



GNSS Short and Crisp

A brief introduction into Global Navigation Satellite Systems

Dr. Philipp Berglez



New2Space Workshop

Vienna, February 17th 2020

OHB Digital Solutions (1/2)

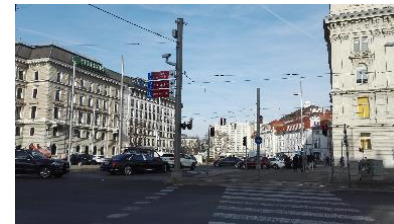
- TeleConsult Austria GmbH, founded 1999, acts as prime partner for anyone looking for data solutions in the arena of Positioning, Navigation and Mobility.
- TeleConsult is since December 2018 a member of the OHB Group of Companies
- Renaming to OHB Digital Solutions in 12/2019



- Our field of work is
 - Precise positioning and reliable navigation
 - Development of navigation, telecommunication and information technologies
- The field of expertise is
 - Telematics and technical consultancy in the field of GNSS
 - Signal processing and algorithm development
 - System design and analysis
 - Software development and testing
 - Mobile computing in particular for location based services
 - Project preparation and management

OHB Digital Solutions (2/2)

- Project related experience
OHB Digital Solutions has been involved in more than **90** projects
 - European Space Agency (ESA)
 - 5th, 6th, and 7th European Framework Programme
 - Horizon 2020 Programme
 - Austrian Space Applications Programme (ASAP)
 - Programme of the Austrian Research Promotion Agency (FFG)
- Office Locations
 - Rettenbacher Straße 22, A-8044 Graz, Austria
 - Lothringerstraße 14, A-1030 Vienna, Austria





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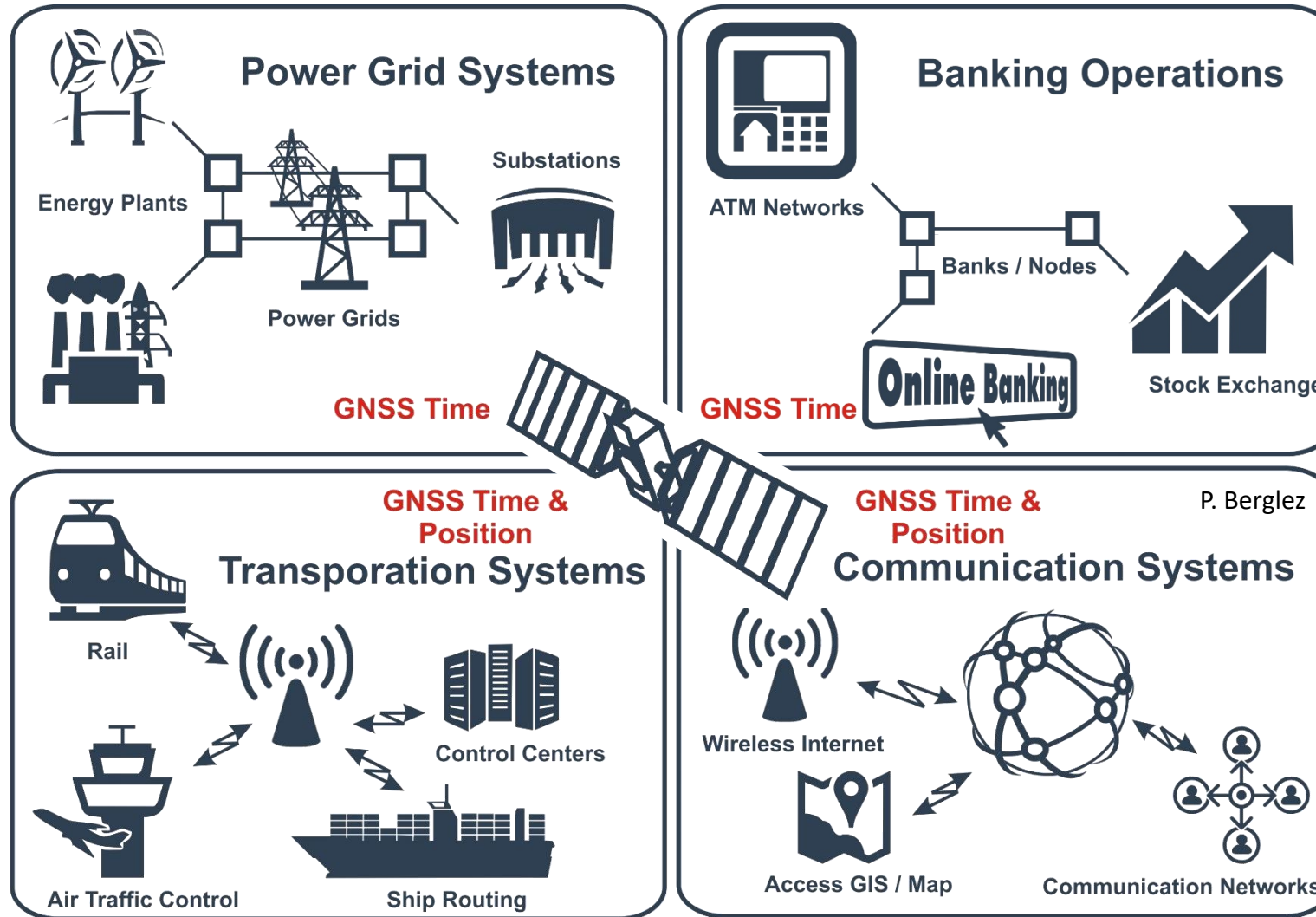
We all are navigators

- Satellite-based position and time determination, orientation and navigation are deeply rooted in our daily lives.
- European GNSS Agency Market Report 2019
 - 6.5 billion GNSS receivers on the market
 - 1.7 billion units shipped in 2019
 - 2029 → 9.5 billion
 - ~ 1 GNSS receiver per person
- 6-7% of gross domestic product in Western countries depends on satellite navigation data?
 - € 800 billion in EU

Ref.: GSA Market Report 2019

Ref.: European Space Agency 2014

GNSS Applications



Even small disruptions can cause severe errors!

