \left[\mathbf{C}^{-1}_{x(i)_{i-1}} + \mathbf{A}^T \mathbf{C}_l^{-1} \mathbf{A}\right]^{-1} \cdot \left[\mathbf{A}^T \mathbf{C}_l^{-1} \cdot (\mathbf{l} - \mathbf{l}(\mathbf{x}_0) + \mathbf{C}^{-1}_{x(i)_{i-1}} \cdot (\mathbf{x}(i)_{i-1} - \mathbf{x}_0)\right] \tag{8}$$

Classical Kalman-Filtering as Least Squares or (robust) M-estimation

Definition of Kalman-Matrix : K

$$\boxed{\mathbf{K} = \left[\mathbf{C}_{x(i)_{i-1}}^{-1} + \mathbf{A}^{T}\mathbf{C}_{l}^{-1}\mathbf{A}\right]^{-1} \cdot \mathbf{A}^{T}\mathbf{C}_{l}^{-1} \qquad (9)}$$

$$d\hat{\mathbf{x}} = \mathbf{K} \cdot [(\mathbf{l} - \mathbf{l}(\mathbf{x}_0) + \mathbf{C}_{x(i)_{i-1}}^{-1} \cdot (\mathbf{x}(i)_{i-1} - \mathbf{x}_0] \qquad (10)$$

$$\hat{\mathbf{x}}(i) = \mathbf{x}_0 + \mathbf{K} \cdot [(\mathbf{l} - \mathbf{l}(\mathbf{x}_0) + \mathbf{C}_{x(i)_{i-1}}^{-1} \cdot (\mathbf{x}(i)_{i-1} - \mathbf{x}_0] \qquad (11)$$

Special choice: $\mathbf{x}_0 =: \mathbf{x}(i)_{i-1}$

$$\hat{\mathbf{x}}(i) = \mathbf{x}(i)_{i-1} + \mathbf{K} \cdot [(\mathbf{l} - \mathbf{l}(\mathbf{x}(i)_{i-1})] \qquad (12)$$

$$\mathrm{C}_{\hat{\mathrm{x}}(i)} = [\mathrm{C}_{\mathrm{x}(i)_{i-1}}^{-1} + \mathrm{A}^{\mathrm{T}}\mathrm{C}_{1}^{-1}\mathrm{A}]^{-1} = [\mathrm{I} - \mathrm{K} \cdot \mathrm{A}] \cdot \mathrm{C}_{\mathrm{x}(i)_{i-1}} \qquad (13)$$

- From (13) it follows, that the Kalman Filtering is more precise than the prediction.
- This does however not mean, that the Kalman-Filtering of the state vector **x** in step i is more precise than the filtering before in step (i-1). This question depends on the the influences, both of the law of error propagation concerning the prediction i from (i-1), namely by (5) as well as by the system design **A**, the control parameters **s** and the system noise $\mathbf{C}_{ss}$.

Ground-Robots
Paticle Filter and SLAM

More flexible than Kalman-Filter: Particle-Filter

General Concept recursive Bayes-Estimation at time t, 1. Order Markov

$$\underbrace{p(\mathbf{y}_t \mid \mathbf{y}_0, \mathbf{l}_{0:t}, \mathbf{u}_{0:t})}_{\text{A-posteriori Density}} = \eta \cdot \underbrace{p(\mathbf{l}_t \mid \mathbf{y}_t)}_{\text{Sensor Measurements Density}} \cdot \int_{-\infty}^{+\infty} \underbrace{p(\mathbf{y}_t \mid \mathbf{y}_{t\text{-}1}, \mathbf{u}_t)}_{\text{Prediction-Density } \mathbf{t}_t} \cdot \underbrace{p(\mathbf{y}_{t\text{-}1} \mid \mathbf{l}_{0:t\text{-}1}, \mathbf{u}_{0:t\text{-}1})}_{\text{A-priori Density}} \cdot d\mathbf{y}_{t\text{-}1}$$

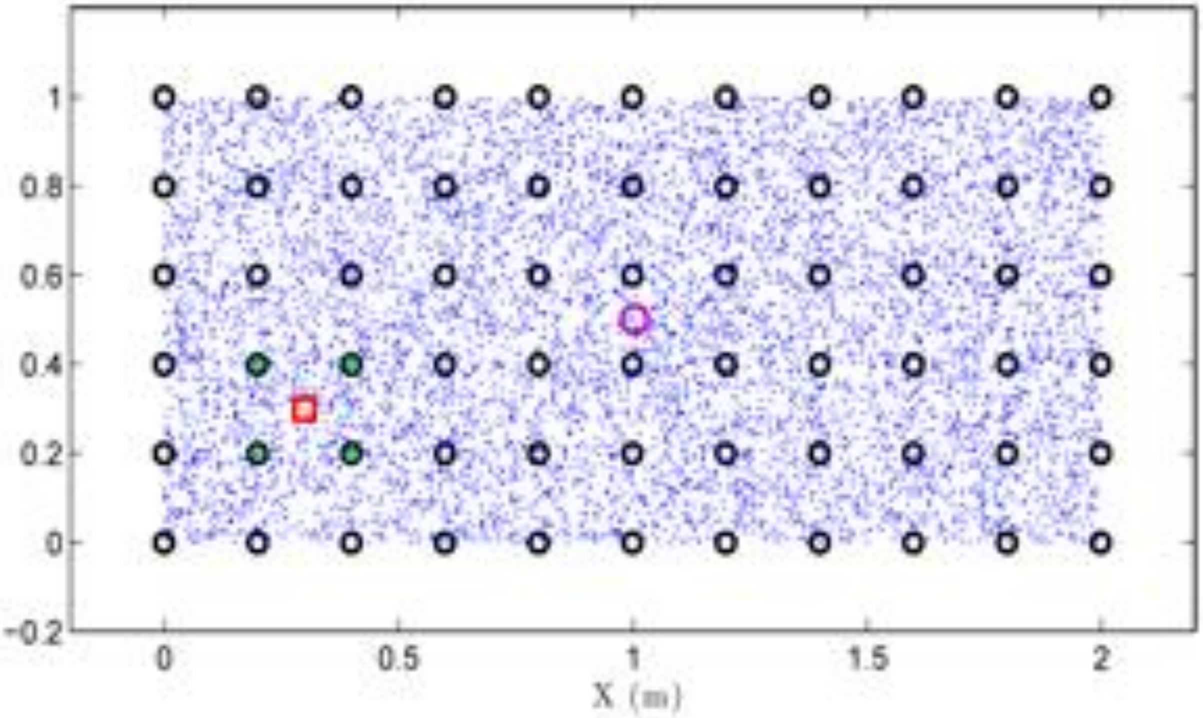
Chapman-Kolmogorov-Equation for Prediction of State from t-1 to t

$$p(\mathbf{y}_t \mid \mathbf{y}_0, \mathbf{l}_{0:t\text{-}1}, \mathbf{l}_t, \mathbf{u}_{0:t\text{-}1}, \mathbf{u}_t, \mathbf{y}_{t\text{-}1}) = \int_{-\infty}^{+\infty} p(\mathbf{y}_t \mid \mathbf{y}_{t\text{-}1}, \mathbf{u}_t) \cdot p(\mathbf{y}_{t\text{-}1} \mid \mathbf{l}_{0:t\text{-}1}, \mathbf{u}_{0:t\text{-}1}) \cdot d\mathbf{y}_{t\text{-}1}$$

Now: Approximation of the density of the preceeding state (form the start state $\mathbf{y}_0$) by N „Particles“ via Dirac Delta Function $\delta(\mathbf{y}_{t-1} - \mathbf{y}^{i}_{t-1})$

$$p(\mathbf{y}_{t-1} \mid \mathbf{l}_{0:t-1}, \mathbf{u}_{0:t-1}) = \sum_{i=1}^{N} w^{i}_{t-1} \cdot \delta(\mathbf{y}_{t-1} - \mathbf{y}^{i}_{t-1}) \quad \text{with} \quad \sum_{i=1}^{N} w^{i}_{t-1} = 1$$

Particle-Filter: Practical Use for the Localisation and Orientation indoors. E.g. Robot: Starting Situation



B-Building: N = 30.000 Particles

More flexible than Kalman-Filter: Particle-Filter

Informative Exploitation of the Prediction Model: $\mathbf{y}_t + \mathbf{s} = \mathbf{T}(\mathbf{y}_{t-1}, \mathbf{u}_t)$

Density Funktion of the Prediction

$$f(\mathbf{y}_t \mid \mathbf{y}_{t-1}, \mathbf{u}_t) = f_{\mathbf{s}}\,(\mathbf{s} = \mathbf{y}_t - \mathbf{T}(\mathbf{y}_{t-1}))$$

