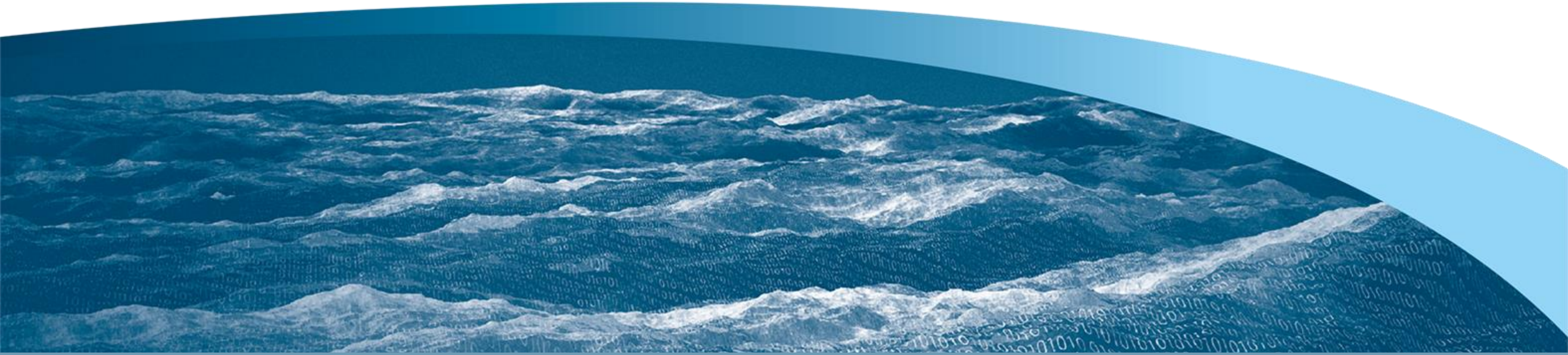
OHB Digital Solutions GmbH
Dr. Philipp Berglez, CTO
Graz, November 25th 2019



GNSS Short and Crisp

An introduction into Global Navigation Satellite Systems

New2Space Workshop

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)

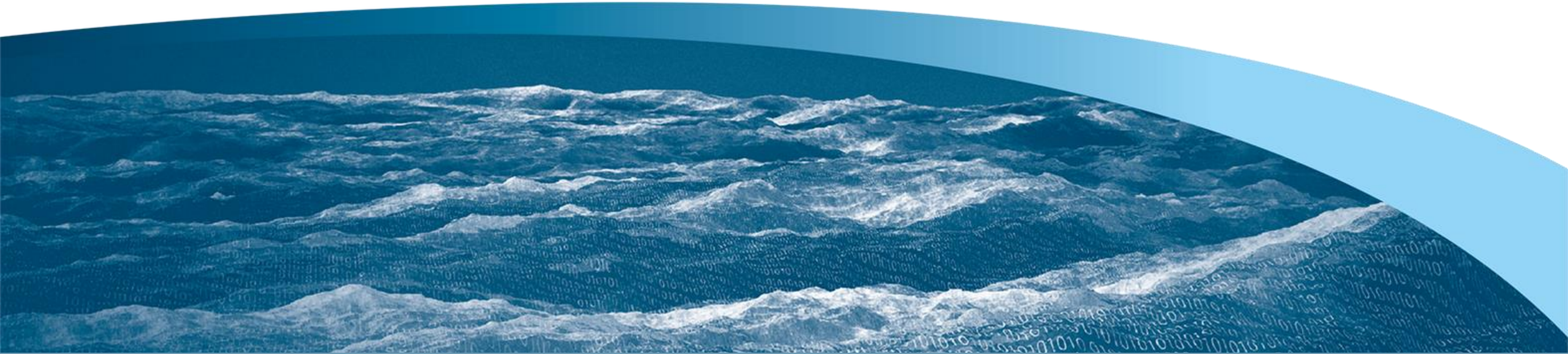
- Project related experience

  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

OHB Digital Solutions GmbH
Dr. Philipp Berglez, CTO
Graz, November 25th 2019



GNSS Short and Crisp

An introduction into Global Navigation Satellite Systems

New2Space Workshop

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

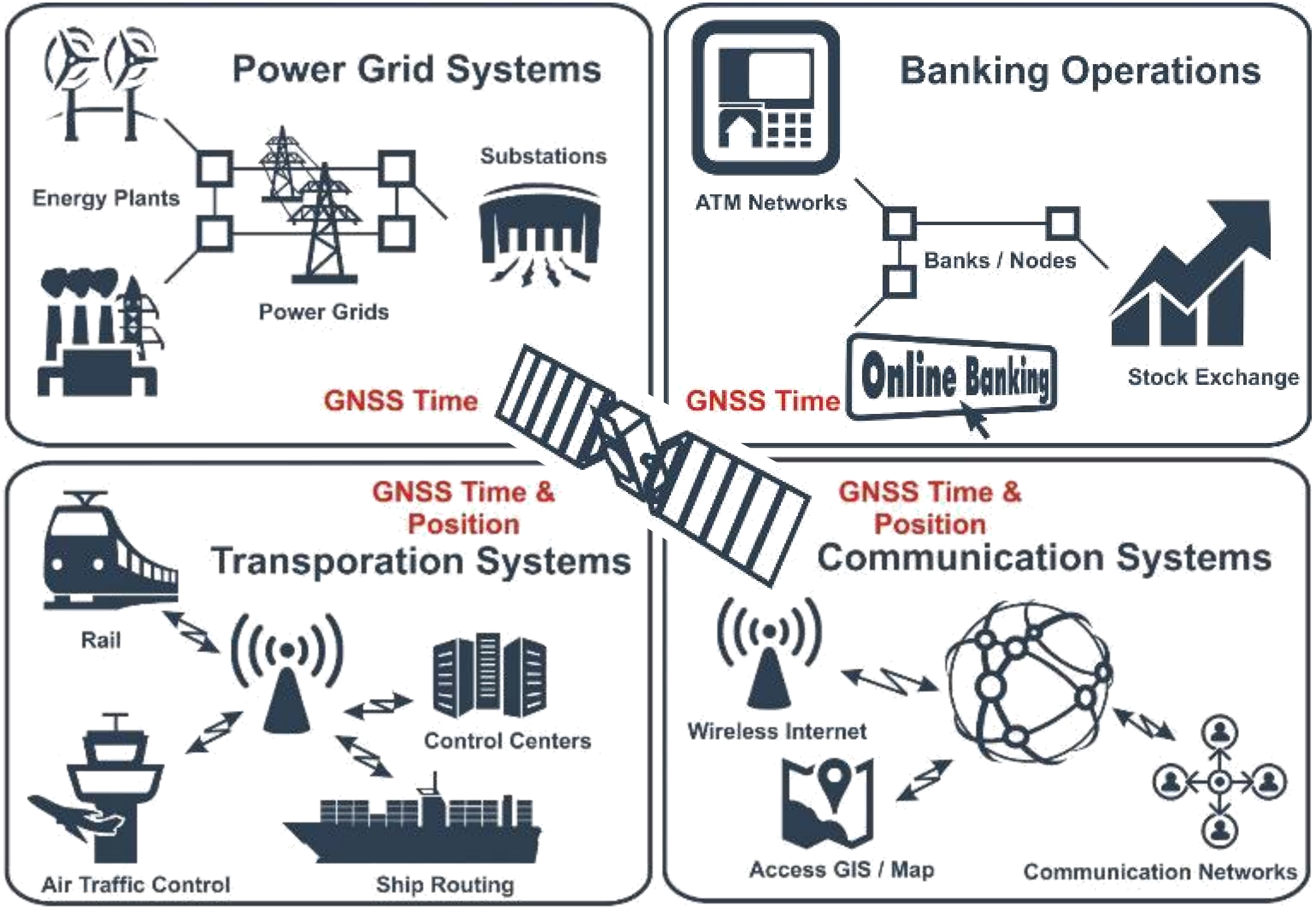
Ref.: GSA Market Report 2019

- 6-7% of gross domestic product in Western countries depends on satellite navigation data?