Space Race



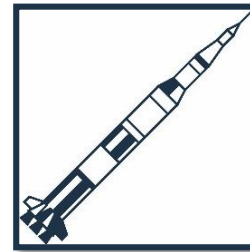
Sputnik

First artifical
satellit
04.10.1957



Wostok 1

First human
in space
12.04.1961



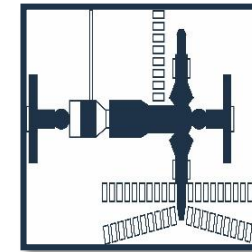
Apollo 11

First man on
the moon
20.07.1969



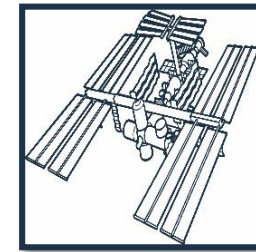
Salyut 1

First space
station
19.04.1971



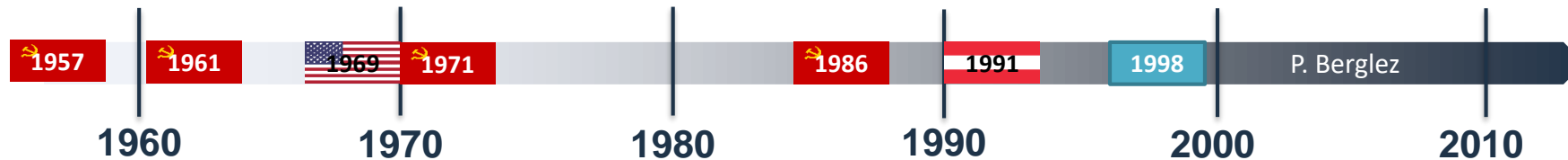
Mir

>5000 days
in space
20.02.1986



ISS

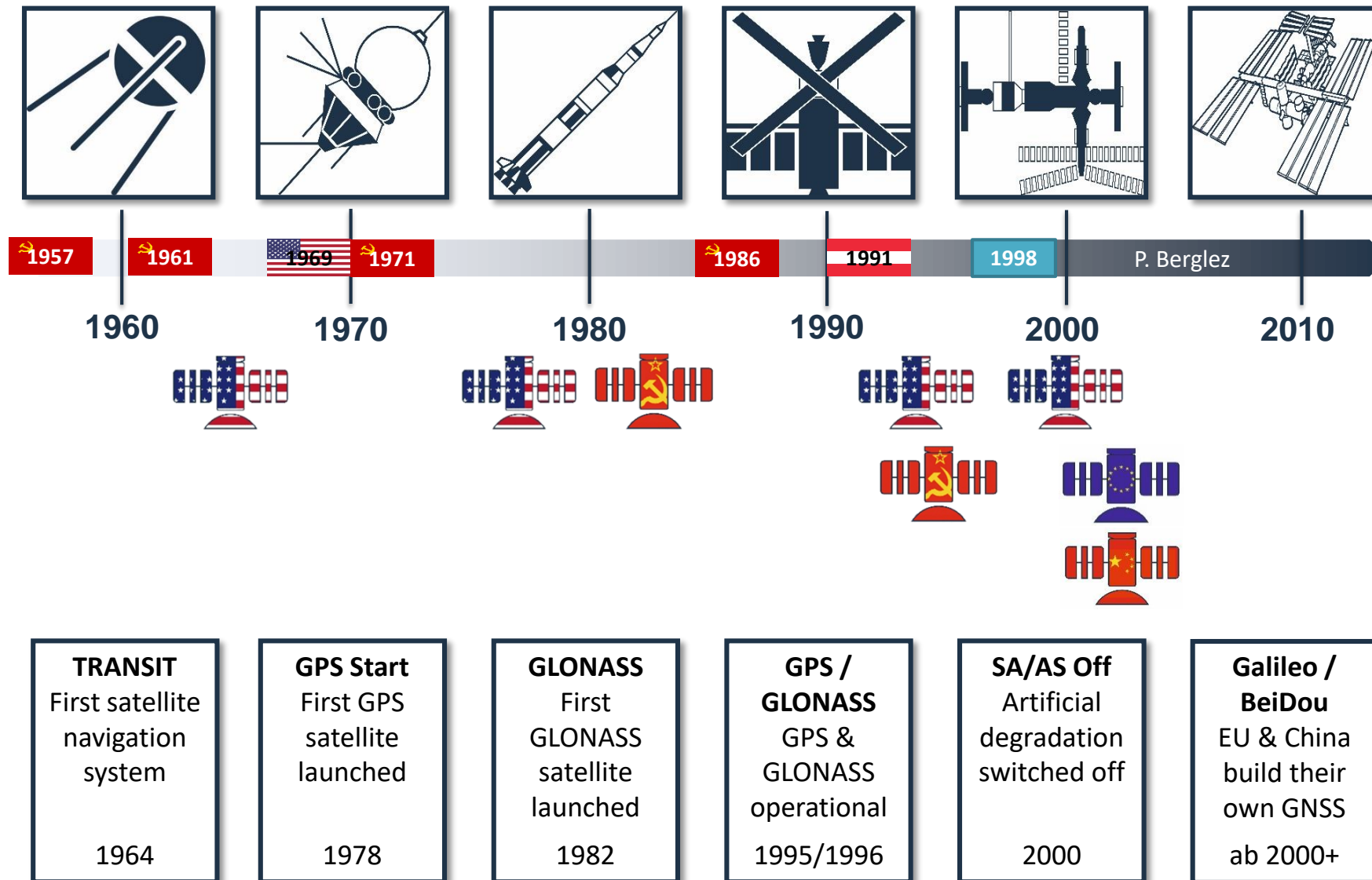
>6700 days
in space
20.11.1998



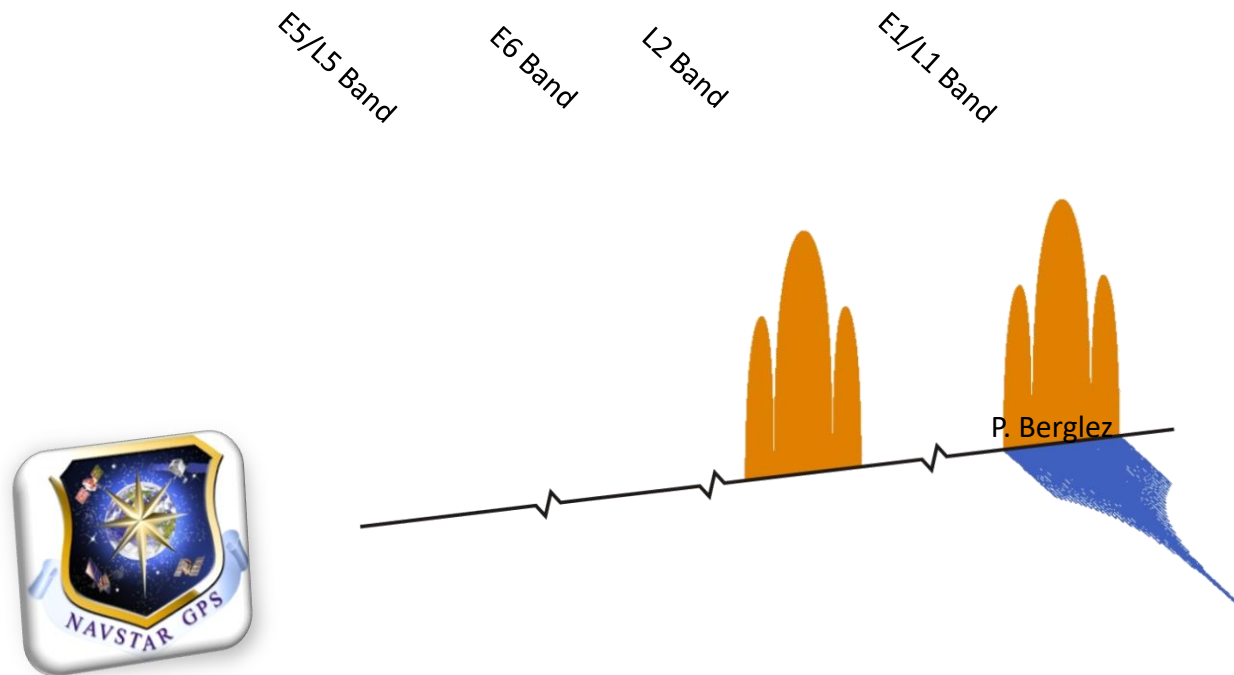
Austromir

02.10.1991

Space Race



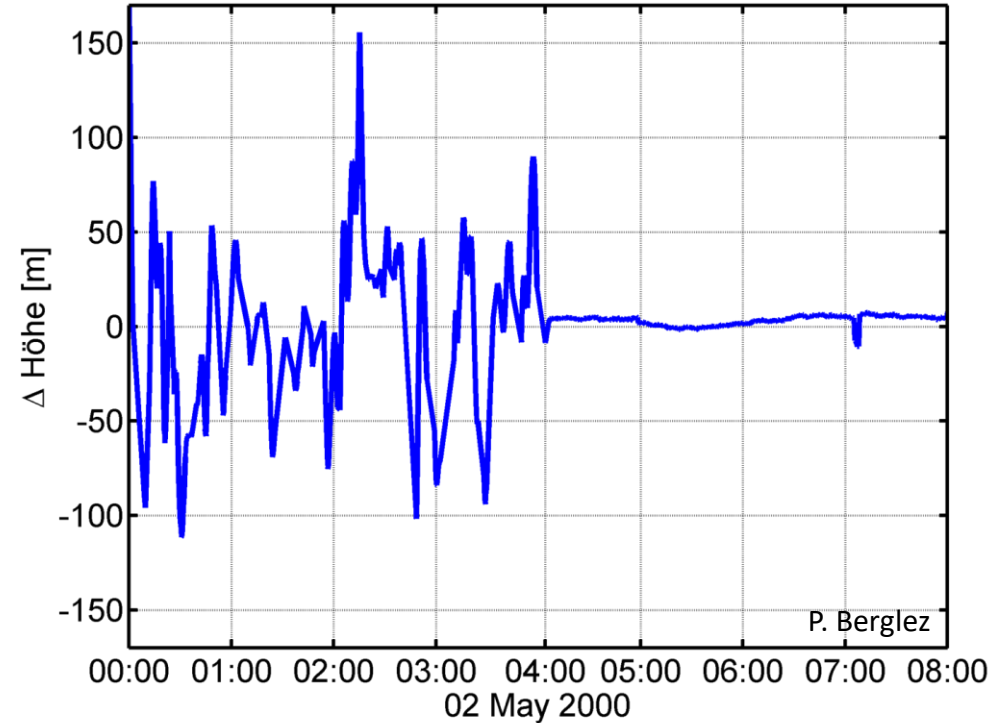
GNSS in 2000



1 system and 1 civil signal

GNSS in 2000

- GPS and GLONASS primarily designed for military applications
- Until 2000, the GPS was artificially degraded



- GPS Station: Graz / Lustbühel
- 2. Mai 2000 at 04:00 UTC
- Selective Availability (SA) and Anti-Spoofing (A-S) switched off



How does GNSS-based positioning work?

Definition

„GNSS is an all-weather, space-based navigation system satisfying the requirements of the users to accurately determine their position, velocity and time in a common reference system, anywhere on or near the Earth on a continuous basis“

Ref.: Wooden (1985)

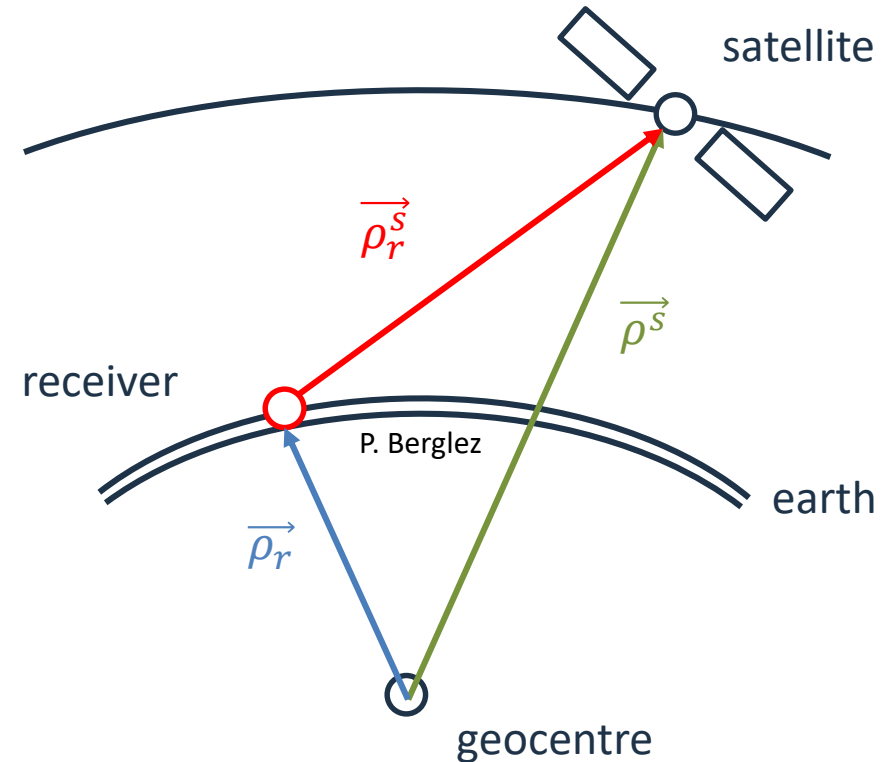
- Global Navigation Satellite System (GNSS)
 - space-based navigation system
 - continuous determination of position, speed and time in a common reference system
 - anywhere on or near the earth
 - all-weather
- GNSS consists of three components
 - Space segment (satellites)
 - Control segment (ground control stations)
 - User segment (receivers)

Complexity reasons

- Multi-user system
 - One-way measurements („listen only“)
- Real-time 3D positioning
 - Simultaneous measurements from multiple satellites
 - Real-time determination of satellite positions
- High accuracy of position, velocity and time solution
 - High frequency signal modulation
 - Carrier frequency in the microwave domain (opaque window)
 - Dual- or multi-frequency transmission due to dispersive character of the ionosphere
- Frequency allocation restrictions and signal robustness
 - ITU regulations
 - Spread spectrum signals
 - Limited signal power
- Mixture of military and civil use
 - Multiple signals