Use in Chapman-Kolmogorov Equation

$$p(\mathbf{y}_t \mid \mathbf{l}_{0:t\text{-}1}, \mathbf{l}_t, \mathbf{u}_{0:t\text{-}1}, \mathbf{u}_t, \mathbf{y}_{t\text{-}1}) = p(\mathbf{y}_t \mid \mathbf{y}_{t\text{-}1}, \mathbf{u}_t)$$

$$= \int_{-\infty}^{+\infty} \underbrace{f_{\mathbf{s}}\,(\mathbf{s} = \mathbf{y}_t - T(\mathbf{y}_{t-1}, \mathbf{u}_t))}_{\substack{\text{Prediction}\\ \text{Model}}} \cdot \underbrace{\left(\sum_{i=1}^{N} w_{t-1}^{i} \cdot \delta(\mathbf{y}_{t-1} - \mathbf{y}_{k-1}^{i})\right)}_{\substack{\text{Preceeding State Estimation}\\ \text{from former predication and}\\ \text{sensor measurements}}} \cdot d\mathbf{y}_{k-1}$$

$$= \underbrace{\sum_{i=1}^{N} w_{t-1}^{i} \cdot f_{\mathbf{s}}(\mathbf{s} = \mathbf{y}_t - T(\mathbf{y}_{t-1}^{i}, \mathbf{u}_t^{i}))}_{\substack{\text{Preceeding State Estimation}\\ \text{using Prediction-Model}\\ \text{and Measurements}}} = \left(\sum_{i=1}^{N} w_{t-1}^{i}{}' \cdot \delta(\mathbf{y}_t - \mathbf{y}_t^{i})\right)$$

More flexible than Kalman-Filter: Particle-Filter

Now: Exploitation of the Information of the Observations

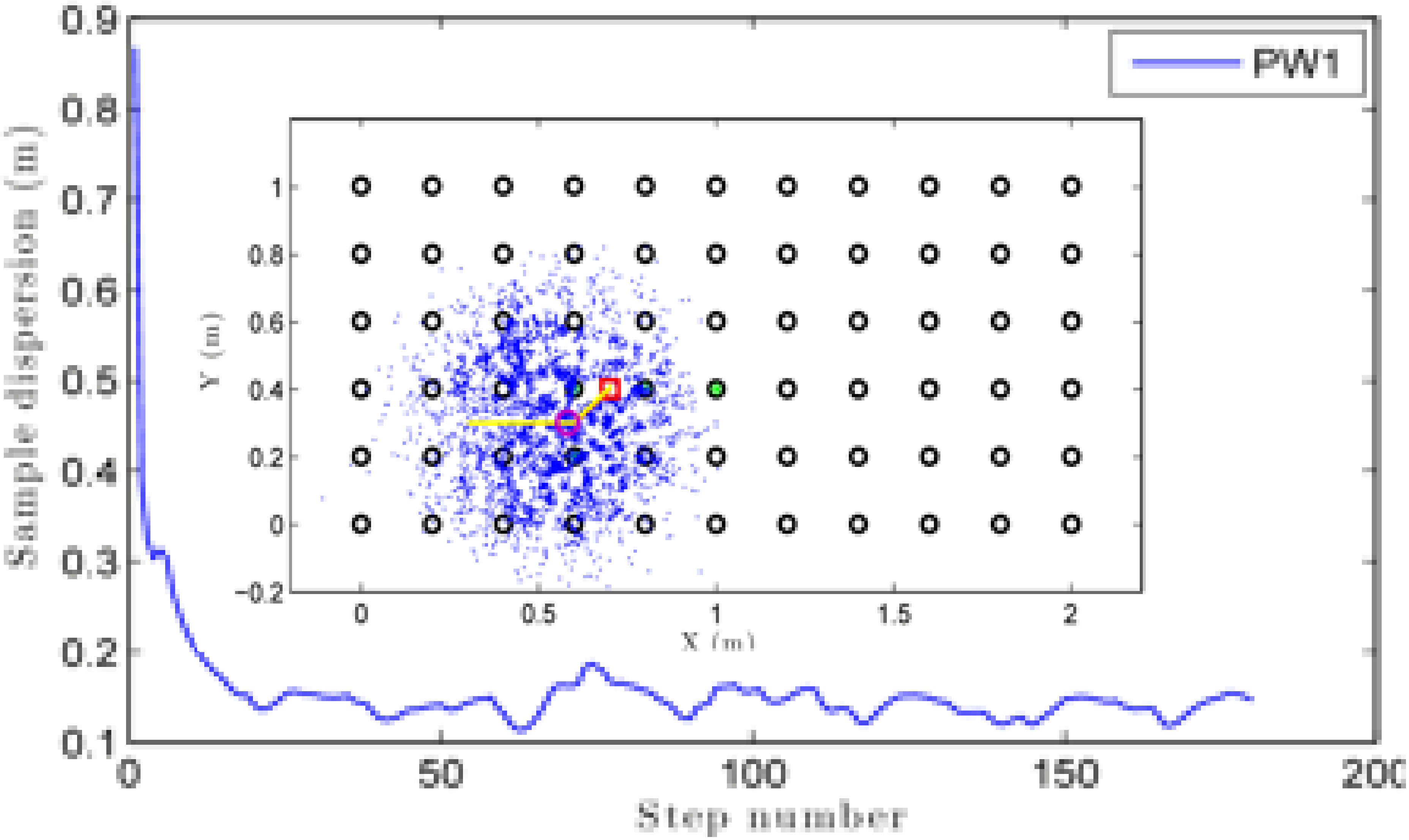
$$f(\mathbf{l}_t \mid \mathbf{y}_t) = f_e(\mathbf{l}_t - \mathbf{l}(\mathbf{y}_t))$$

$$f(\mathbf{y}_t \mid \mathbf{l}_{1:t}, \mathbf{u}_{1:t}) = f_{\mathbf{e}}(\mathbf{l}_t - \mathbf{l}(\mathbf{y}_t)) \cdot c \cdot \sum_{i=1}^{N} w_{t-1}^{i} \cdot \delta(\mathbf{y}_t - \mathbf{y}_t^i)$$

$$= \sum_{i=1}^{N} \underbrace{c \cdot w_{t-1}^{i} \cdot f_{\mathbf{e}}(\mathbf{l}_t - \mathbf{l}(\mathbf{y}_t^i))}_{w_t^i} \cdot \delta(\mathbf{y}_t - \mathbf{y}_t^i)$$

Computation of new weights in step t with condition $\sum_{1}^{N} w_t^i = 1$

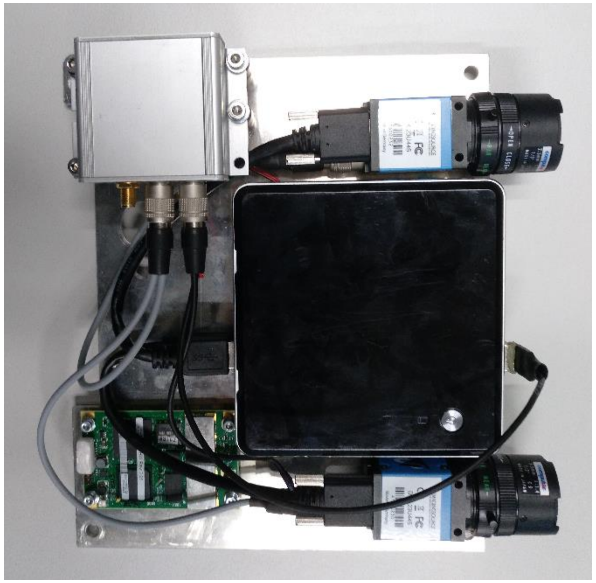
$$w_t^i = c \cdot w_{t-1}^i \cdot f_{\mathbf{e}}(\mathbf{l}_t - \mathbf{l}(\mathbf{x}_t^i)) \quad \text{mit} \quad c = \frac{1}{\sum_{1}^{N} f_{\mathbf{e}}(\mathbf{l}_t - \mathbf{l}(\mathbf{y}_t^i)) \cdot w_{t-1}^i}$$