→ € 800 billion in EU

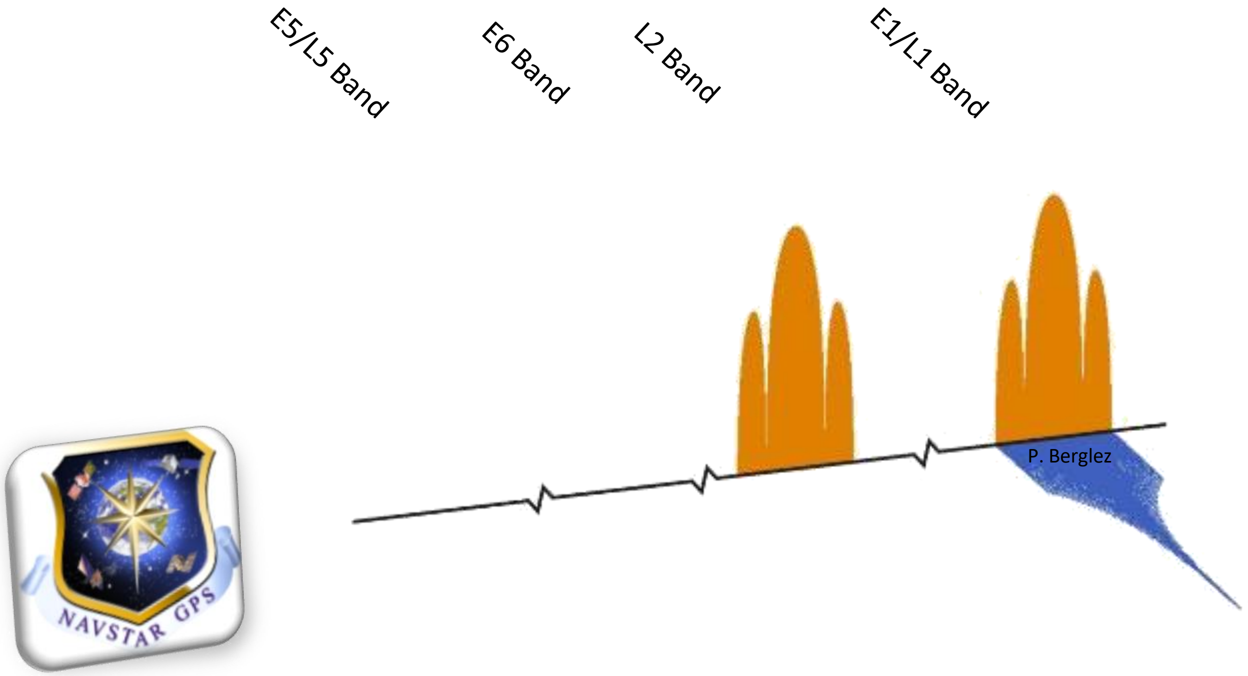
Ref.: European Space Agency 2014

GNSS Applications



Even small disruptions can cause severe errors!

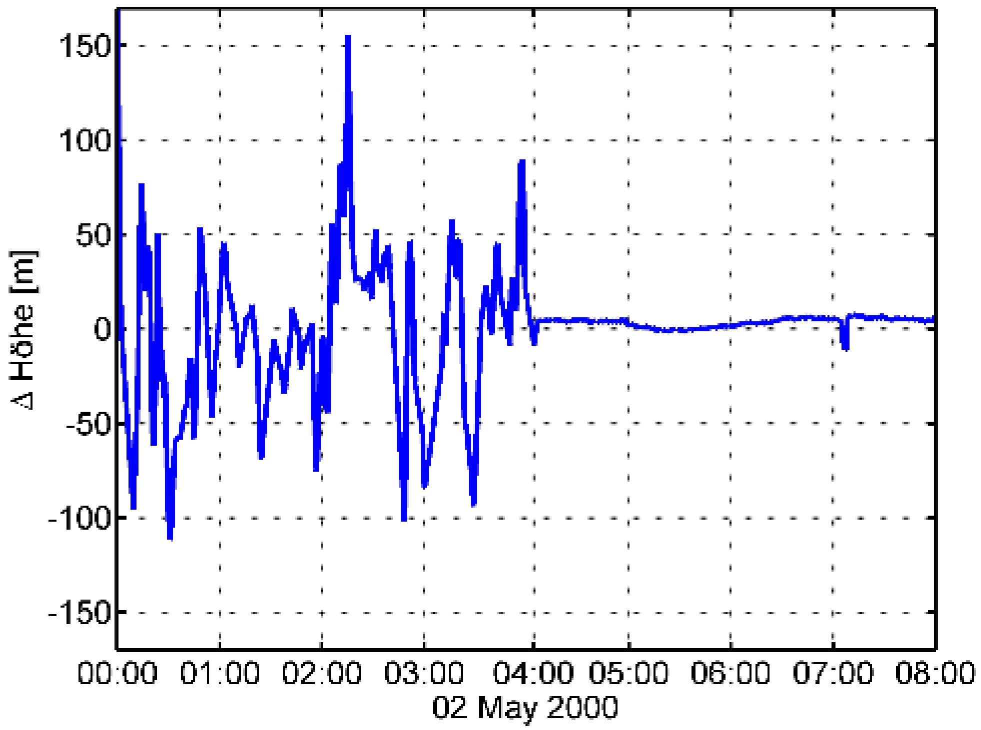
GNSS in 2000



1 system and 1 civil signal

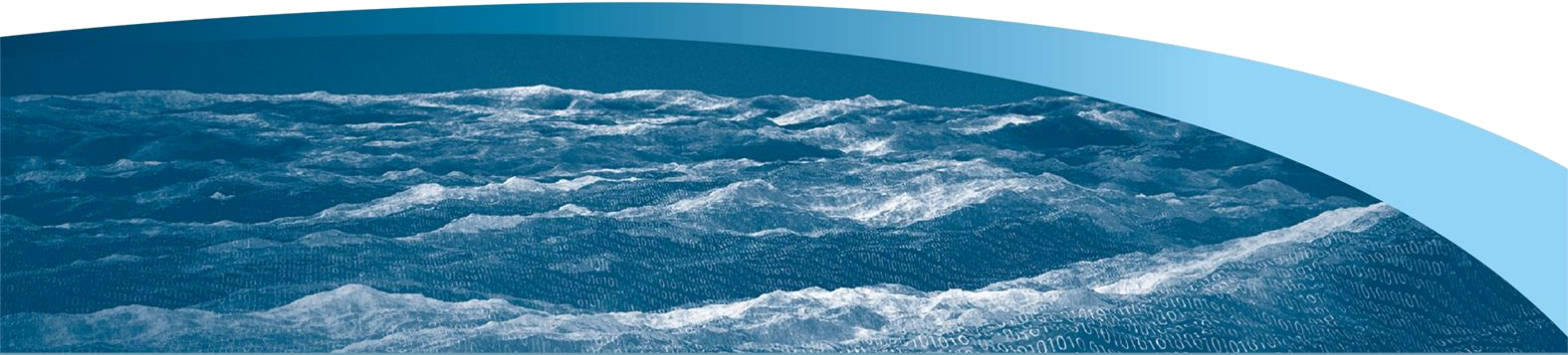
GNSS in 2000

- 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

OHB Digital Solutions GmbH
Dr. Philipp Berglez
New2Space Workshop
November 25th 2019



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)

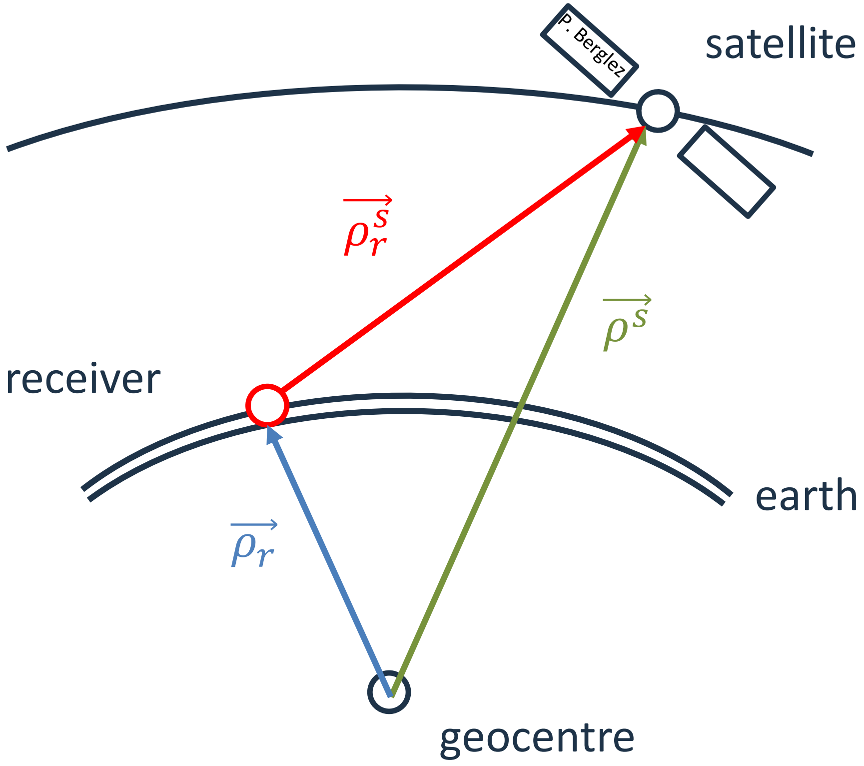
- Global Navigation Satellite System (GNSS)
  - space-based navigation system
  - continuous determination of position, speed and <u>time</u> in a common reference system
  - anywhere on or near the earth
  - all-weather

- 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
  - Orbit determination (receiver position known)
  - Positioning (satellite position known)