Satellite Geodesy

- Satellite geodesy
 - Orbit determination
(receiver position known)
 - Positioning
(satellite position known)
- Geometric observations
(e.g. ranges) are measured

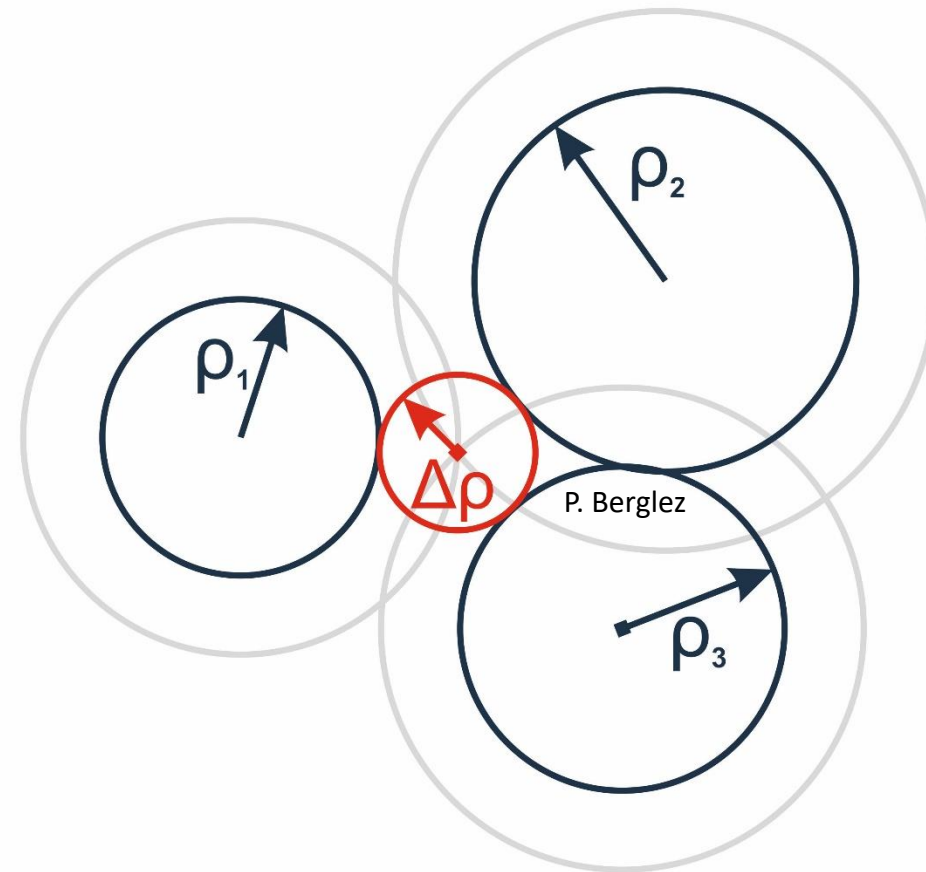


$$\rho_r^s = \left\| \vec{\rho}_r^s \right\| = \sqrt{(X^s - X_r)^2 + (Y^s - Y_r)^2 + (Z^s - Z_r)^2}$$

Principle of position determination

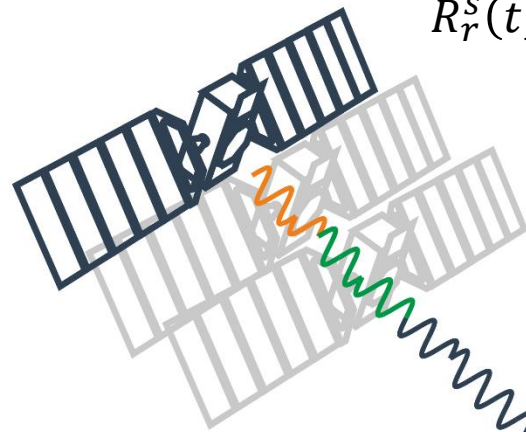
- Principle is based on runtime time measurements (distances) between the satellites and the receiver
 - Known satellite position (transmitted by satellite)
 - Intersection of spheres
- Unsynchronized satellite and receiver clocks
 - No intersection
 - Additional uncertainty
 - Pseudorange measurements
- Additional measurement (at least 4 satellites) necessary
 - Coordinates (X,Y,Z) + clock error

$$R_r^s(t) = \rho_r^s(t) + c \cdot \Delta\delta_r^s(t)$$



Error sources

$$R_r^S(t) = \rho_r^S(t) + c \cdot \Delta\delta_r^S(t) + \delta I_{ono}^S(t) + (\delta T + \delta\phi_r^S(t)) + \epsilon_r^S$$



Satellite errors

- Satellite orbit error (1 – 10m)
- Satellite clock error (0 – 2m)

Propagation errors

- Ionosphere (0 – 30m)
- Troposphere (0 – 10m)

Receiver errors

- Antenna
- Receiver clock
- Multipath effect
- Receiver noise
- Signal processing losses

Interference

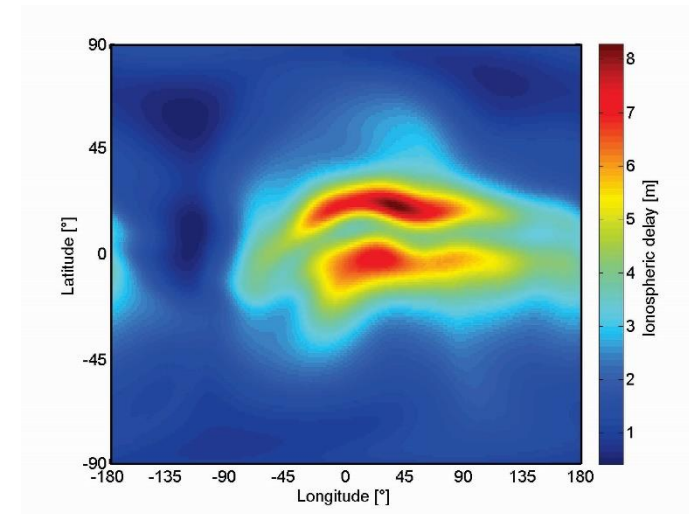


Satellite orbit and satellite clock errors

- Satellite orbit and clock determination performed by control segment
 - Monitoring station network and data processing facility
 - Upload of information (ephemeris and clock corrections) to the satellite
 - Data dissemination by satellite via signal
- Broadcast ephemeris
 - Predicted, transmitted via satellite, accuracy of some metres, validity of a few hours
- Almanac data
 - Predicted, transmitted via satellite (real-time), accuracy of some kilometres, validity of several days
- Precise ephemeris
 - Post-processed, high-accuracy (a few centimetres)
- Satellite clocks are atomic clocks with a very high frequency stability → satellite clock errors are modelled and broadcasted
- Receiver clocks are (typically) crystal clocks with a low frequency stability → receiver clock error

Ionosphere

- The ionosphere (extending in various layers from about 50 km to 1000 km above earth) is a dispersive medium with respect to radio waves.
- The ionospheric refraction is due to the presence of ionized gas molecules in the ionosphere and mainly caused by solar radiation.
- Dependency
 - sunspot activity (11-year cycle)
 - season and epoch
 - position of observation site
 - position of satellites
- Treatment
 - estimate → additional unknown coefficients
 - model → use of ionosphere models, e.g. Klobuchar, NeQuick, ...
 - eliminate → use measurements on multiple frequencies

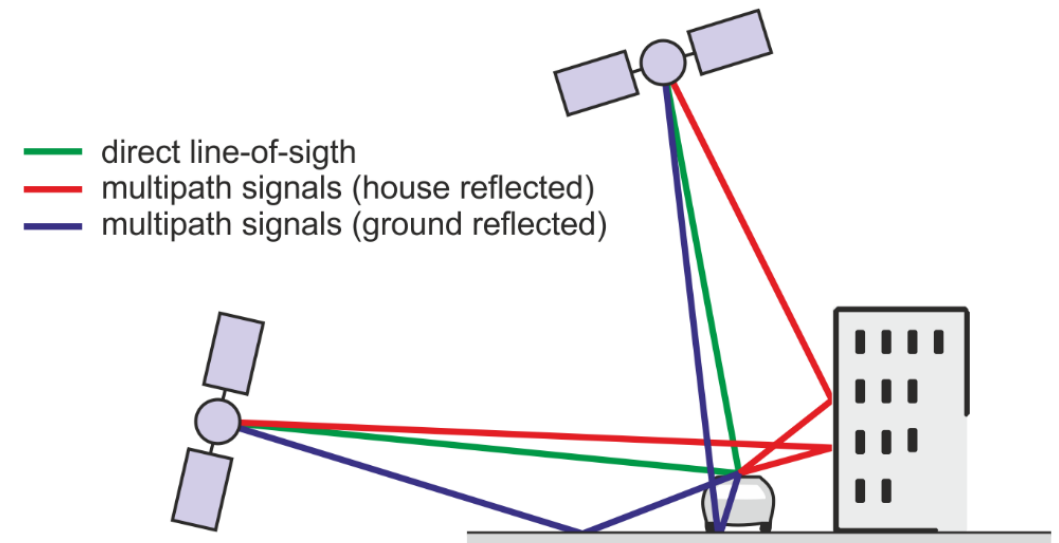


Troposphere

- Troposphere includes the stratosphere and extends to about 50 km above earth
- The troposphere is non-dispersive with respect to radio waves
- Tropospheric refraction is due to atmospheric parameters
 - atmospheric pressure
 - temperatur
 - partial water vapor pressure
- Treatment
 - Estimate
 - Model → Hopfield or Saastamoinen model
- Numerical example
 - For standard atmospheres, the tropospheric zenith delay amounts to about 2.3 m according to the Saastamoinen model.
 - At an elevation angle of 10° , the tropospheric refraction increases by a factor of 3.