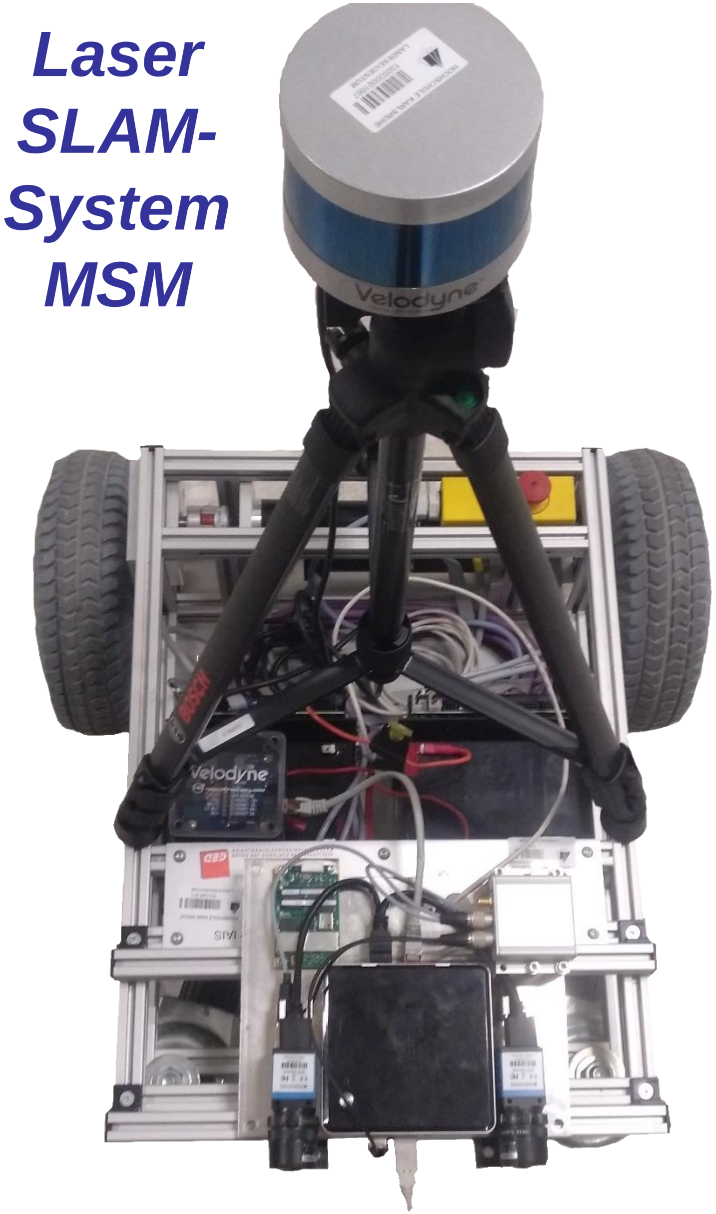

Sample dispersion (m)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
50
100
150
Step number
PW1
Y (m)
1
0.8
0.6
0.4
0.2
0
-0.2
0
0.5
1
1.5
2
X (m)

SLAM
Simultaneous Localization and Mapping

Based on a Kalman- or a Particle Filter Navigation State Estimation $y(t)$

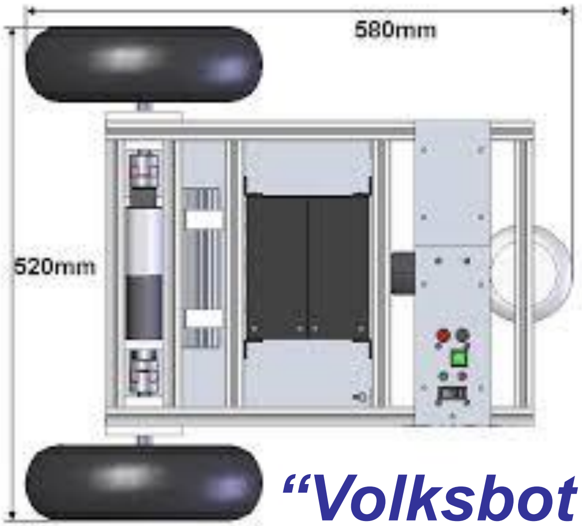
Ground-Robots – Particle-Filter and SLAM





Laser SLAM-System MSM

Odometry Model Improving Prediction Part



“Volksbot”

SLAM (Simult. Localization and Mapping) Development

RaD “MultisensorSelfreferencing Localization & Mapping System (MSM)”

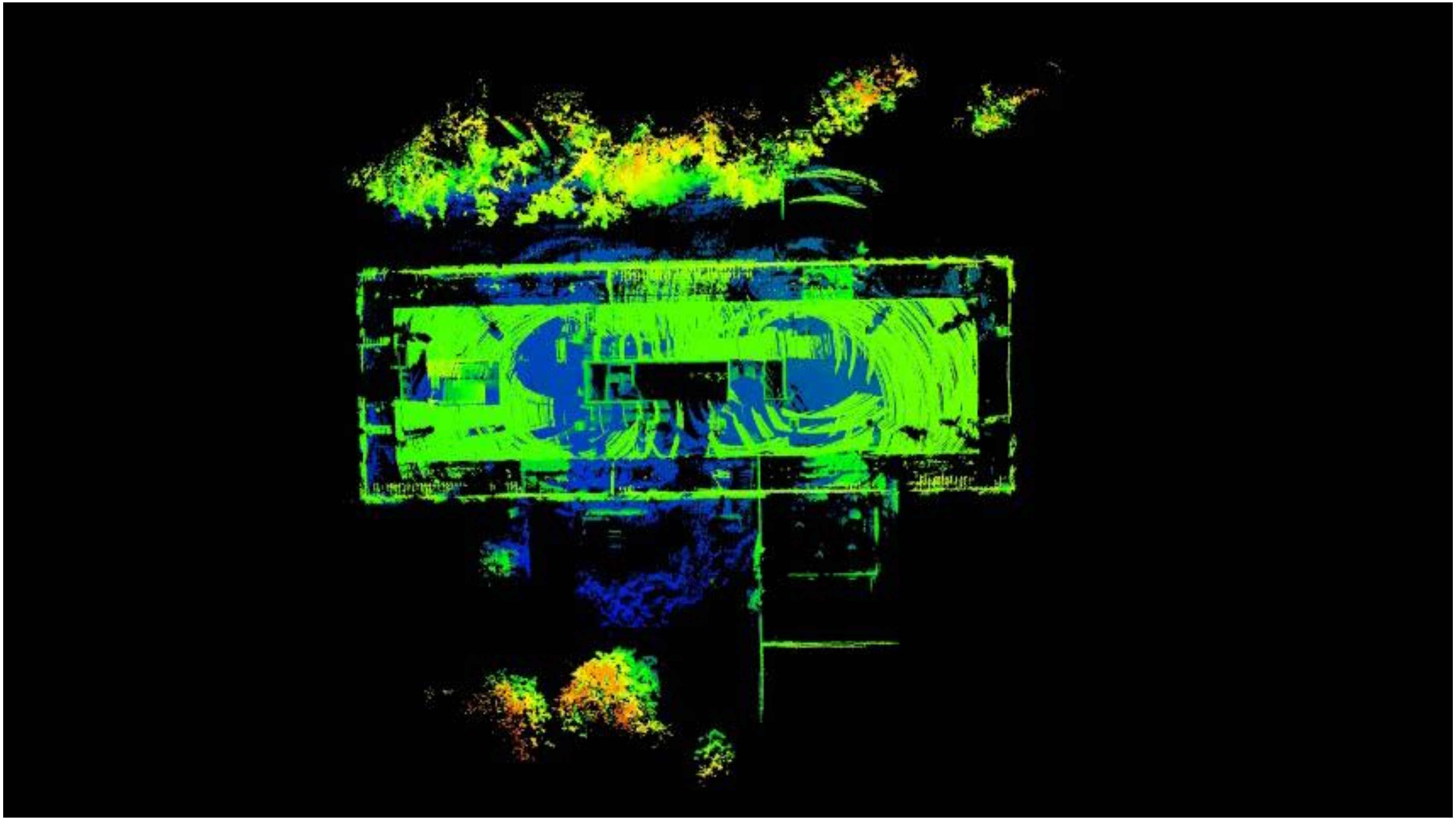
http://www.navka.de/index.php/de/weitere-projekte/fue-projekte-produkte