- Geometric observations (e.g. ranges) are measured

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

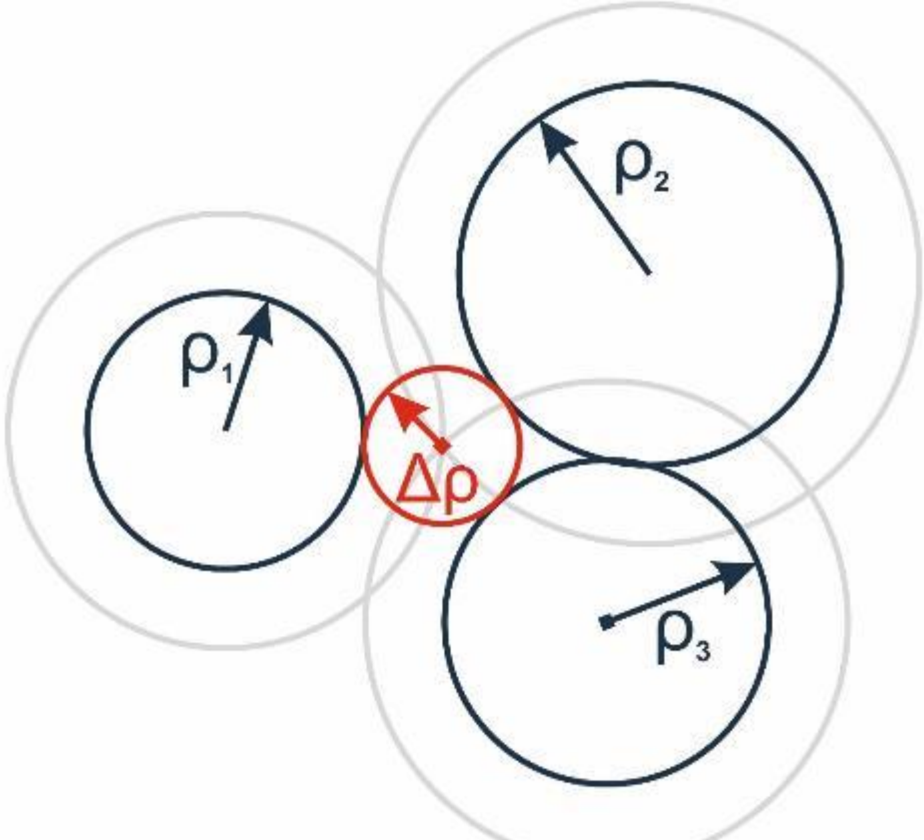
Principle of position determination

- 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

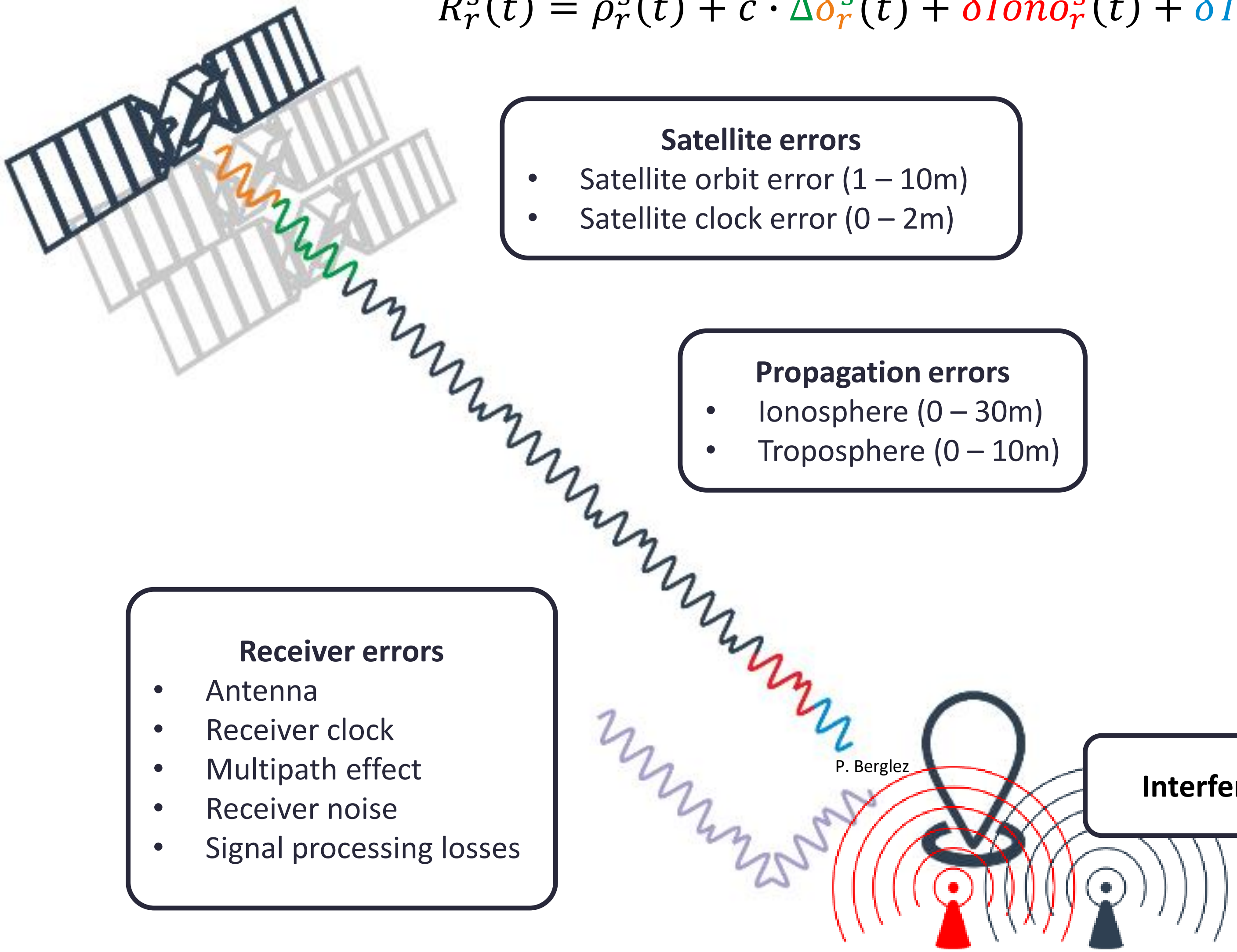
$$R_r^s(t) = \rho_r^s(t) + c \cdot \Delta\delta_r^s(t)$$



P. Berglez

Error sources

$$R_r^s(t) = \rho_r^s(t) + c \cdot \Delta\delta_r^s(t) + \delta Iono_r^s(t) + \delta Tropo_r^s(t) + \epsilon_r^s$$



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

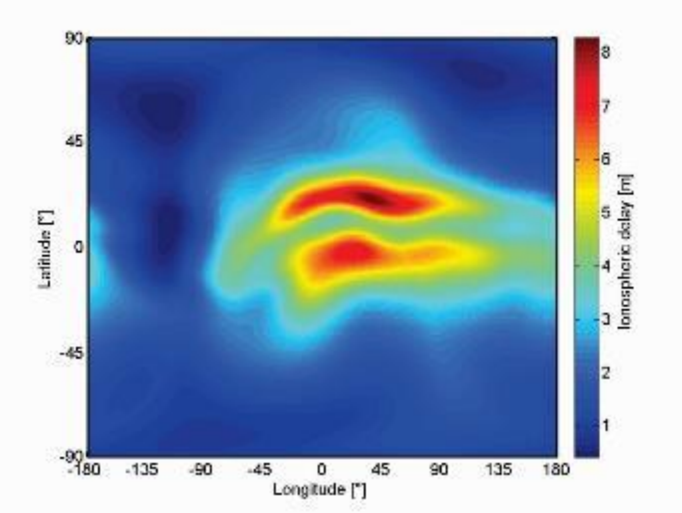
- Broadcast ephemeris
  - Predicted, transmitted via satellite, accuracy of some metres, validity of a few hours
- Almanac data
  - Predicted, transmitted via satellite (real-time), accuracy of some kilometres, validity of several days
- Precise ephemeris
  - Post-processed, high-accuracy (a few centimetres)

- 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 dipersive 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

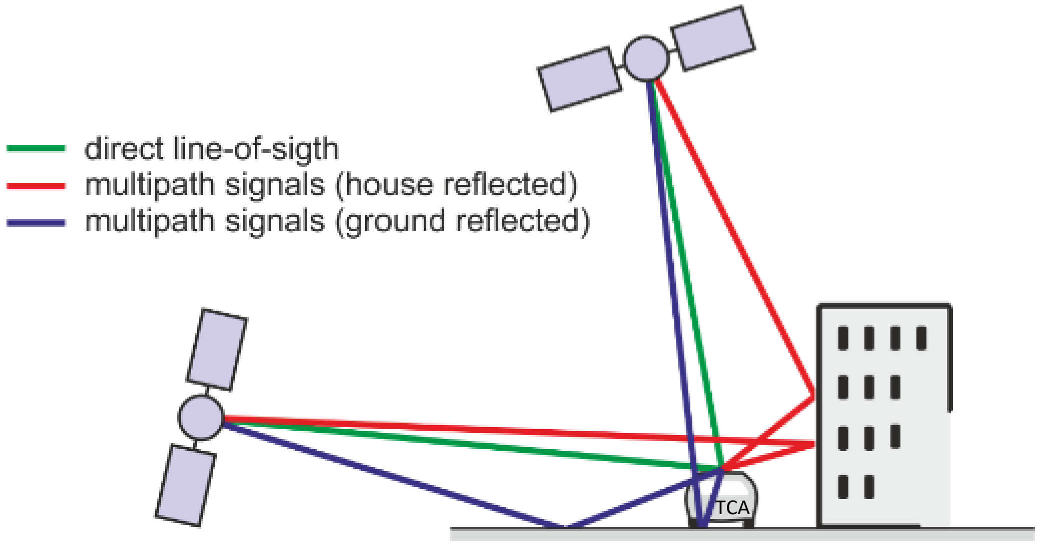
- Troposphere includes the stratosphere and extends to about 50 km above earth
- The troposphere is non-dispersive with respect to radio waves
- Tropospheric refraction is due to atmospheric parameters
  - atmospheric pressure
  - temperatur
  - partial water vapor pressure