Multipath effect

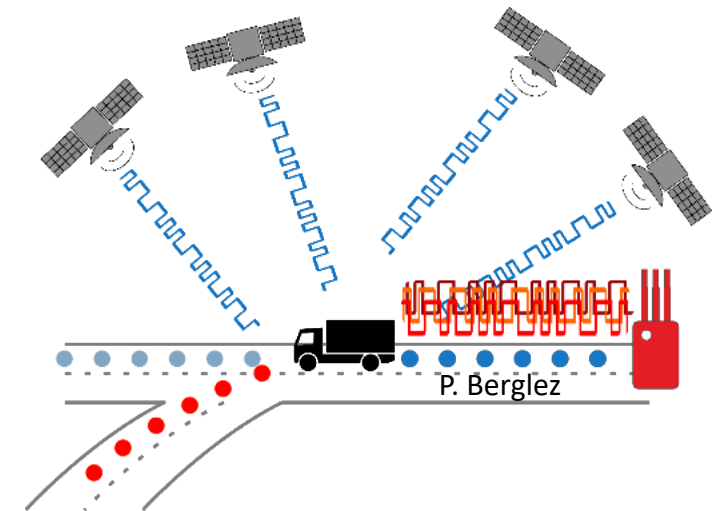
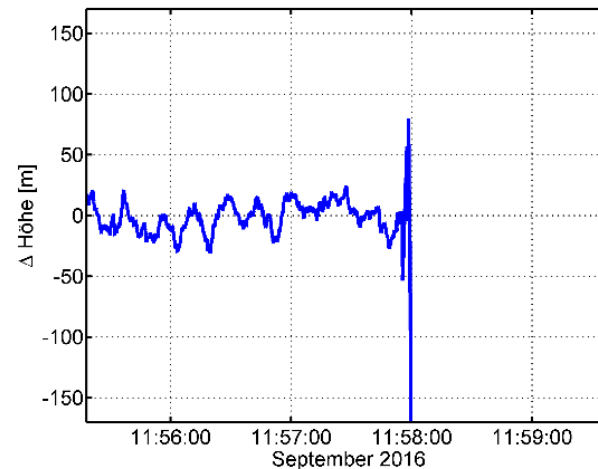
- Caused by reflected signals
 - Multipath signals are delayed and weaker



- Pseudorange errors up to 100 m possible
- Mitigation
 - Avoid reflection surfaces close to the antenna (especially tinted glass)
 - Reduction by using improved antennas (ground plates, choke rings)
 - Improved receiver technology

Interference

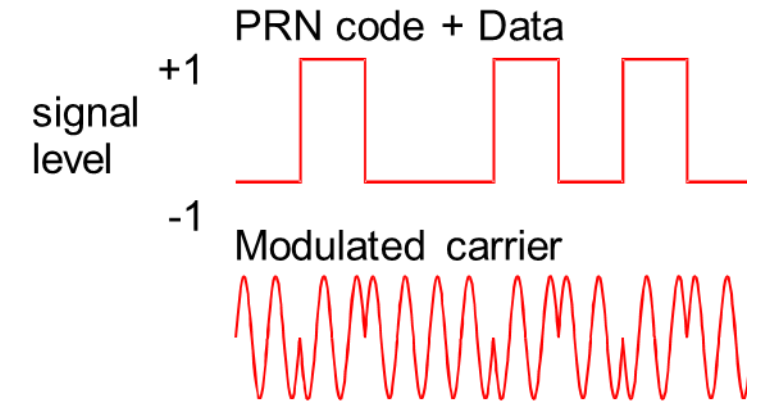
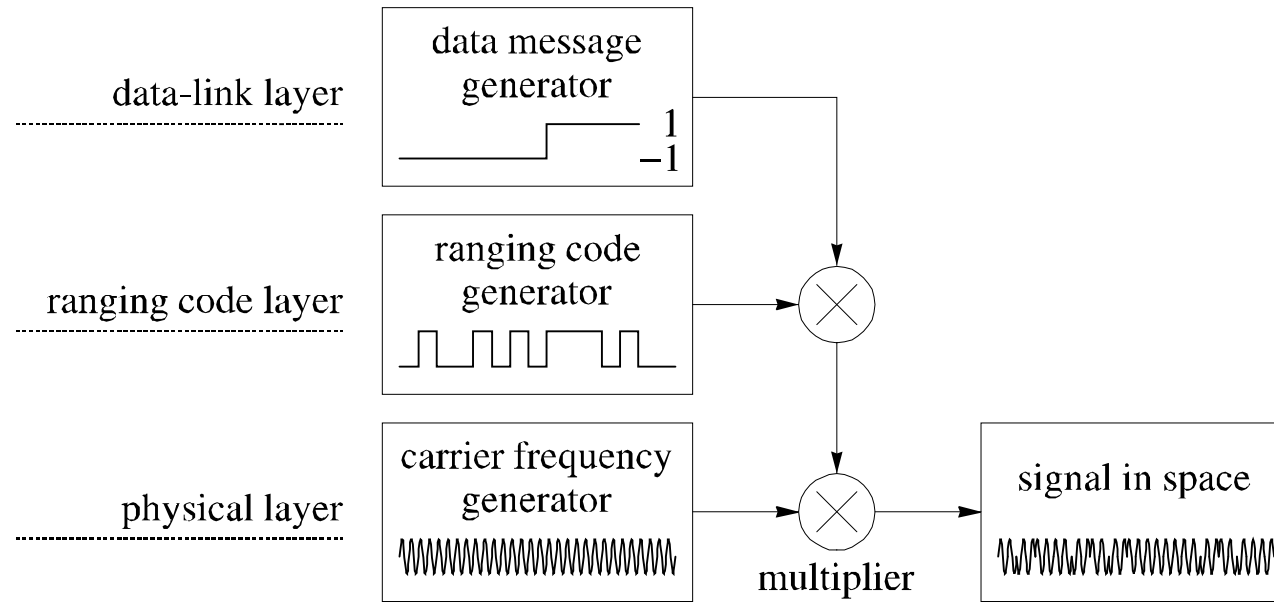
- Interference can be described as the effect of energy change due to the superposition of electromagnetic waves
- Unintentional interference
 - Caused by nature, other systems/signals, multipath effects, etc.
 - Well known and countermeasures available
- Intentional interference
 - Jamming
 - Spoofing
 - Meaconing





Our interface to GNSS – GNSS signals

GNSS signal structure



- Physical layer / carrier frequency
 - Sinusoidal wave \rightarrow centre frequency (e.g. 1.575 GHz)
- Ranging code
 - Distinction of satellites and range estimation using PRN codes
- Data-link layer
 - Navigation message (e.g. satellite position, correction data)

GNSS signal power

- GPS minimum power received for L1 C/A: -158,5 dBW

Ref.: GPS SIS ICD 200H

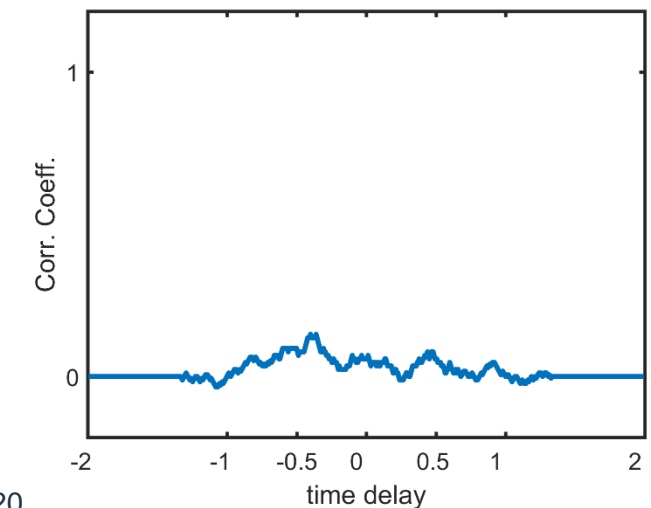
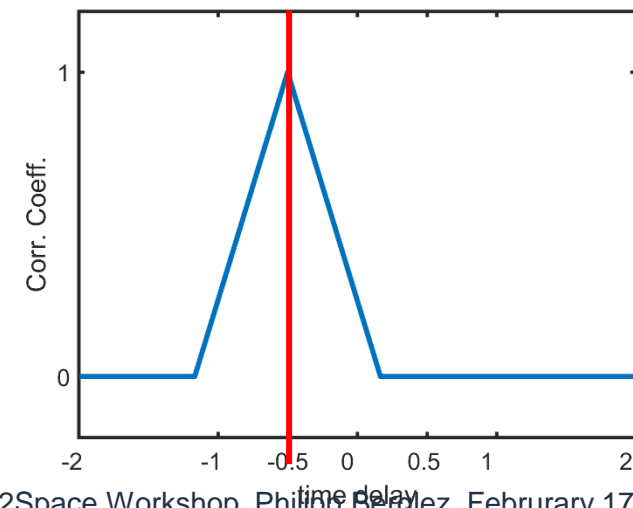
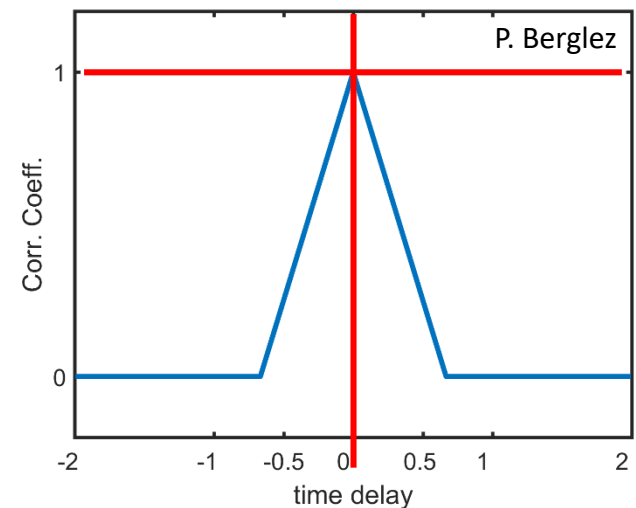
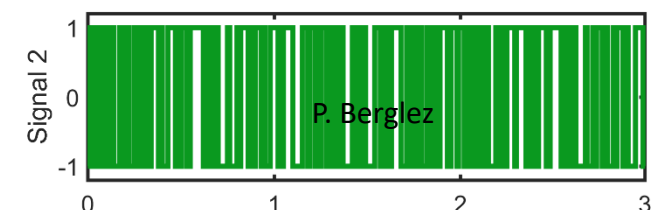
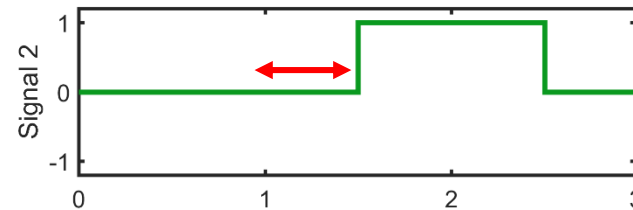
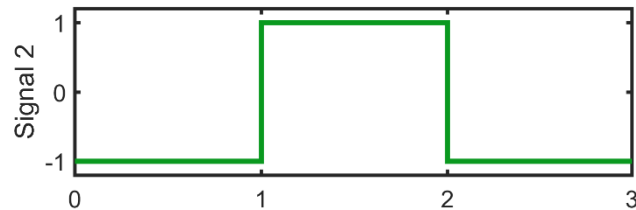
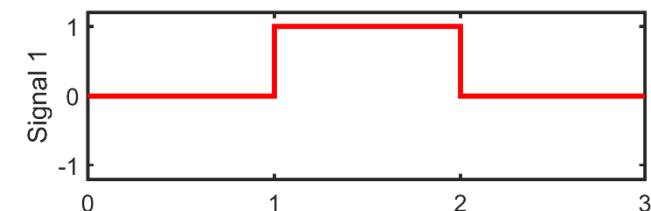
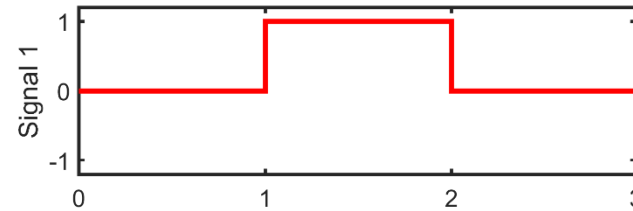
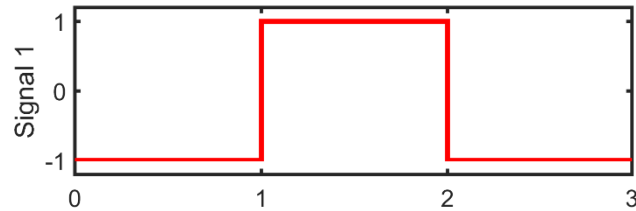
	Power (based on calculations, not measured)	
	Watt	dBW
UHF/VHF transmission (maritime)	25 W	14 dBW
Mobile phone transmission	1 W	0 dBW
Bluetooth low energy	1.0000e-02 W	-20 dBW
Mobile phone reception	1.0000e-04 W	-40 dBW
ZigBee	3.1623e-12 W	-115 dBW
Thermal Noise	1.0000e-14 W	-140 dBW