SLAM-based Mapping of B-Building HSKA, 2nd

RaD "Multisensor Selfreferencing Localization & Mapping System (MSM)"

http://www.navka.de/index.php/de/weitere-projekte/abgeschlossene-projekte

SLAM-based Mapping of B-Building HSKA, 2nd Floor



UAV => UAS

Full Circuit

Navigation and Control

Flight Dynamics of a Quadropter - 4 Propellers and Symmetry

Motion of Body

$$\vec{F}_T = \begin{pmatrix} 0 \\ 0 \\ -\sum_i (T_i) \end{pmatrix}$$

Total Motor Thrust F

$$\vec{M}_{T,i} = \vec{r}_i \times \vec{T}_i$$

Total MotorTorque M

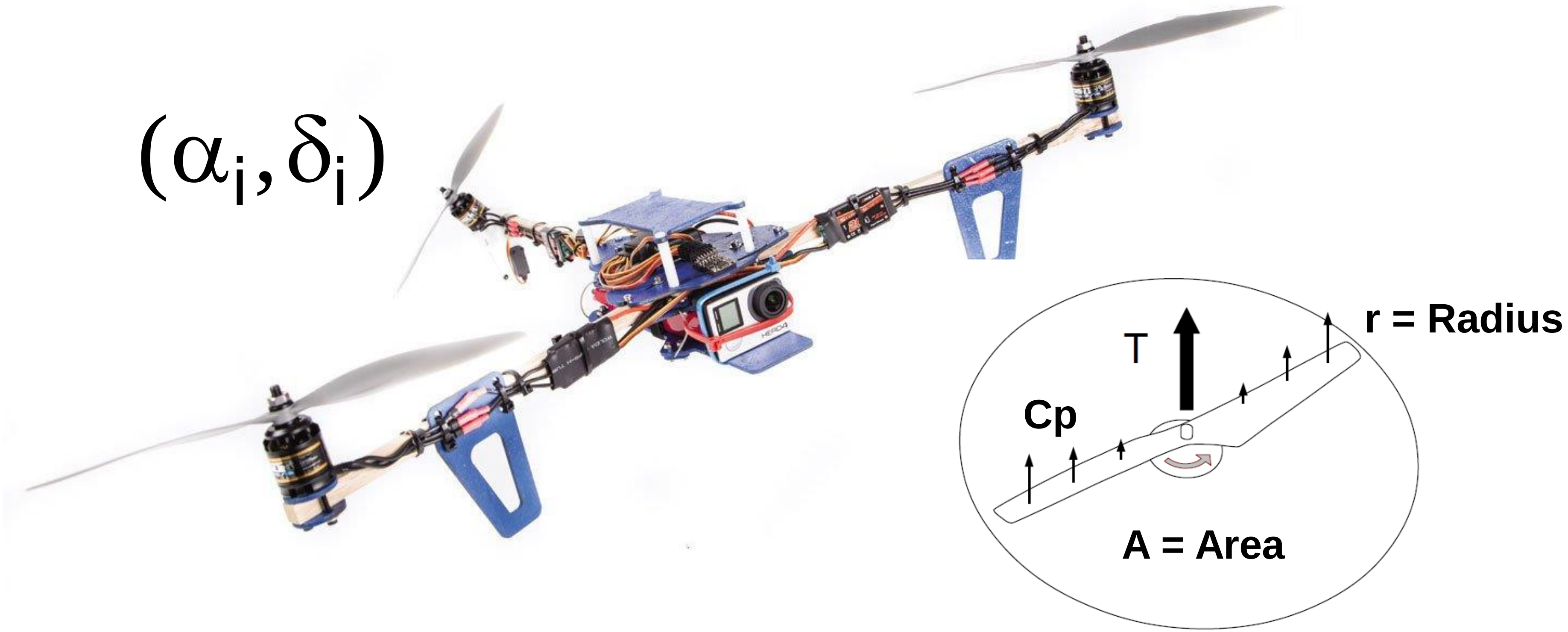
$$\vec{M}_T = \sum \vec{r}_i \times \vec{T}_i$$

$$= \begin{pmatrix} l \\ 0 \\ -h \end{pmatrix} \times \begin{pmatrix} 0 \\ 0 \\ -T_V \end{pmatrix} + \begin{pmatrix} -l \\ 0 \\ -h \end{pmatrix} \times \begin{pmatrix} 0 \\ 0 \\ -T_H \end{pmatrix} + \begin{pmatrix} 0 \\ -l \\ -h \end{pmatrix} \times \begin{pmatrix} 0 \\ 0 \\ -T_L \end{pmatrix} + \begin{pmatrix} 0 \\ l \\ -h \end{pmatrix} \times \begin{pmatrix} 0 \\ 0 \\ -T_R \end{pmatrix}$$

$$\vec{M}_T = \begin{bmatrix} l \cdot (T_L - T_R) \\ l \cdot (T_V - T_H) \\ 0 \end{bmatrix}$$

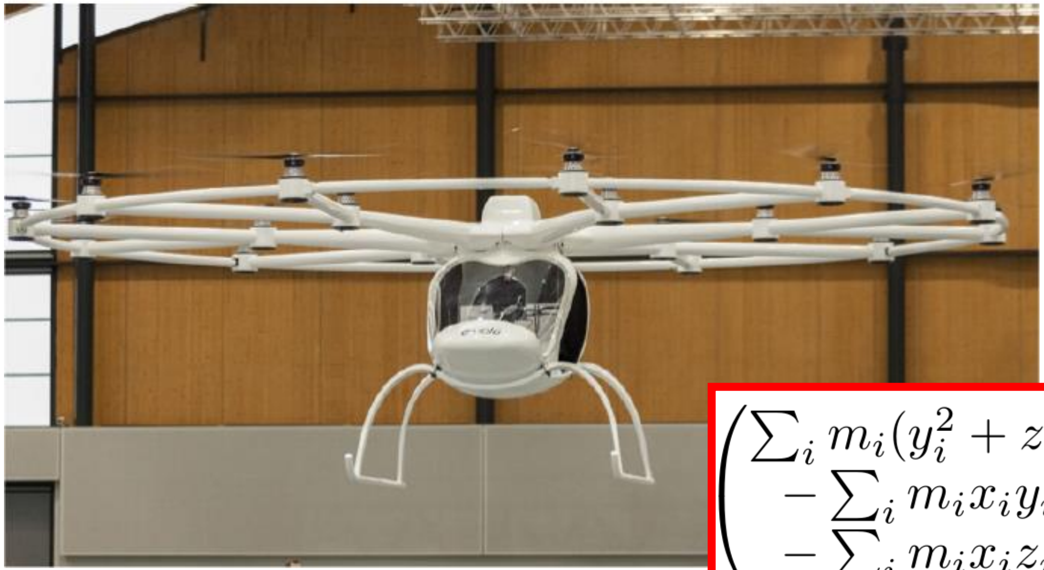
Flight Dynamics with arbitrary propeller orientation

$$(\alpha_i, \delta_i)$$



$$\mathbf{T}_i^b = \rho \cdot \pi \cdot c_i \cdot R_i^4 \omega_i^2 \cdot (\cos\alpha_i \cdot \sin\delta_i, \sin\alpha_i \cdot \sin\delta_i, -\cos\delta_i)^T$$

Flight Control Development Multicopter – n Prop.,no Symmetry



Manned Volocopter VC 200
ZIM Project, Flight Control
by IAF / HSKA

$$\mathbf{J} = $$

$$\boxed{\begin{pmatrix} \sum_i m_i(y_i^2+z_i^2) & -\sum_i m_i x_i y_i & -\sum_i m_i x_i z_i \\ -\sum_i m_i x_i y_i & \sum_i m_i(x_i^2+z_i^2) & -\sum_i m_i y_i z_i \\ -\sum_i m_i x_i z_i & -\sum_i m_i y_i z_i & \sum_i m_i(x_i^2+y_i^2) \end{pmatrix}}$$

Euler Equations

- Discrete J Momentum of Inertia
- Dynamically changing J

$$\mathbf{M}^b_{ges} = \sum_{1}^{n} \mathbf{M}^b_i + \mathbf{M}^b_{env}(d_i) = \boldsymbol{\omega}^b_{ib} \times (\mathbf{J} \cdot \boldsymbol{\omega}^b_{ib}) + \mathbf{J} \cdot \dot{\boldsymbol{\omega}}^b_{ib}$$

$$\mathbf{M}^b_i = \mathbf{r}_i \times \mathbf{T}^b_i$$

$$\boxed{\omega_{P_i}, [i = 1, n]}$$

- General Propeller Design (l, h, r, Cp ,….)