- 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



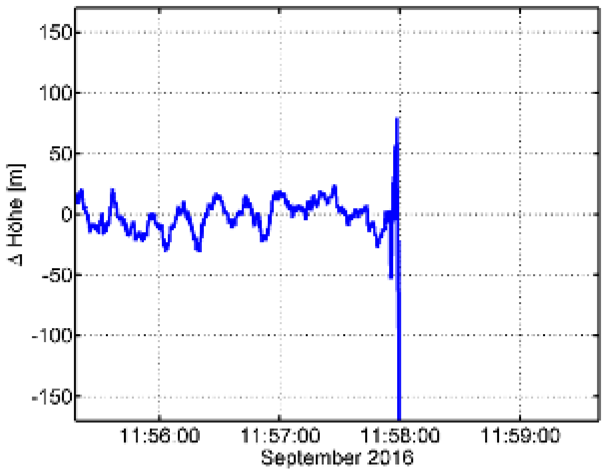
- Pseudorange errors up to 100 m possible
- Mitigation
  - Avoid reflection surfaces close to the antenna (especially tinted glass)
  - Reduction by using improved antennas (ground plates, choke rings)
  - Improved receiver technology

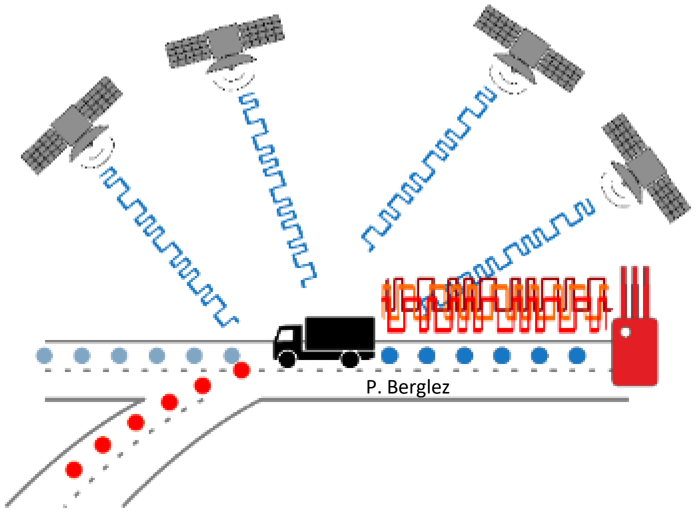
Interference

- 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

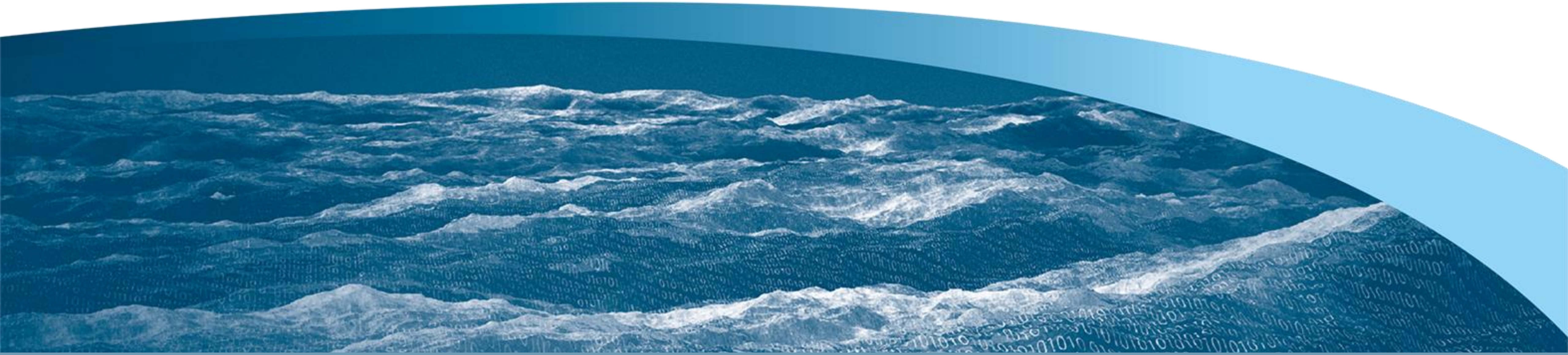
- Intentional interference
  - Jamming
  - Spoofing
  - Meaconing





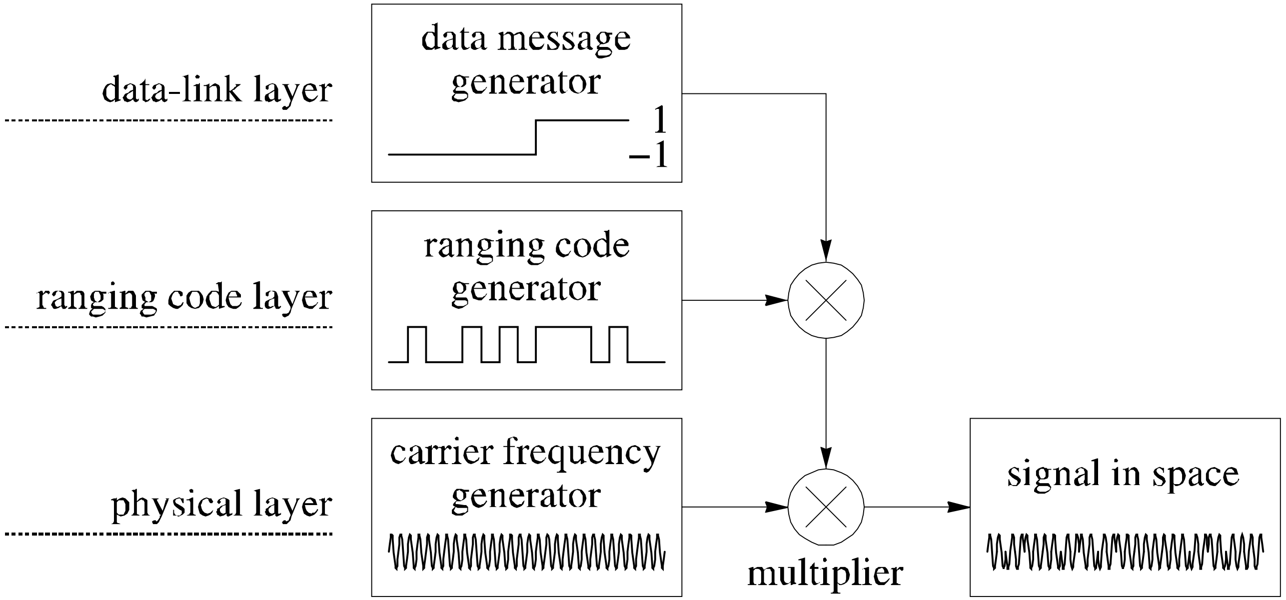
OHB Digital Solutions GmbH
Dr. Philipp Berglez
New2Space Workshop
November 25th 2019

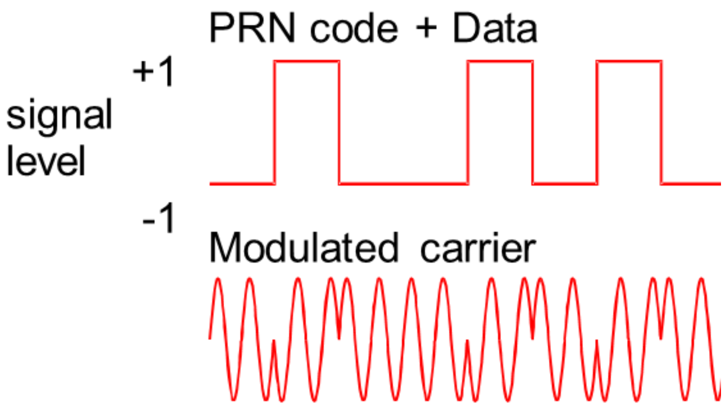
OHB Digital Solutions



Our interface to GNSS – GNSS signals

GNSS signal structure





- Physical layer / carrier frequency
  - Sinusoidal wave → 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