- GNSS signals are below thermal noise floor
- Satellite transmission power
 - Assuming: 13 dBi satellite antenna gain, 1.25 dB cable losses at satellite, 182.6 dB path loss, 2 dB receiver loss, 0 dBi receiver antenna gain
 - 14,35 dBW → 27,2 W

<http://www.igs.org/assets/pdf/W2017-PY08-02%20-%20Steigenberger.pdf>
https://www.navtechgps.com/gnss_facts/
http://www.unoosa.org/documents/pdf/icg/2018/ait-gnss/09_M1.pdf

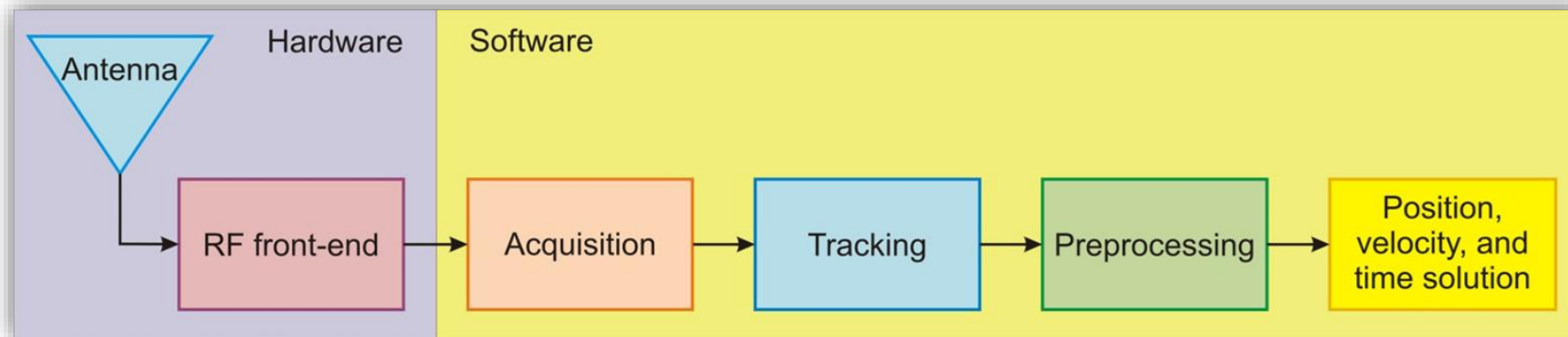
Signal processing basics

- Basic principle of GNSS signal processing is signal correlation
 - Receiver generates replica signal and correlates it with the received signal



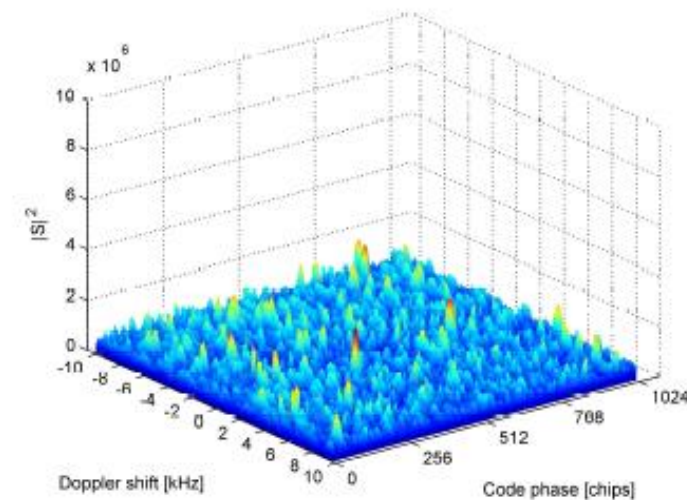
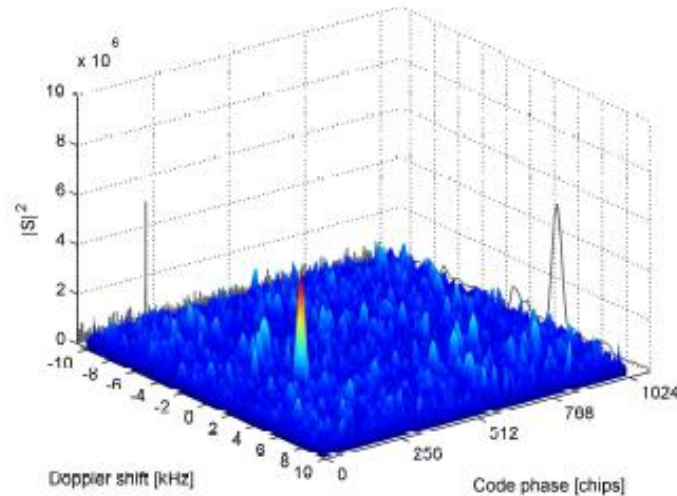
Generic GNSS receiver design

- Purpose of GNSS receiver
 - Receive the signal (antenna)
 - Find visible satellites (acquisition)
 - Track the signal over time (tracking)
 - Split it up into the three components → carrier, PRN code, data
 - Perform runtime measurement (pseudoranges)
 - Decode the navigation data (pre-processing)
 - Compute position, velocity and time (PVT) solution



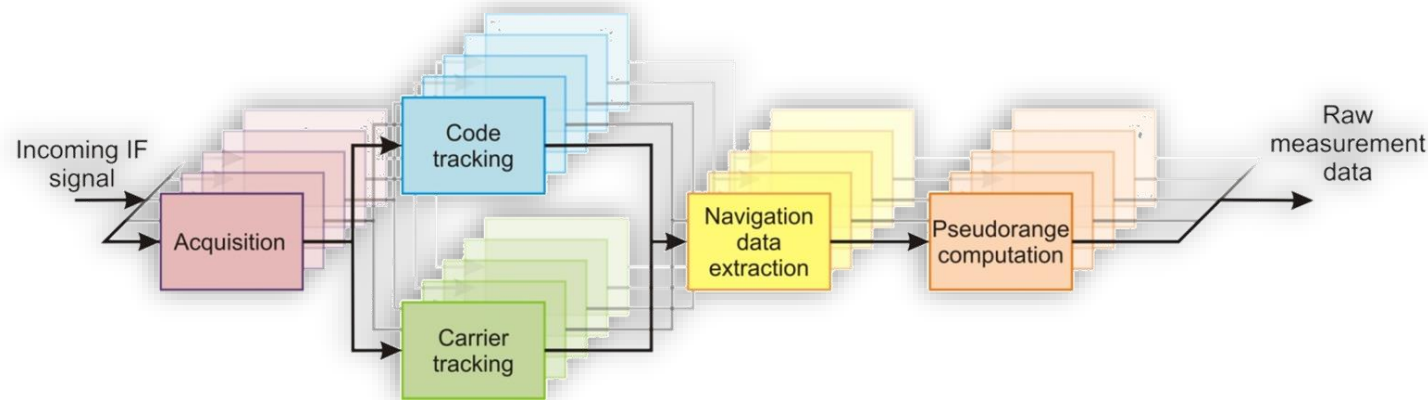
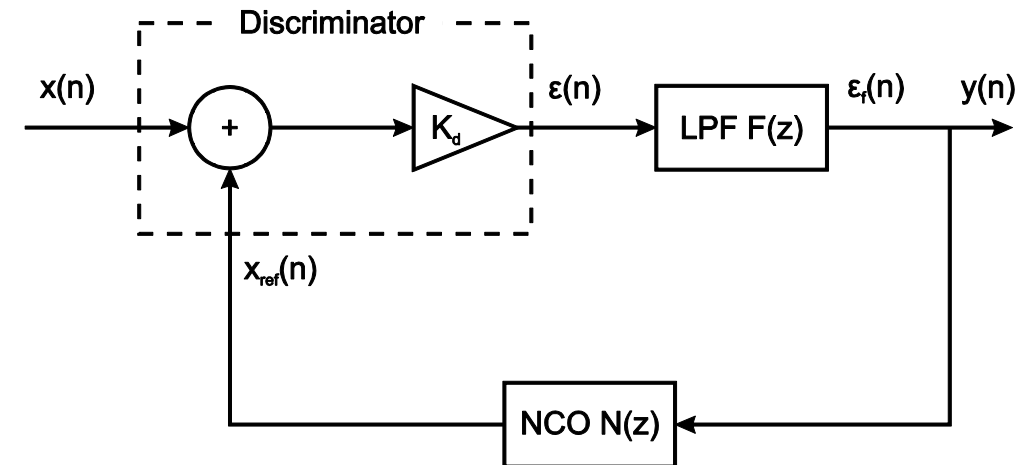
Acquisition