Flight Control Development Multicopter – n Prop.,no Symmetry

Manned Volocopter
VC 200

ZIM Project

Flight Control
by IAF / HSKA

Newton Equations

$$\boxed{\omega_{P_i}, [i = 1, n]}$$

$$\overline{F}_{total} = \left[\frac{d(m \cdot v)}{dt}\right]_i$$

$$\overline{F}_{total} = \overline{\mathbf{F}}^b + m \cdot \mathbf{R}_i^b \mathbf{g}^i = \left[\frac{d(m \cdot \mathbf{v})}{dt}\right]_b + \boldsymbol{\omega}_{ib}^b \times m \cdot \mathbf{v}_b = m \cdot \dot{\mathbf{v}}_b + \boldsymbol{\omega}_{ib}^b \times m \cdot \mathbf{v}_b$$

Flight Control Development Multicopter – n Prop.,no Symmetry

Control Deviation
(German: Regelabweichung)

$$\mathbf{e}(t) = \mathbf{y}(t)_{desired} - \mathbf{y}(t)_{Nav.State}$$

$$\left[\mathbf{F}^{b}_{ges}, \mathbf{M}^{b}_{ges}\right]^{T} = \mathbf{F}(m, \mathbf{J}, \mathbf{g}^{e}, \mathbf{y}(t), \dot{\mathbf{y}}(t))$$

$$= \mathbf{F}_{PD}(m, \mathbf{J}, \mathbf{g}^{e}, \mathbf{y}(t), \mathbf{e}(t), \dot{\mathbf{e}}(t))$$

$$\left[\mathbf{F}^{b}_{ges}, \mathbf{M}^{b}_{ges}\right]^{T} =: \mathbf{u}'(t) = \mathbf{F}_{PD}(m, \mathbf{J}, \mathbf{g}^{e}, \mathbf{e}(t), \dot{\mathbf{e}}(t))$$

$$\begin{aligned}
T &= \left(g + K_{z,D}\left(\dot{z}_d - \dot{z}\right) + K_{z,P}\left(z_d - z\right)\right)\frac{m}{C_\phi C_\theta},\\
\tau_\phi &= \left(K_{\phi,D}\left(\dot{\phi}_d - \dot{\phi}\right) + K_{\phi,P}\left(\phi_d - \phi\right)\right) I_{xx},\\
\tau_\theta &= \left(K_{\theta,D}\left(\dot{\theta}_d - \dot{\theta}\right) + K_{\theta,P}\left(\theta_d - \theta\right)\right) I_{yy},\\
\tau_\psi &= \left(K_{\psi,D}\left(\dot{\psi}_d - \dot{\psi}\right) + K_{\psi,P}\left(\psi_d - \psi\right)\right) I_{zz},
\end{aligned}$$

$$\left\{ \mathbf{u}'(t) = \begin{bmatrix} T \\ \tau_\varphi \\ \tau_\theta \\ \tau_\psi \end{bmatrix} = \mathbf{u}(\mathbf{e}(t)) \right.$$

$\mathbf{u}'(t)$

Control Variable

1. Instance

Flight Control Development Multicopter – n Prop.,no Symmetry

Control Deviation
(German: Regelabweichung)

$$\mathbf{e}(t) = \mathbf{y}(t)_{desired} - \mathbf{y}(t)_{Nav.State}$$

$$\left[\mathbf{F}^{b}_{ges}, \mathbf{M}^{b}_{ges}\right]^{T} = \mathbf{F}(m, \mathbf{J}, \mathbf{g}^{e}, \mathbf{y}(t), \dot{\mathbf{y}}(t))$$

$$= \mathbf{F}_{PD}(m, \mathbf{J}, \mathbf{g}^{e}, \mathbf{y}(t), \mathbf{e}(t), \dot{\mathbf{e}}(t))$$

$$\left[\mathbf{F}^{b}_{ges}, \mathbf{M}^{b}_{ges}\right]^{T} =: \mathbf{u}'(t) = \mathbf{F}_{PD}(m, \mathbf{J}, \mathbf{g}^{e}, \mathbf{e}(t), \dot{\mathbf{e}}(t))$$

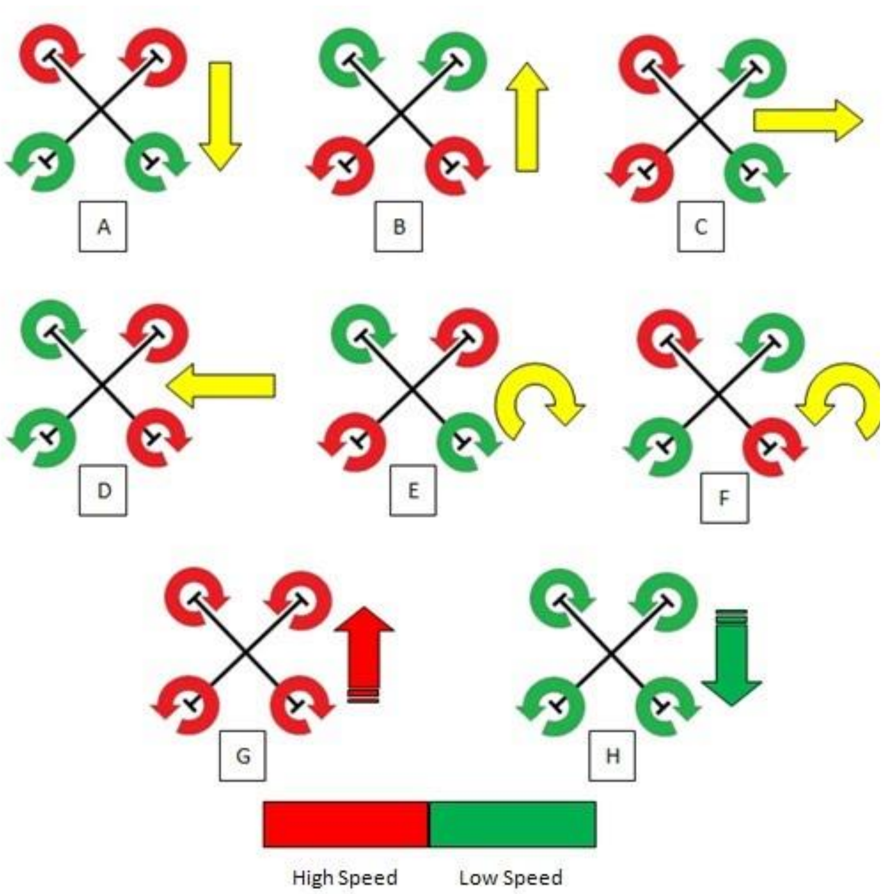
PD-Controller and PID-Controller, respect.

$$\mathbf{u}'(t) = \mathbf{K}_P \cdot \mathbf{e}(t) + \mathbf{K}_I \cdot \int_0^{\tau} \mathbf{e}(t) \cdot dt + \mathbf{K}_D \cdot \dot{\mathbf{e}}(t)$$

Flight Control Development Multicopter – n Prop.,no Symmetry

Control:

$$\mathbf{e}(t) \Rightarrow \mathbf{u}'(t) \Rightarrow \mathbf{u}(t) \text{ Final Control Variables } \omega_{P_i}, [i = 1, n]$$



n=4

$$\begin{aligned}
\omega_1^2 &= \frac{T}{4k} - \frac{\tau_\theta}{2kl} - \frac{\tau_\psi}{4b} \\
\omega_2^2 &= \frac{T}{4k} - \frac{\tau_\phi}{2kl} + \frac{\tau_\psi}{4b} \\
\omega_3^2 &= \frac{T}{4k} + \frac{\tau_\theta}{2kl} - \frac{\tau_\psi}{4b} \\
\omega_4^2 &= \frac{T}{4k} + \frac{\tau_\phi}{2kl} + \frac{\tau_\psi}{4b}
\end{aligned}$$

Flight Control Development Multicopter – n Prop.,no Symmetry

Control Deviation (German: Regelabweichung)

$$\mathbf{e}(t) = \mathbf{y}(t)_{\mathrm{Soll}} - \mathbf{y}(t)_{\mathrm{Ist}}$$

$$\mathbf{u'}_i(\mathrm{t}) = \mathbf{K}_{p,i} \cdot \mathbf{e}_i(t) + \mathbf{K}_{I,i} \cdot \sum_{0}^{\tau} \mathbf{e}(\mathbf{t})\mathrm{dt} + \mathbf{K}_{D,i} \cdot \frac{\mathbf{e}_i(t) - \mathbf{e}_i(t-\Delta t)}{\Delta t}.$$

$$\Delta\mathbf{u'}(\mathrm{t}) = [\Delta\mathbf{F}, \Delta\mathbf{M}]^{\mathrm{T}} = \mathbf{K} \cdot [\Delta\omega_1, \ldots \Delta\omega_{\mathrm{i}}, \ldots., \Delta\omega_{\mathrm{n}}]^{\mathrm{T}} = \mathbf{K} \cdot \mathbf{u}(\mathrm{t})$$