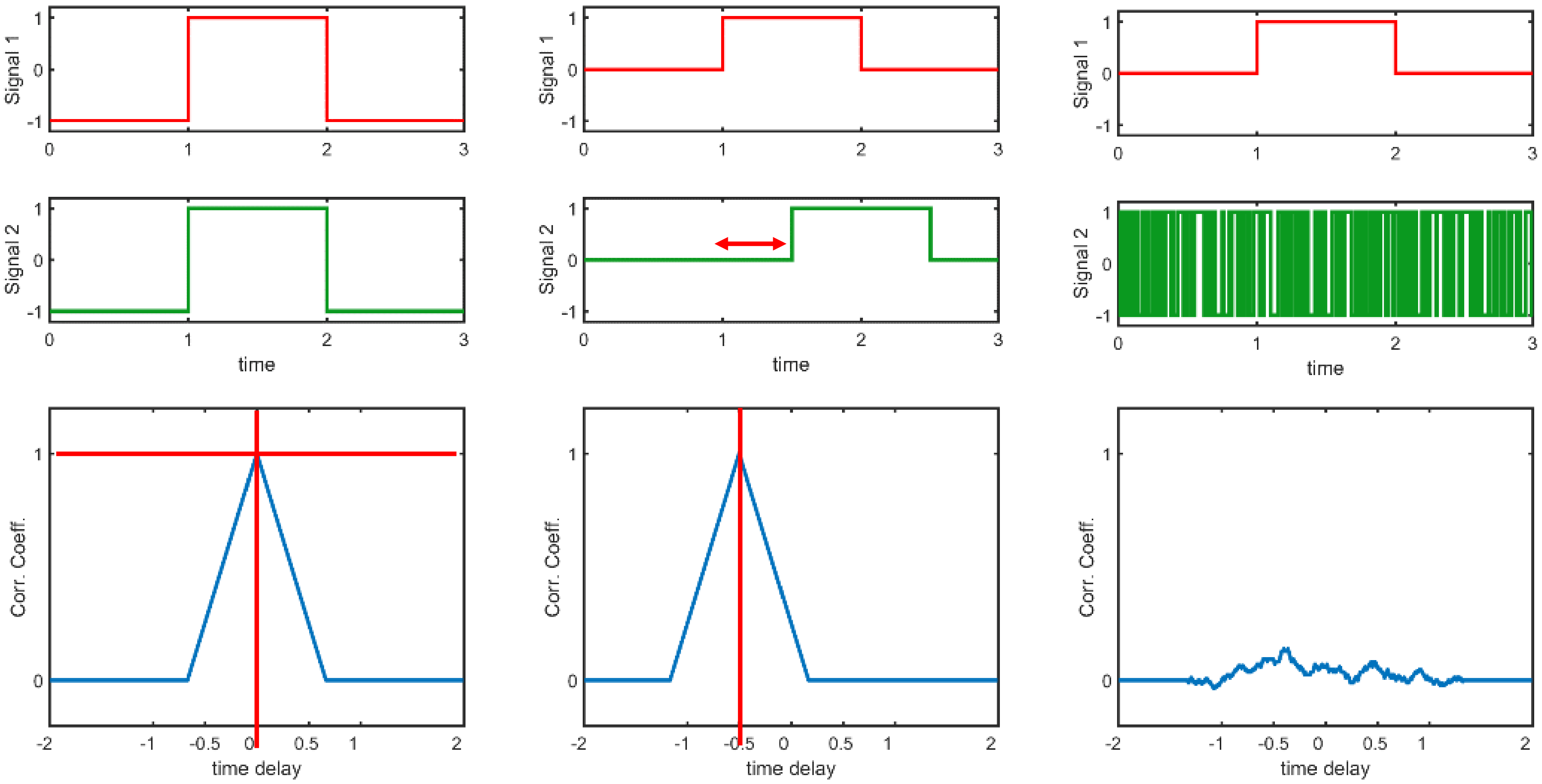
	Power (based on calculations, not measured)	
	Watt	dBW
UHF/VHF transmission (maritime)	25 W	14 dBW
Mobile phone transmission	1 W	0 dBW
Bluetooth low energy	1.0000e-02 W	-20 dBW
Mobile phone reception	1.0000e-04 W	-40 dBW
ZigBee	3.1623e-12 W	-115 dBW
Thermal Noise	1.0000e-14 W	-140 dBW

- 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

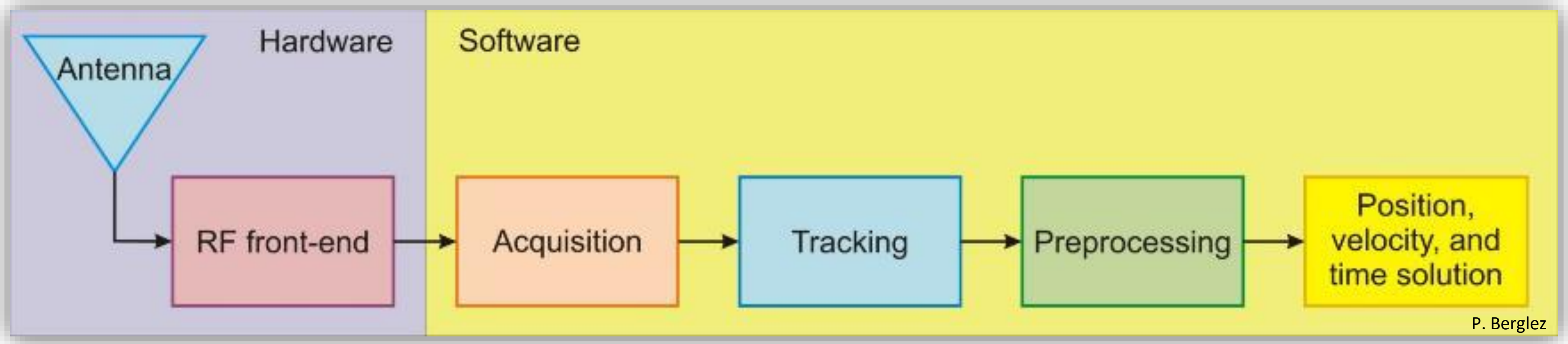
Signal processing basics

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



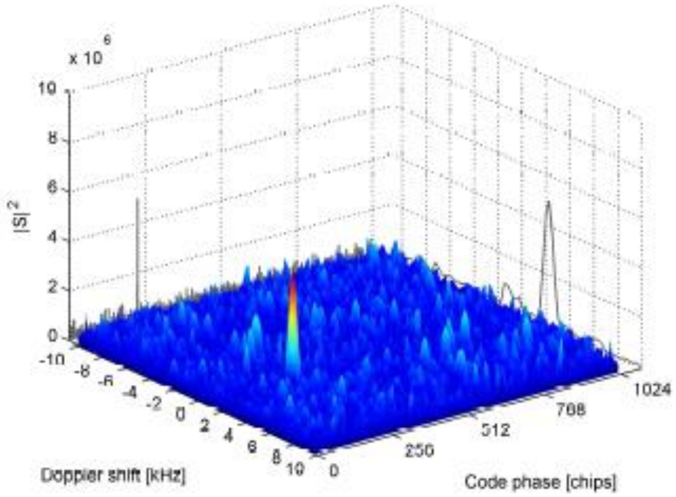
Generic GNSS receiver design

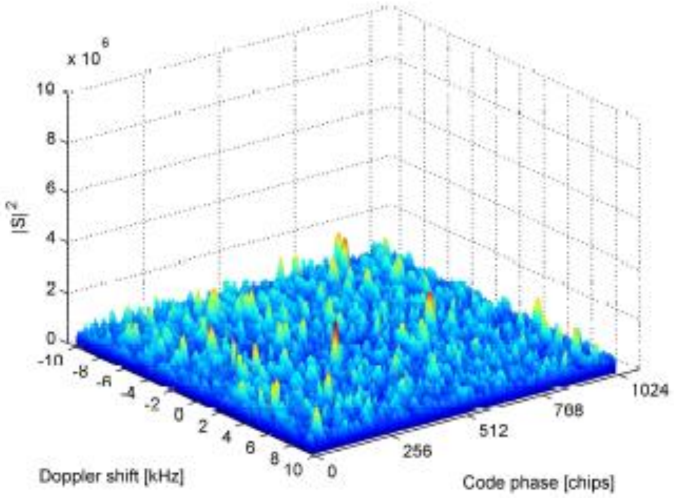
- Purpose of GNSS receiver
  - Receive the signal (antenna)
  - Find visible satellites (acquisition)
  - Track the signal over time (tracking)
    - Split it up into the three components → carrier, PRN code, data
    - Perform runtime measurement (pseudoranges)
  - Decode the navigation data (pre-processing)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