- Acquisition is a search process
 - Decide if satellite signal is present
 - Determine rough estimates of Doppler frequency shift and code phase
- Receiver generates replica signals and correlates them with the incoming signal
 - Since satellites and receiver are moving different code delays and Doppler frequency shifts have to be tested
 - Once a signal has been detected the rough estimates have to be refined and tracked over time



Tracking

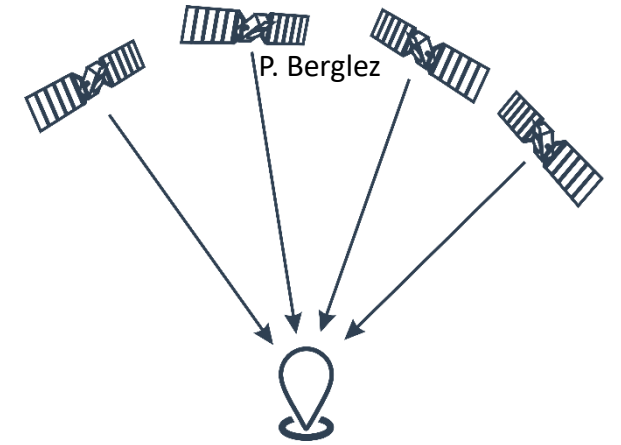
- Keep track of the satellite signal
 - Correlation of incoming signal with signal replica within receiver → tracking loop
- Split up the signal into its components
 - Delay-locked loop (DLL) → PRN code
 - Phase-locked loop (PLL) → carrier
 - Navigation message bits/symbols



Positioning Methods

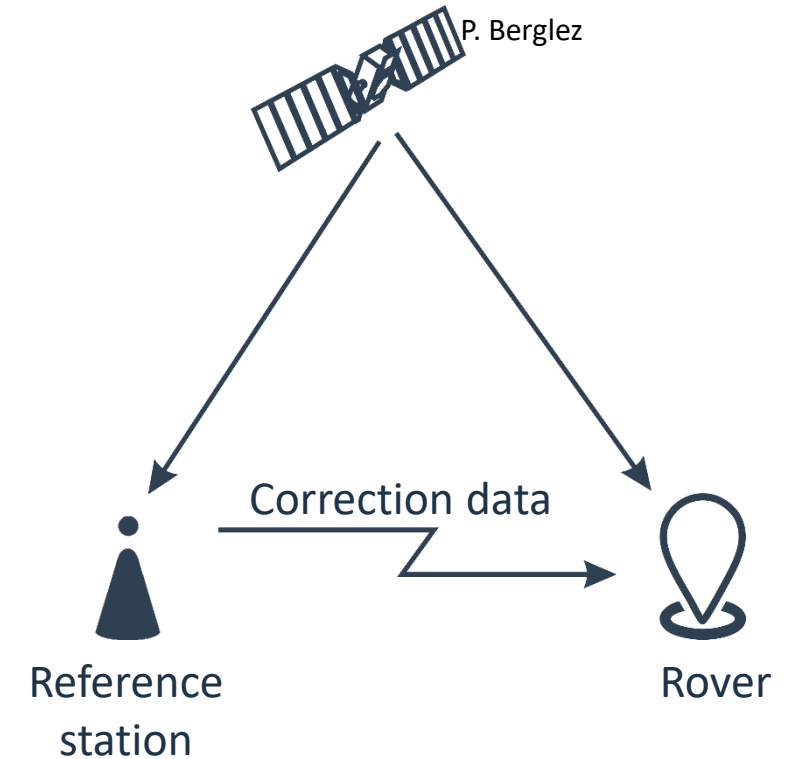
- Single point positioning (stand-alone)
 - Most receivers use this technique
 - Measurements to at least 4 satellites (X,Y,Z + clock)
 - Errors are modelled using broadcast data
 - Time-to-first-fix: a few seconds up to a few minutes
 - Accuracy of a couple of metres
 - Single frequency (95%): ± 15 m horizontal and ± 22 m vertical
 - Dual frequency (95%): ± 4 m horizontal and ± 8 m vertical
- Single point positioning using satellite-based augmentation systems (SBAS)
 - Most receivers are capable of handling SBAS signals (e.g. EGNOS, WAAS, etc.)
 - Provision of correction data via satellite (more precise than broadcast corrections)
 - Accuracy (95%): ± 3 m horizontal

Ref.: www.gsa.europa.eu



Differential GNSS

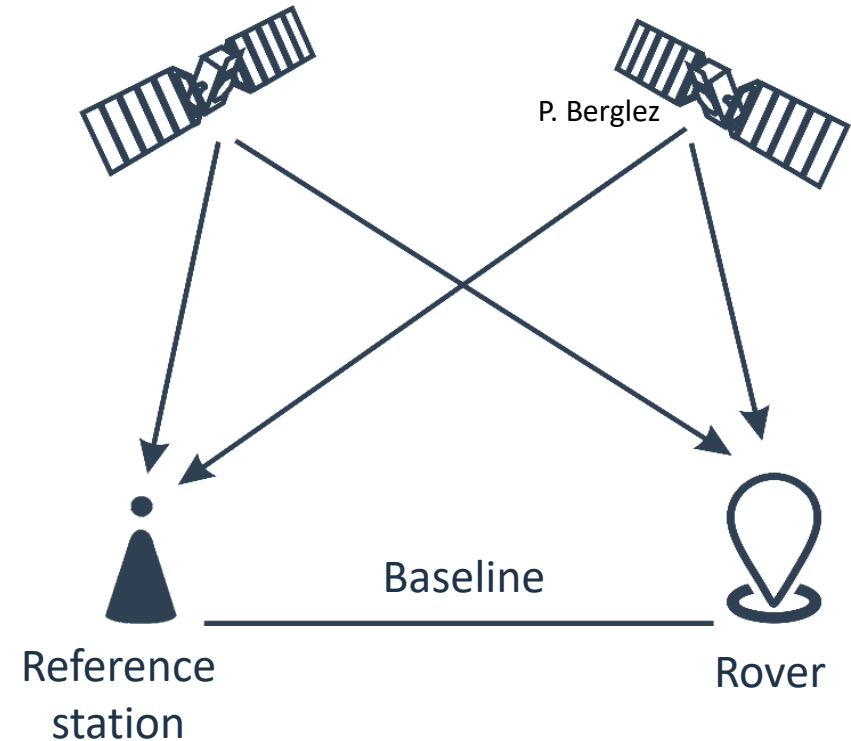
- The quality of correction data strongly depends on
 - Area covered (e.g. global, regional, local)
 - Update rate (e.g. every 2 hours, every 15 minutes, every second)
- Differential GNSS (DGNSS or D-GNSS)
 - Local reference station (at known coordinates) computes correction data
 - Dissemination via communication link (e.g. GPRS, UMTS, VHF)
 - Receiver applies the corrections (receiver has to have a communication link)
- DGNSS services
 - Use your own reference station (hardware costs)
 - Use commercial service (pay per use, pay per month,)



Accuracy (95%): 0.5 – 1 m horizontal

Relative positioning (1/2)

- Determination of unknown rover position w.r.t. a known reference position using a baseline vector
- Simultaneous observation of identical satellites at both the reference and the rover position
- Forming differences between observations from identical satellites and between reference and rover station
 - Elimination of satellite errors
 - Elimination of receiver errors
 - Reduction of propagation errors
- Benefit → high accuracy
- Drawback → simultaneous measurements to identical satellites



Relative positioning (2/2)

- Evaluation can be done in post-processing or real-time
 - Post-processing has a higher accuracy
 - Global reference station networks (e.g. IGS, CODE) exist and provide reference data
 - Longer observation time (> 30 min)
 - Accuracy
 - Static: $\pm (5\text{mm} + 0.5 \text{ ppm})$
 - Kinematic: $\pm (5\text{cm} + 5 \text{ ppm})$
- Real Time Kinematics – RTK
 - Relative positioning in real-time
 - Transmission of measurements from reference to rover in near-real-time (1-2 seconds)
 - Accuracy: cm-accuracy (1 – 5 cm) in real-time
 - Use your own reference station (hardware costs)
 - Use commercial service (pay per use, pay per month,)
 - APOS, EPOSA, NTRIP

Precise Point Positioning (PPP)

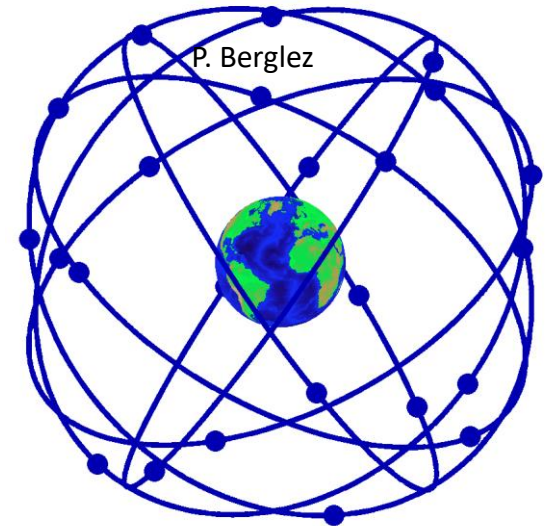
- Precise Point Positioning
 - Cost efficient technique for precise positioning with a single GNSS receiver
 - No need for reference stations
 - Using precise models and data
 - Predicted precise orbits and clocks
 - Ionospheric grid data or dual-frequency measurements
 - Taking into account effects like differential code biases, phase wind-up effects, phase centre offset & variation, etc.
 - Filtering of observations and data
- PPP algorithms require a certain amount of time to achieve an accuracy of a few centimetres → Convergence time (between 10 to 30 minutes)
 - Reduction of convergence time in the last years by a factor of 2
- Data available from e.g.
 - International GNSS Service (IGS)
 - Center for Orbit Determination in Europe (CODE)
 - European Space Agency – European Space Operations Centre (ESA - ESOC)