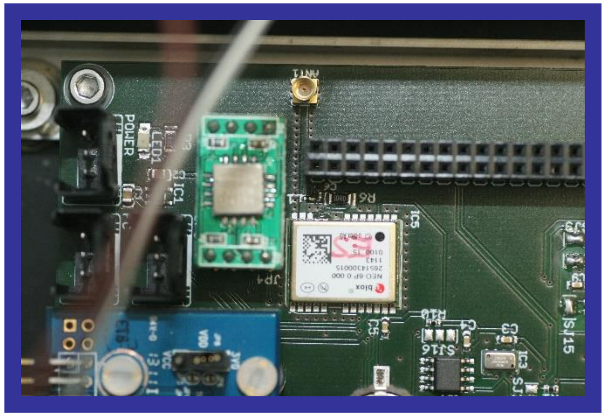
$$\Delta\mathbf{u} = [\Delta\omega_1, \ldots, \Delta\omega_{\mathrm{i}}, \ldots, \Delta\omega_{\mathrm{n}}]^{\mathrm{T}} = \mathbf{K}^{-} \cdot [\Delta\mathbf{F}, \Delta\mathbf{M}]^{\mathrm{T}}$$

NAVKA Flight Control Mathematical Model and Algorithms

$$\Delta\omega_{P_i}, [i=1,n]$$

Motorcontroller

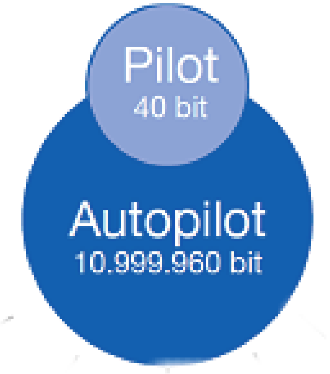
$$\omega_{P_i}, [i=1,n]$$



$$y(t) = \begin{bmatrix} x^e\ y^e\ z^e \mid \dot{x}^e \dot{y}^e \dot{z}^e \mid r^e\ p^e\ y^e \parallel \\ \ddot{x}^e\ \ddot{y}^e\ \ddot{z}^e \mid \omega^b_{eb,x}\ \omega^b_{eb,y}\ \omega^b_{eb,z} \mid \mathbf{s} \end{bmatrix}^T$$

Flight Control Algorithms

Cascade Adaptive Controller



$$\Delta y(t) = \Delta\left[x^e\ y^e\ z^e \mid \dot{x}^e \dot{y}^e \dot{z}^e \mid r^e\ p^e\ y^e\right]^T$$

Flight Control Developments - Multicopter n Propellers
ZIM-Project „E-Volocopter 2012-2015
6 Consortium Members (including IAF/HSKA)

Bundesministerium
für Wirtschaft
und Technologie

Gefördert
aufgrund eines Beschlusses
des Deutschen Bundestages

Task of the Consortium Member IAF/ HS Karlsruhe
Development of the Flight-Control

Project-Leading: Prof. Dr.-Ing. Reiner Jäger

www.navka.de/index.php/de/weitere-projekte/abgeschlossene-projekte/e-volo-bemannte-multikopter

ZIM-Project „e-Volocopter 2012-2015“
Flight Control Developments - Multicopter n Propellers
IAF/HSKA

Flight Demonstration VC25 Ironbird (3m)

NAVKARINE “FC2”

Flight Control Developments Multicopter n Propellers

NAVKA-UAV and NAVKArine FC4 Flight Control Position Hold

IAF/HSKA Flight Control Developments Multicopters n Propellers

ZIM-Project „e-Volocopter“ 2012-2015
www.e-volo.com

NAVKArine-FC4 IAF/HSKA (right)

- **Any Manned Volocopter**
- **Any UAV/UAS**

e-Volopter, June-2017: AUTONOMOUS FLYING AIRTAXI in Dubai

www.e-volo.com

„Dubai beginnt 2017 weltweit ersten Testbetrieb autonomer Lufttaxis mit dem Volocopter“

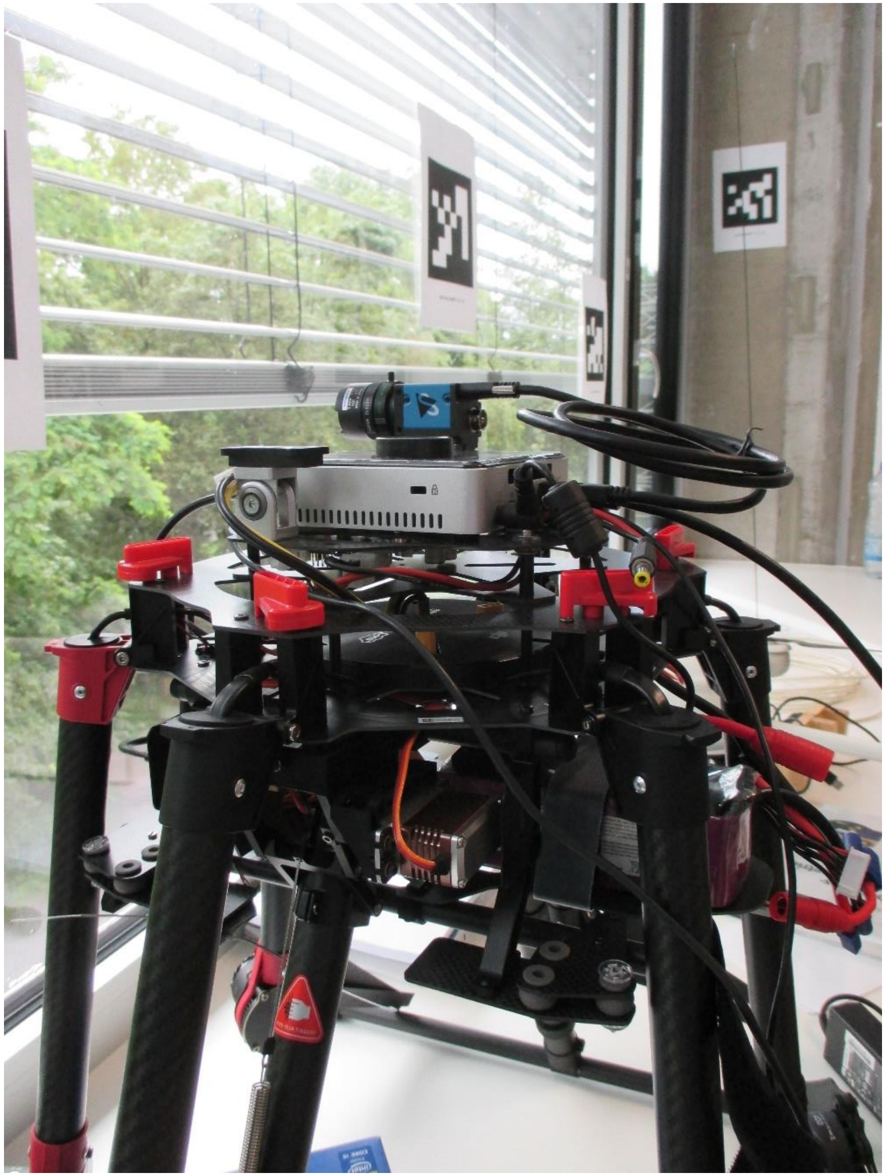
https://www.youtube.com/watch?v=V08IQz7Rk3o

NAVKA Flight Control
NAVKArine-FC4/FC5

- Environment friendly, silent: air taxis, individuals
- 3D mapping and geosensing
- Film industry
- Search and rescue of people
- Agriculture UAV
- Facility management & monitoring
- Wild life protection
- Transport UAV
- Fire Fighting air vehicles
- ABC sensing UAV for emergency event

NAVKA-Project – Daimler Indoor UAV

http://www.navka.de/index.php/de/aktuelles/news



Marker Georeferencing
Daimler Crash Hall Sindelfingen

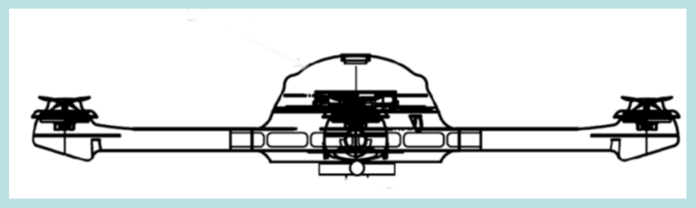
NAVKA-Project – Multisensor Selfreferencing 3D-Mapping System (MMS)

http://www.navka.de/index.php/de/aktuelles/news

http://www.navka.de/index.php/de/ueberblick-msm

NAVKA Seamless Out-/Indoor-Navigation-Concepts

Further Developments
Multisensor Selfreferencing 3D-Mapping System (MSM)