Acquisition

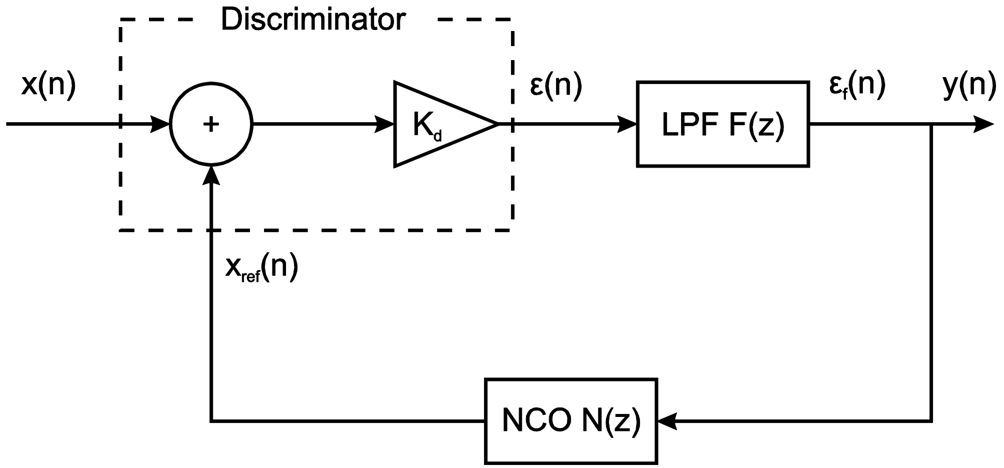
- Acquisition is a search process
  - Decide if satellite signal is present
  - Determine rough estimates of Doppler frequency shift and code phase
- Receiver generates replica signals and correlates them with the incoming signal
  - Since satellites and receiver are moving different code delays and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

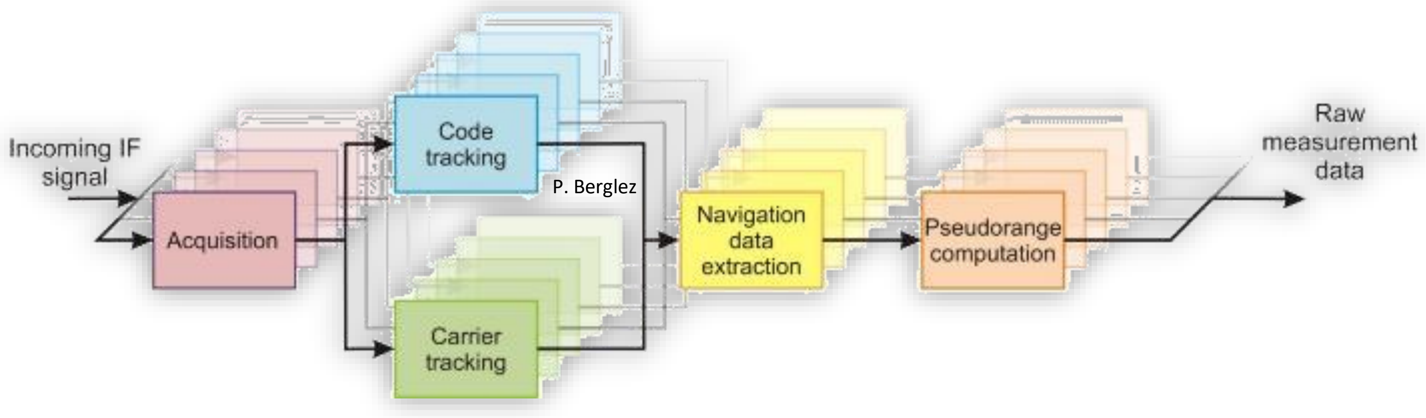




Tracking

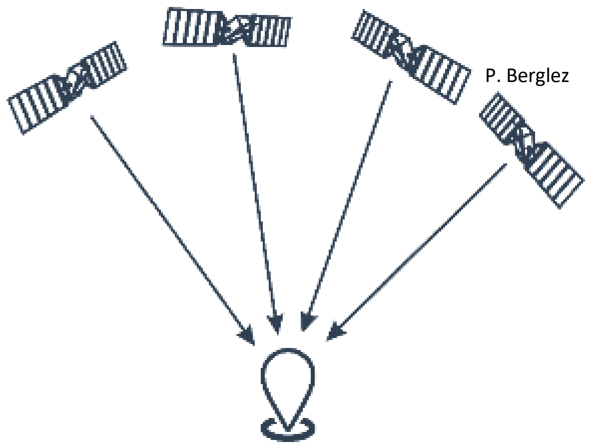
- Keep track of the satellite signal
  - Correlation of incoming signal with signal replica within receiver → tracking loop
- Split up the signal into its components
  - Delay-locked loop (DLL) → PRN code
  - Phase-locked loop (PLL) → carrier
  - Navigation message bits/symbols





P. Berglez

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

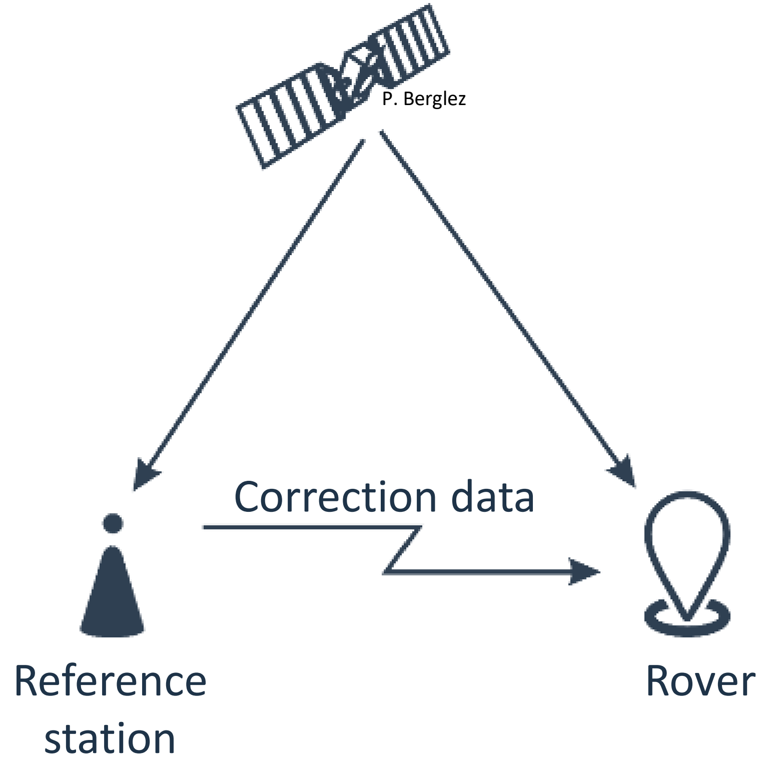
- Single point positioning using satellite-based augmentation systems (SBAS)
    - Most receivers are capable of handling SBAS signals (e.g. EGNOS, WAAS, etc.)
    - Provision of correction data via satellite (more precise than broadcast corrections)
    - Accuracy (95%): ± 3 m horizontal

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)



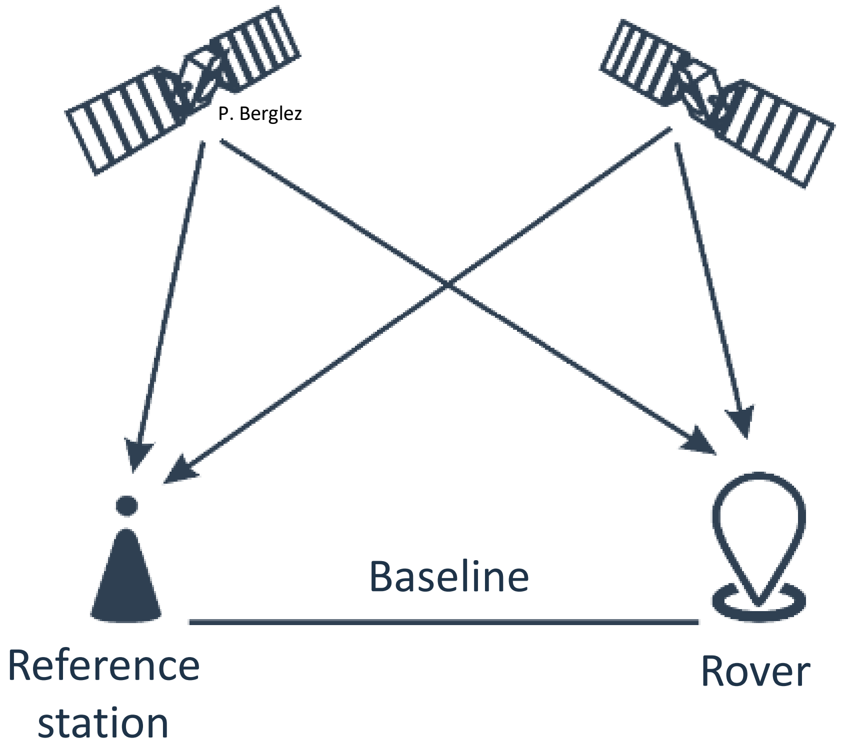
Accuracy (95%): 0.5 – 1 m horizontal

- DGNSS services
  - Use your own reference station (hardware costs)
  - Use commercial service (pay per use, pay per month, ….)