GPS, Galileo, GLONASS and more

Global Positioning System (GPS)

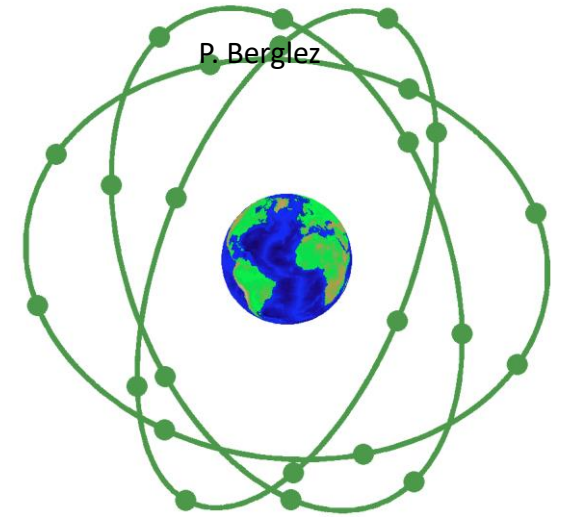
- Maintained by the United States government
- Currently 31 satellites
 - 6 orbital planes
 - Nearly circular orbits
 - Altitude approx. 20.200 km
 - Inclination of 55°
- Signals on 3 different frequencies (5 out of 9 are for civil use)



L1 (1575.42 MHz)	L2 (1227.60 MHz)	L5 (1176.45 MHz)
C/A	L2C	L5-I
P(Y)	P(Y)	L5-Q
L1C	M	
M		

GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (GLONASS)

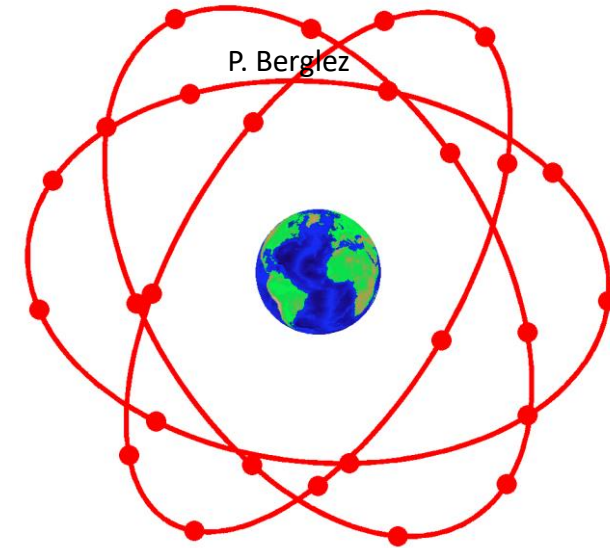
- Maintained by the Russian government
- Currently 27 satellites
 - 3 orbital planes
 - Nearly circular orbits
 - Altitude approx. 19.100 km
 - Inclination of 64.8°
- Signals on 3 different frequencies (currently 2 out of 4 are for civil use)
 - In future 6 out of 10 will be for civil use



G1 (1598 - 1605 MHz)	G2 (1242 - 1248 MHz)	G3 (1176.45 MHz)
L1OF	L2OF	L3OC-I
L1SF	L2SF	L3OC-Q
L1OC	L2OC	
L1SC	L2SC	

European Union's Global Satellite Navigation System – Galileo (1/2)





- European Union, European GNSS Agency (GSA) and ESA
- Currently 23 satellites in orbit (nominal 24 + 6 spares)
 - 3 orbital planes
 - Nearly circular orbits
 - Altitude approx. 23.222 km
 - Inclination of 56°
- Signals on 3 different frequencies (6 signals are currently freely available – up to 7 in future)



E1 (1575.42 MHz)	E5a (1176.45 MHz)	E5b (1207.14 MHz)	E6 (1278.75 MHz)
E1A	E5a-I	E5b-I	E6A
E1B	E5a-Q	E5b-Q	E6B
E1C			E6C

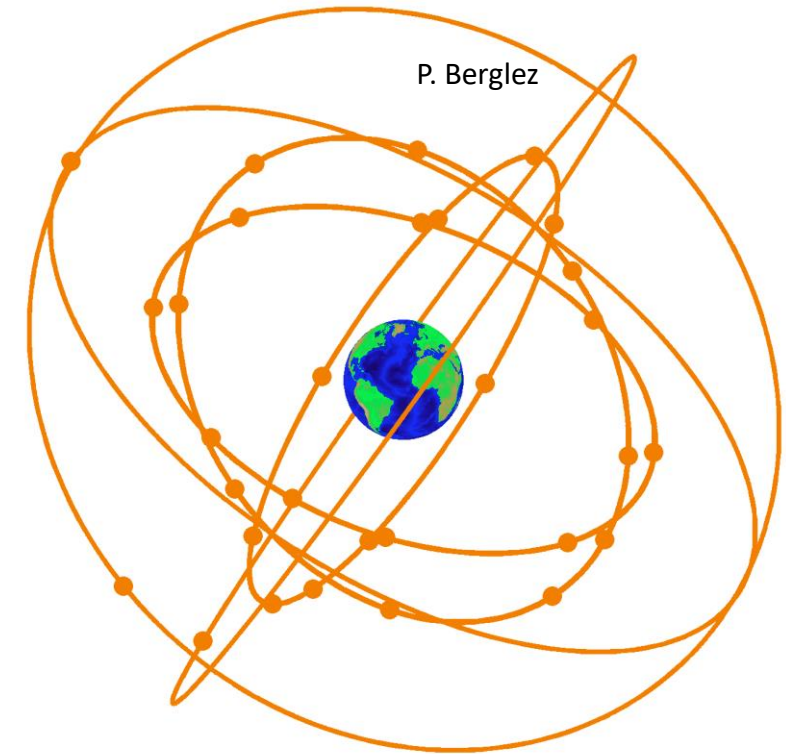
European Union's Global Satellite Navigation System – Galileo (2/2)

- Galileo provides different services

Navigation	Open Service (OS)	Open access and free of charge for positioning and timing	
	High Accuracy Service (HAS)	Additional navigation signal; can be encrypted; high accuracy;	
	Public Regulated Service (PRS)	Restricted to government-authorised users; sensitive applications needing continuous availability; encrypted	
SAR	Search and Rescue Service (SAR)	Contribution to COSPAS-SARSAT; near real-time; return link feasible	

BeiDou (BDS)

- Maintained by the government of China
- Nominal 27+5+3 (35) satellites
 - Currently 21 MEOs, 8 IGSOs and 5 GEOs
 - Nearly circular orbits
 - Altitude approx. 21.500 km
 - Inclination of 55°
- Signals on 3 different frequencies
(6 signals will be freely available)



B1 (1575.42 MHz)	B2 (1191.79 MHz)	B3 (1268.52 MHz)
B1-CD	B2aD	B3
B1-CP	B2aP	B3-AD
B1D	B2bD	B3-AP
B1P	B2bP	

GNSS comparison

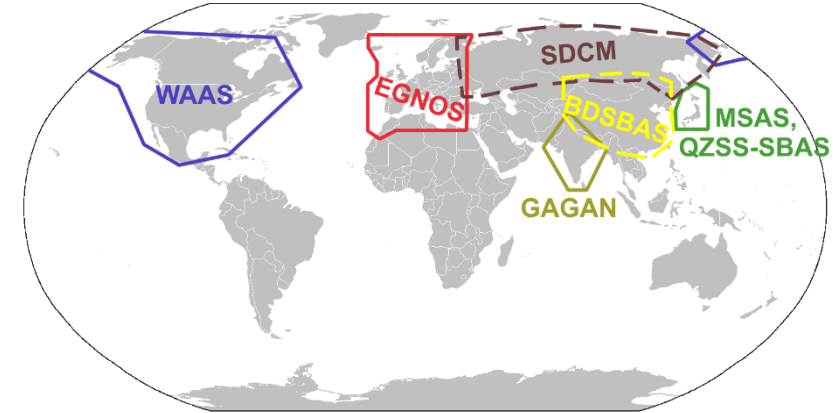
	GPS	Galileo	GLONASS	BeiDou
Operator	USA	Europa	Russia	China
Nominal number of satellites	24+3 MEO	30 MEO	24 MEO	27 MEO, 5 GEO, 3 IGSO
Orbital planes	6	3	3	6
Altitude	20.200 km	23.222 km	19.100 km	21.500 km
Inclination	55°	56°	64.8°	55°
Orbital period	11h 58m	14h 04min	11h 15min	12h 38min
Ground Track Repeat	~ 1 day	~ 10 days	~ 8 days	~ 9 days
Number of civil signals	5	7	6	6
Global accuracy civil signal (95%)	5 – 10 m	4 – 8 m	~ 10 m	< 10 m

- Which one to choose?
- Is more better?
- Is there any need for it?