UAS NAVKArine-FC5 and 6

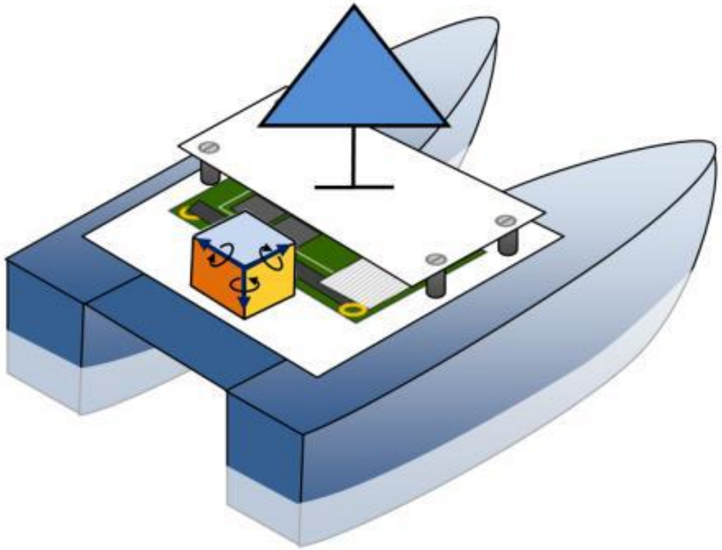
+

Light Weight Laserscanner

LOD4 Building Models

NAVKA - SLAM-Algorithms

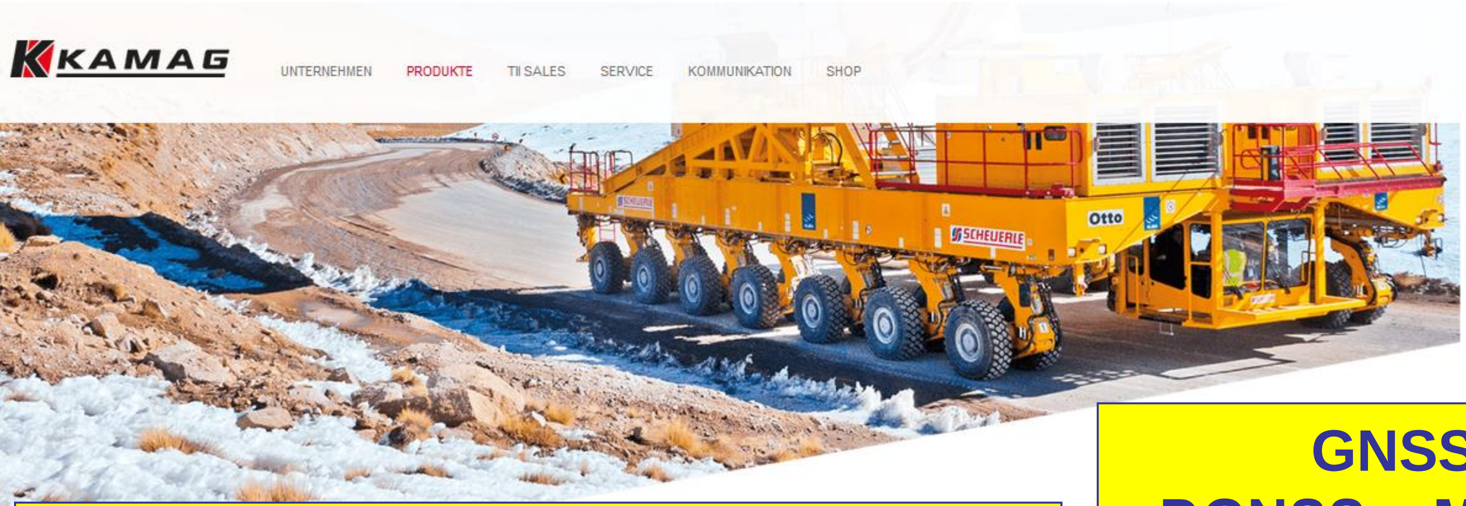
Scalable Multisensor Umanned Maritim Vehicle (UMV)