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: ± (5mm + 0.5 ppm)
    - Kinematic: ± (5cm + 5 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)

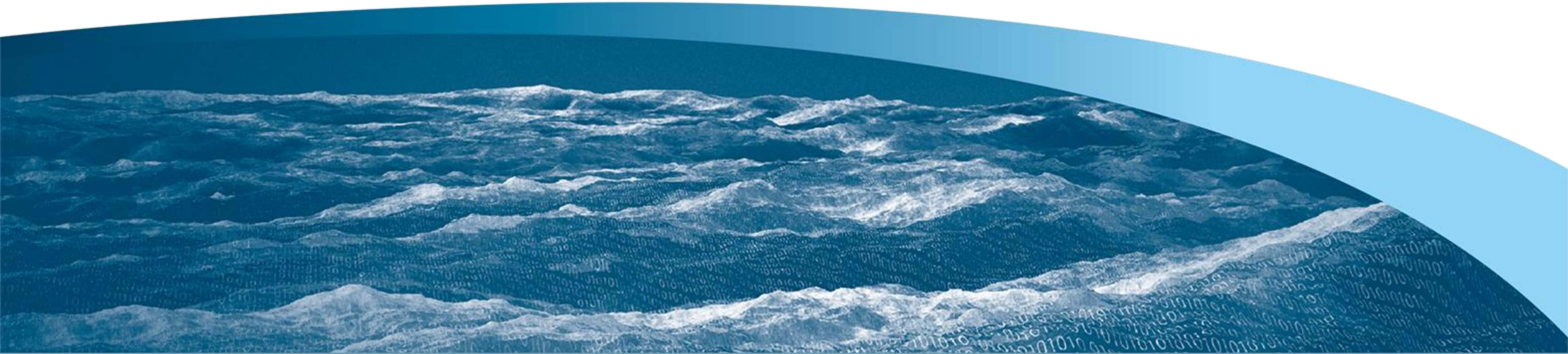
- Precise Point Positioning
  - Cost efficient technique for precise positioning with a single GNSS receiver
  - No need for reference stations
  - Using precise models and data
    - Predicted precise orbits and clocks
    - Iono grid data or dual-frequency measurements
  - Taking into account effects 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)

OHB Digital Solutions GmbH
Dr. Philipp Berglez
New2Space Workshop
November 25th 2019

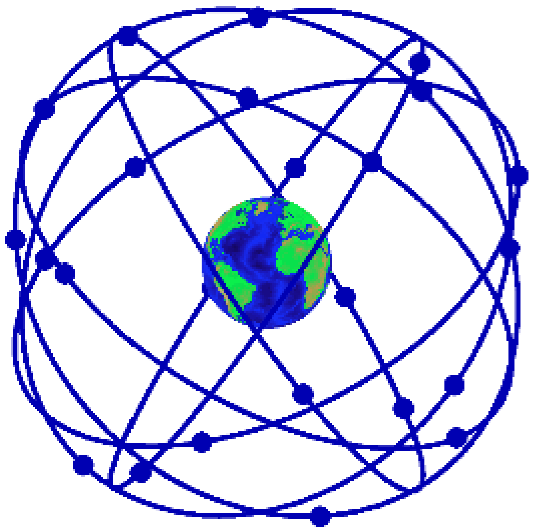
Digital Solutions



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°



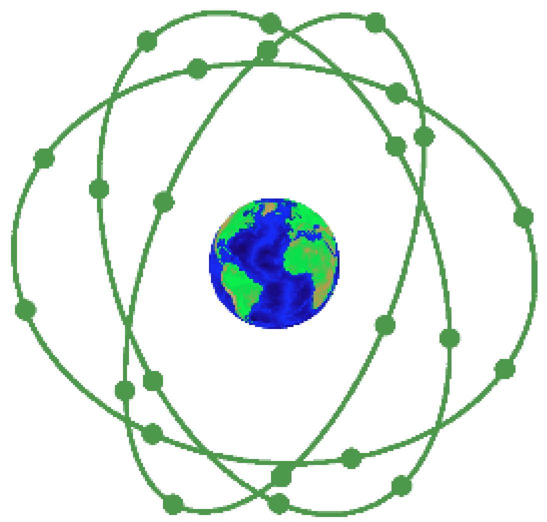
- Signals on 3 different frequencies (5 out of 9 are for civil use)

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

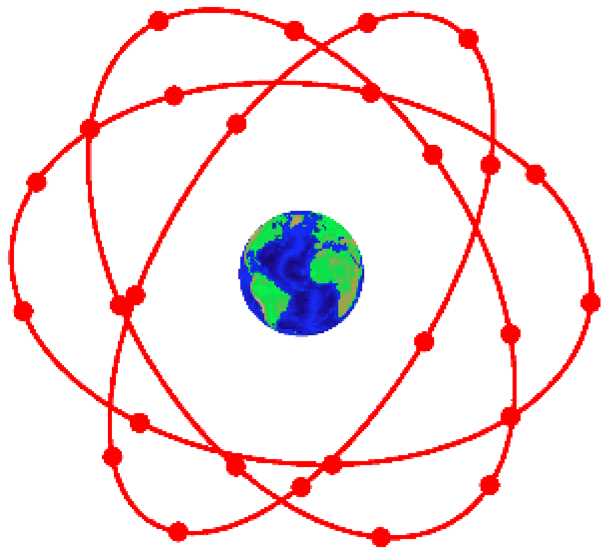
- Currently 27 satellites
  - 3 orbital planes
  - Nearly circular orbits
  - Altitude approx. 19.100 km
  - Inclination of 64.8°



- 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

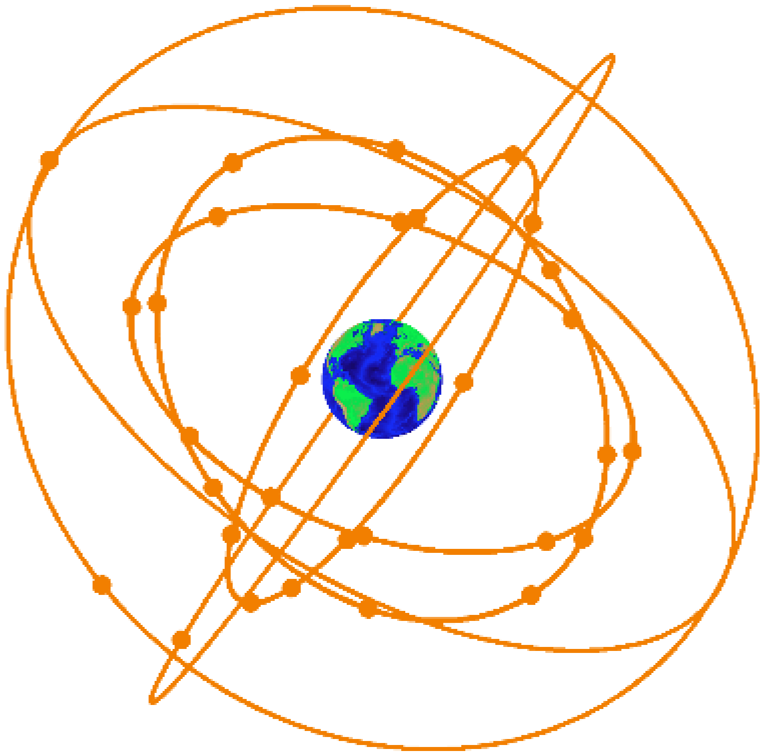
European Union's Global Satellite Navigation System – Galileo (2/2)

- 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

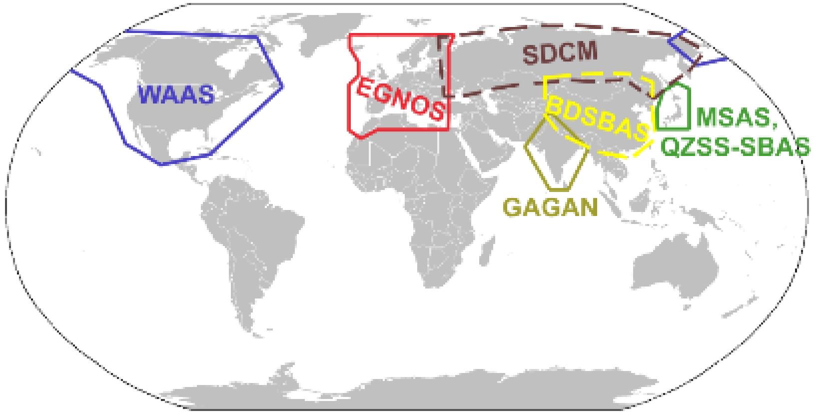
	GPS	Galileo	GLONASS	BeiDou
Operator	USA	Europa	Russia	China
Nominal number of satellites	24+3 MEO	30 MEO	24 MEO	27 MEO, 5 GEO, 3 IGSO
Orbital planes	6	3	3	6
Altitude	20.200 km	23.222 km	19.100 km	21.500 km
Inclination	55°	56°	64.8°	55°
Orbital period	11h 58m	14h 04min	11h 15min	12h 38min
Ground Track 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)