Ref.: Navipedia <http://gssc.esa.int/navipedia/index.php>

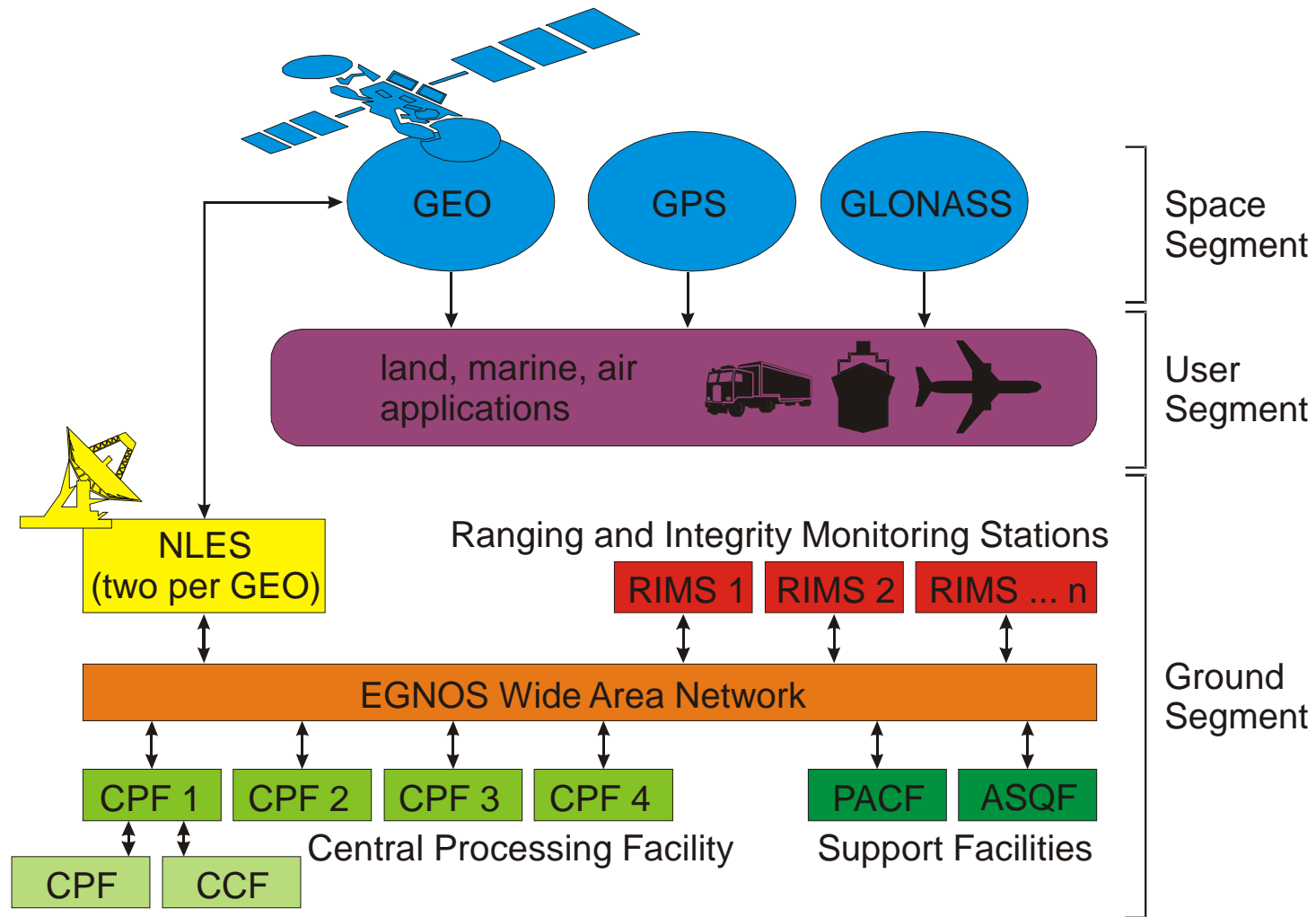
Satellite-based augmentation system (SBAS)

- European Geostationary Navigation Overlay Service (EGNOS)
 - Wide Area Augmentation System (WAAS)
 - Multi-functional Satellite Augmentation System (MSAS)
 - Quazi-Zenith Satellite System (QZSS)
 - GPS Aided Geo Augmented Navigation (GAGAN)
 - System for Differential Correction and Monitoring (SDCM)
- All systems use the same signal definition → interoperable
- SBAS systems provide
- GPS-like signal for obtaining range measurements (additional measurement)
 - Information about GPS system integrity (warnings in case of system errors)
 - Correction data
 - Improving positioning and timing accuracy
 - Corrections for system / satellite related errors (orbit and clock)
 - Corrections for environmental conditions (ionosphere)



Ref: wikipedia.org

EGNOS system concept



Ref: EGNOS Project Office (2003)



Ref: EGNOS OS SDD (2015)

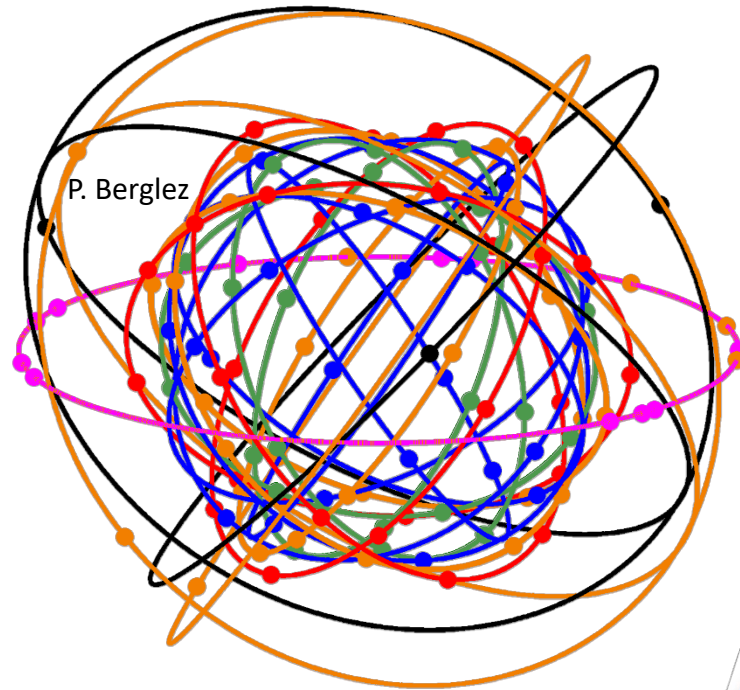
EGNOS Data Access Service (EDAS)

- EGNOS Data Access Service
 - Obtain EGNOS data via internet
 - Real-time or archive



- Different data types
 - GPS, GLONASS and EGNOS GEO observations and navigation data collected by entire network
 - EGNOS augmentation message
 - Differential GNSS and RTK messages (via NTRIP)

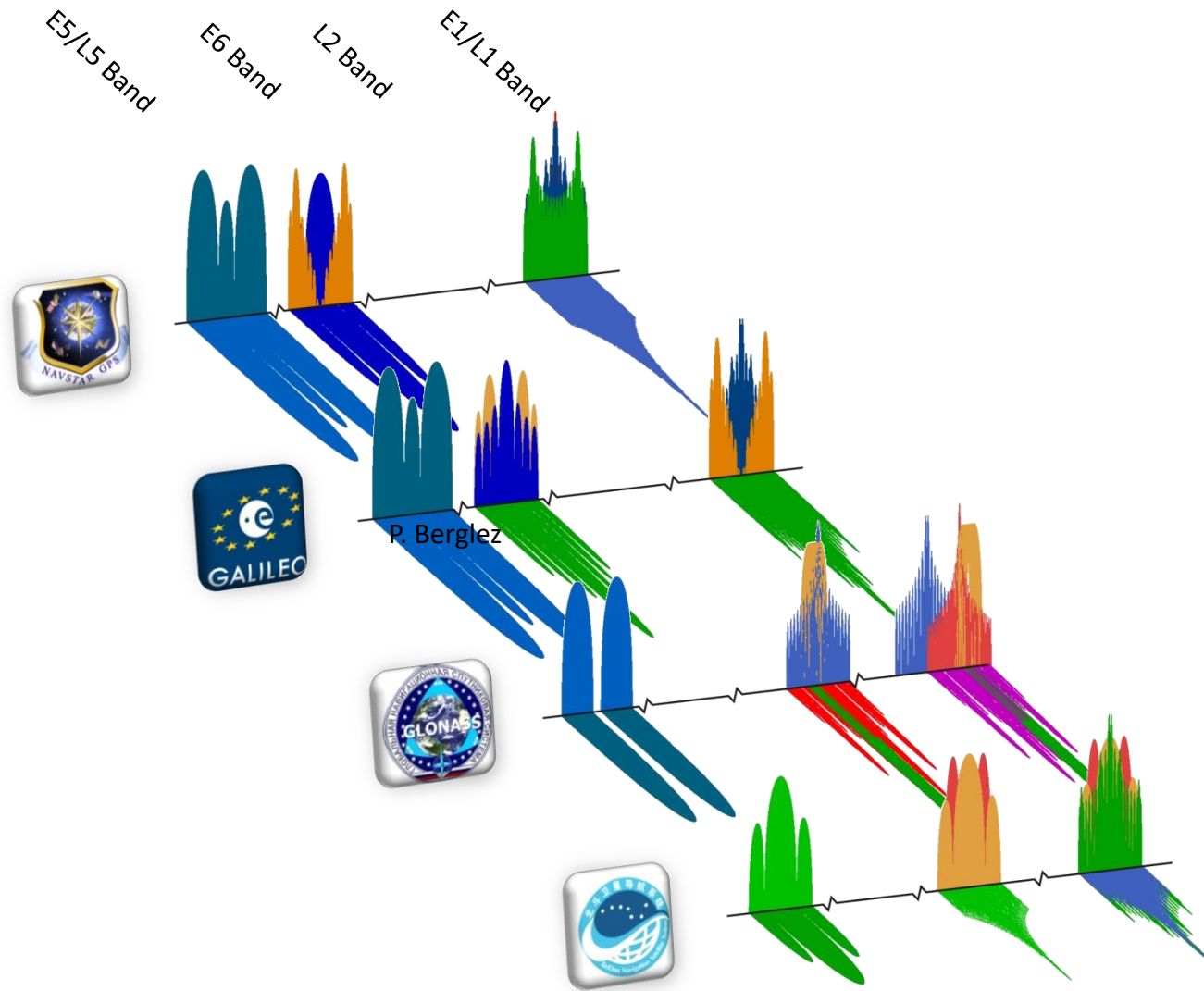
Globale Navigationssatellitensysteme (GNSS)



GPS
GLONASS
Galileo
BeiDou/COMPASS
EGNOS, WAAS, MSAS, NAVIC, SDCM, etc.
QZSS



GNSS signals today



4 global systems and > 40 signals + augmentation systems

Conclusions

By 2029, some 9.5 billion GNSS users/devices are the perspective.

This is the potential of GNSS!

- But provision of reliable and robust positioning solutions is and will be a major challenge!





Thank you for your attention

Dr. Philipp Berglez
Chief Technical Officer

OHB Digital Solutions
Rettenbacher Straße 22
8044 Graz, Austria

Tel: +43-316-890971-14
Mail: philipp.berglez@ohb-digital.at
www.ohb-digital.at



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