Ground Vehicles

Multisensor Navigation

NAVKA RaD Project „Autonomous Out-/Indoor Driving“



http://www.navka.de/index.php/de/aktuelles/news

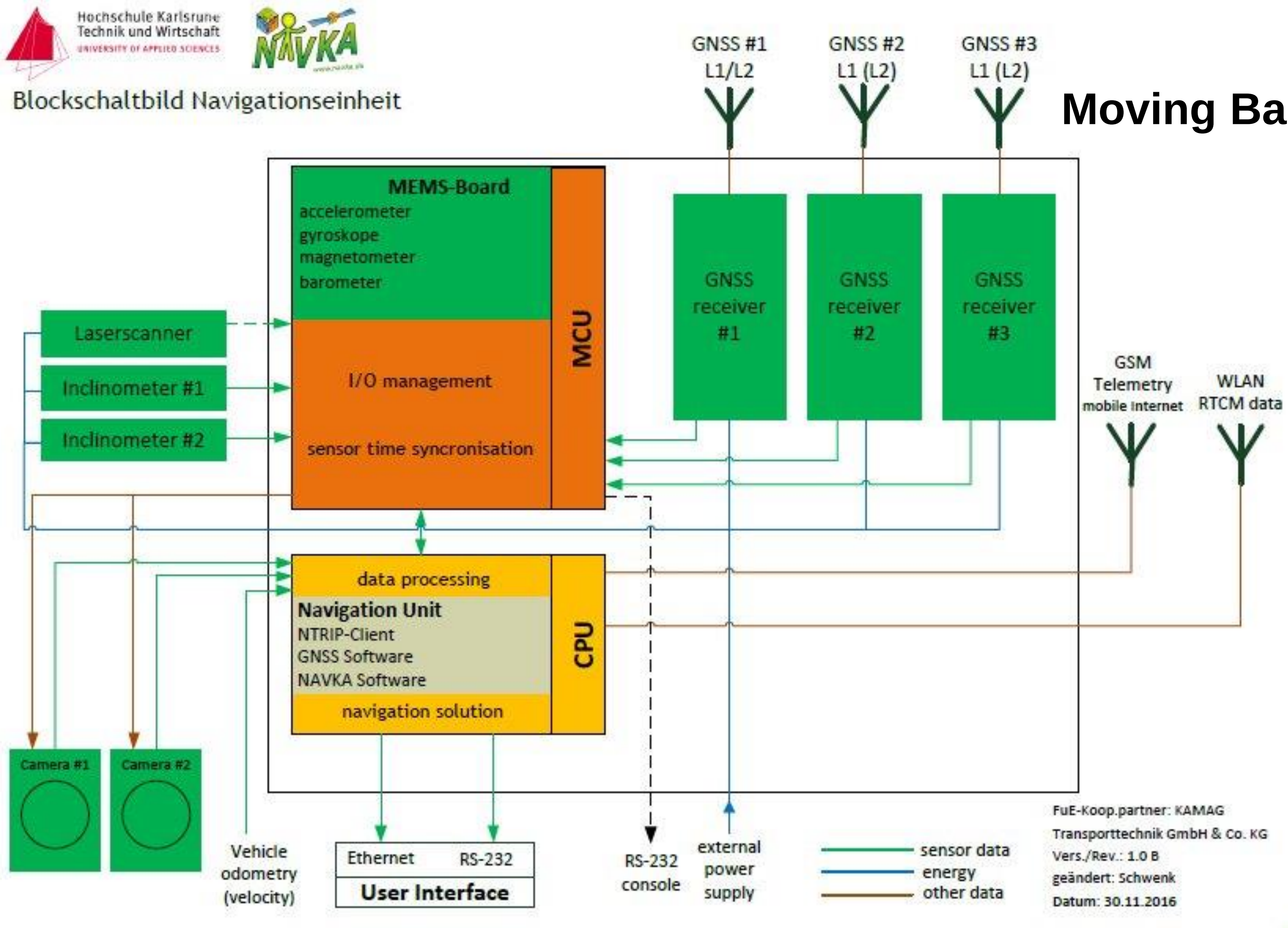
GNSS: PPP-K
DGNSS: „Moving- Base“

SELBSTANGETRIEBENE TRANSPORTER

SPEZIALTRANSPORTER

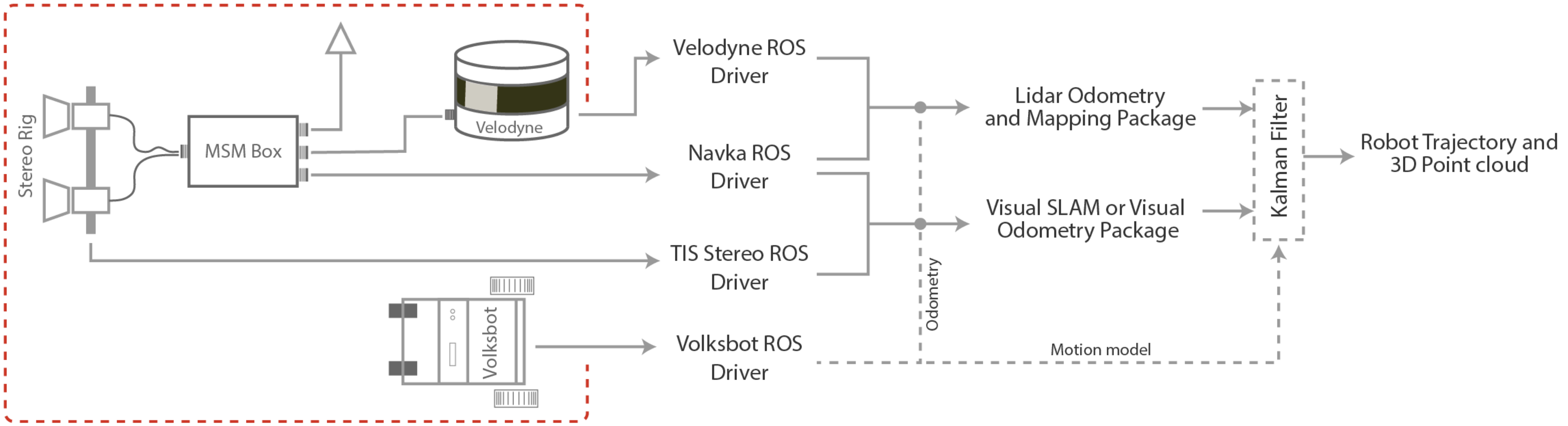
Further Sensor Dynamic Inclinometer

NAVKA RaD Project: KAMA Autonomous Out-/Indoor Driving“



Moving Base!

Partikelfilter => SLAM (Simultaneous Localization & Mapping)



Stereo Rig

MSM Box

Velodyne

Volksbot

Velodyne ROS Driver

Navka ROS Driver

TIS Stereo ROS Driver

Volksbot ROS Driver

Odometry

Motion model

Lidar Odometry and Mapping Package

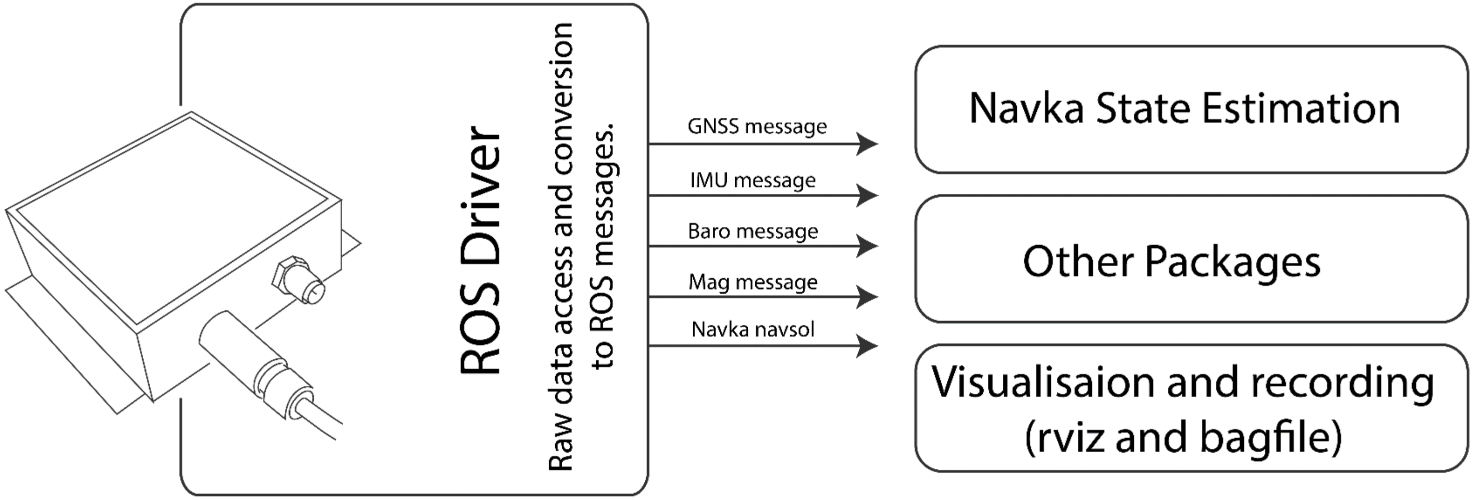
Visual SLAM or Visual Odometry Package

Kalman Filter

Robot Trajectory and 3D Point cloud

FuE-Projekt Multisensorisches Selbstreferenzierendes Mapping System (MSM)

http://www.navka.de/index.php/de/weitere-projekte/fue-projekte-produkte



ROS Driver

Raw data access and conversion to ROS messages.

GNSS message

IMU message

Baro message

Mag message

Navka navsol

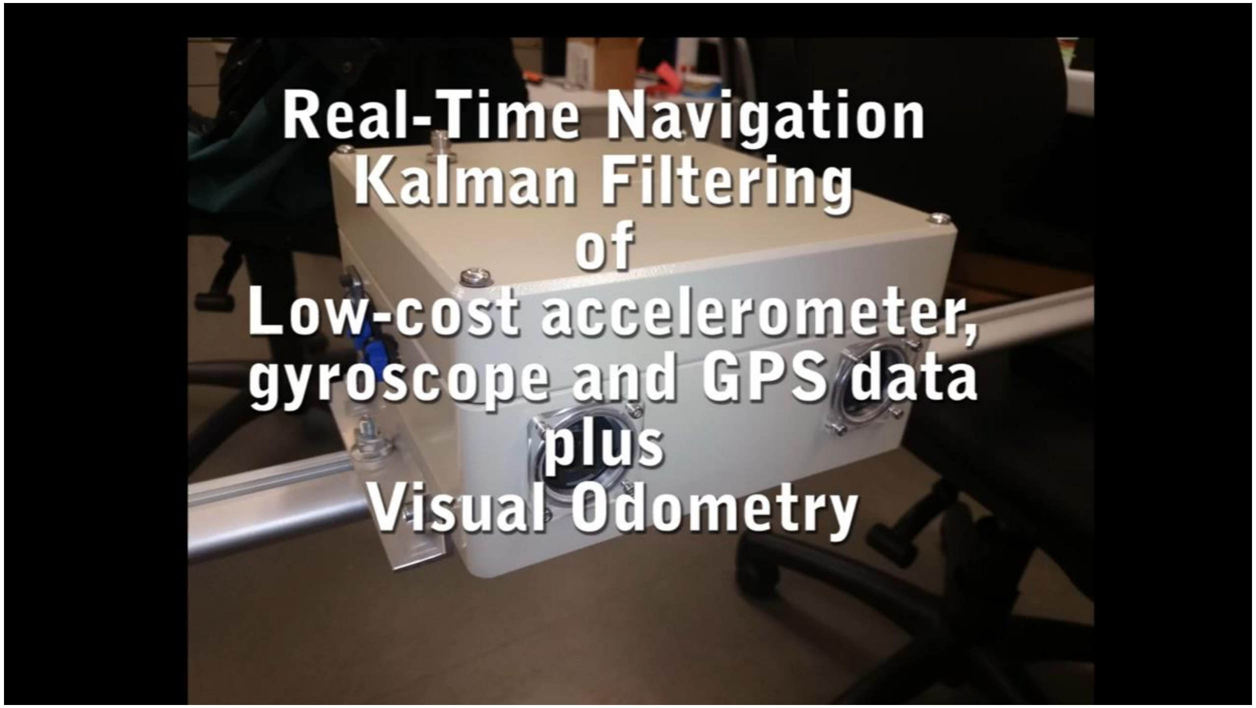
Navka State Estimation

Other Packages

Visualisaion and recording (rviz and bagfile)

Examples
for
NAVKA
Developments

GNSS,MEMS, CAMERA
Out & Indoor



Real-Time Navigation
Kalman Filtering
of
Low-cost accelerometer,
gyroscope and GPS data
plus
Visual Odometry

GNSS &MEMS
Outdoor

Further Information: www.navka.de

Book on Parameter-Estimation including Naviagtion 12/2017

https://www.amazon.de/Klassische-robuste-Ausgleichungsverfahren-Ausbildung-Geoinformatikern/dp/3879076154