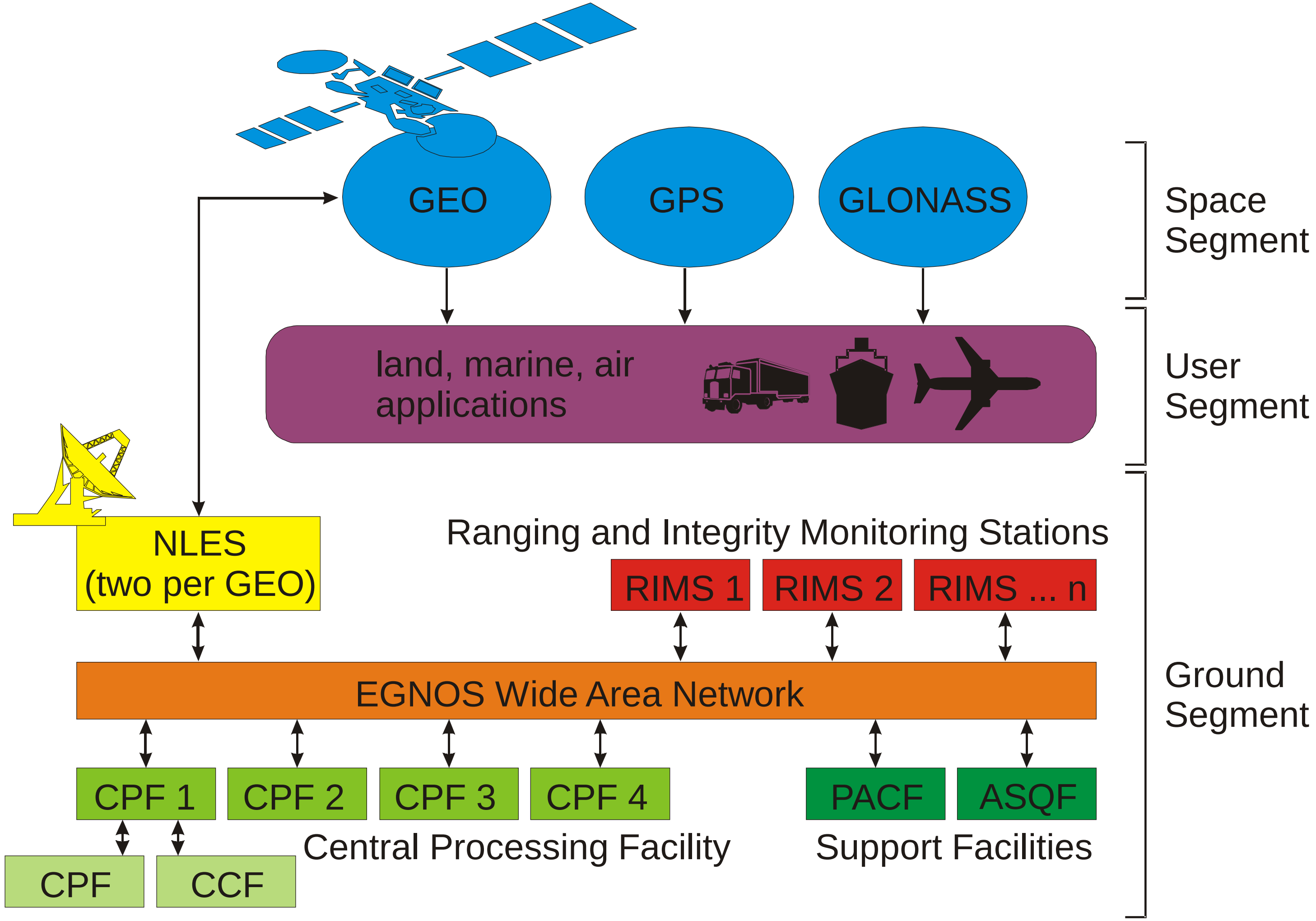


Ref: wikipedia.org

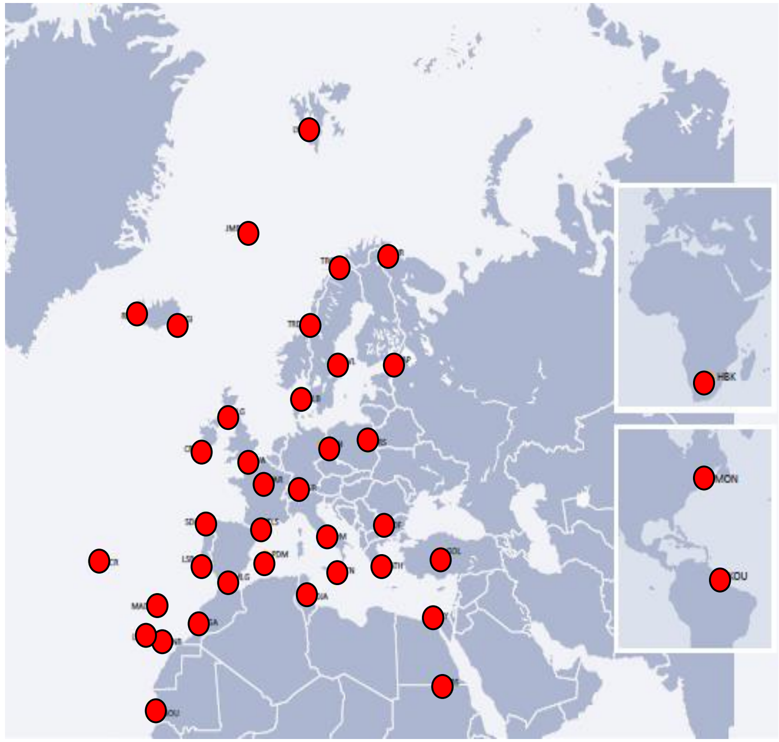
- All systems use the same signal definition → interoperable

- 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)

EGNOS system concept



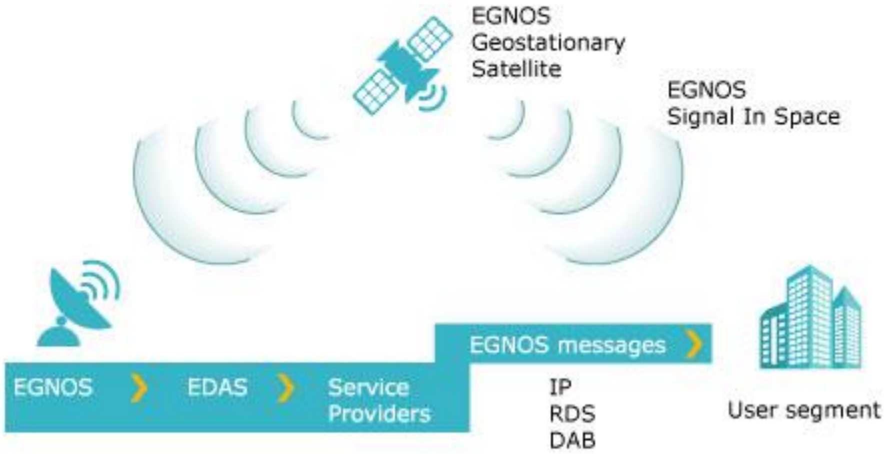
Ref: EGNOS Project Office (2003)



Ref: EGNOS OS SDD (2015)

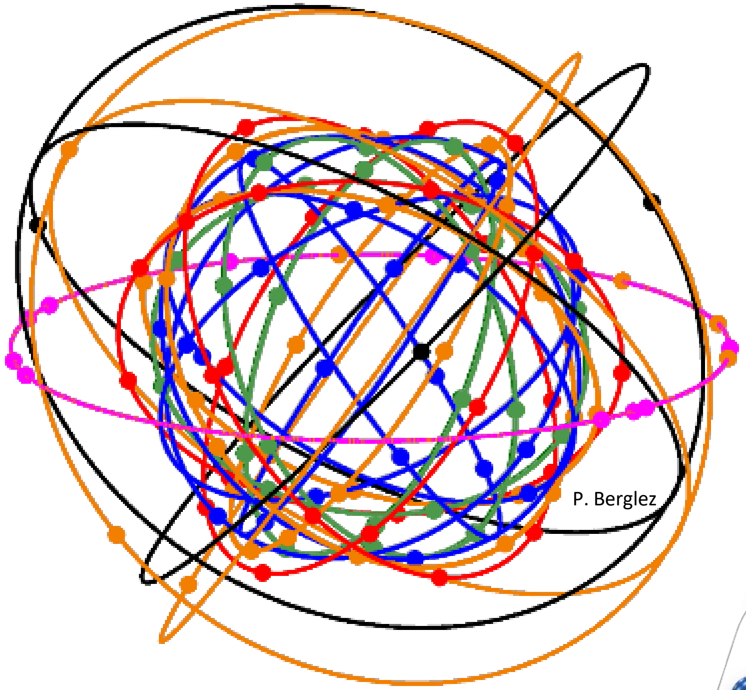
EGNOS Data Access Service (EDAS)

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



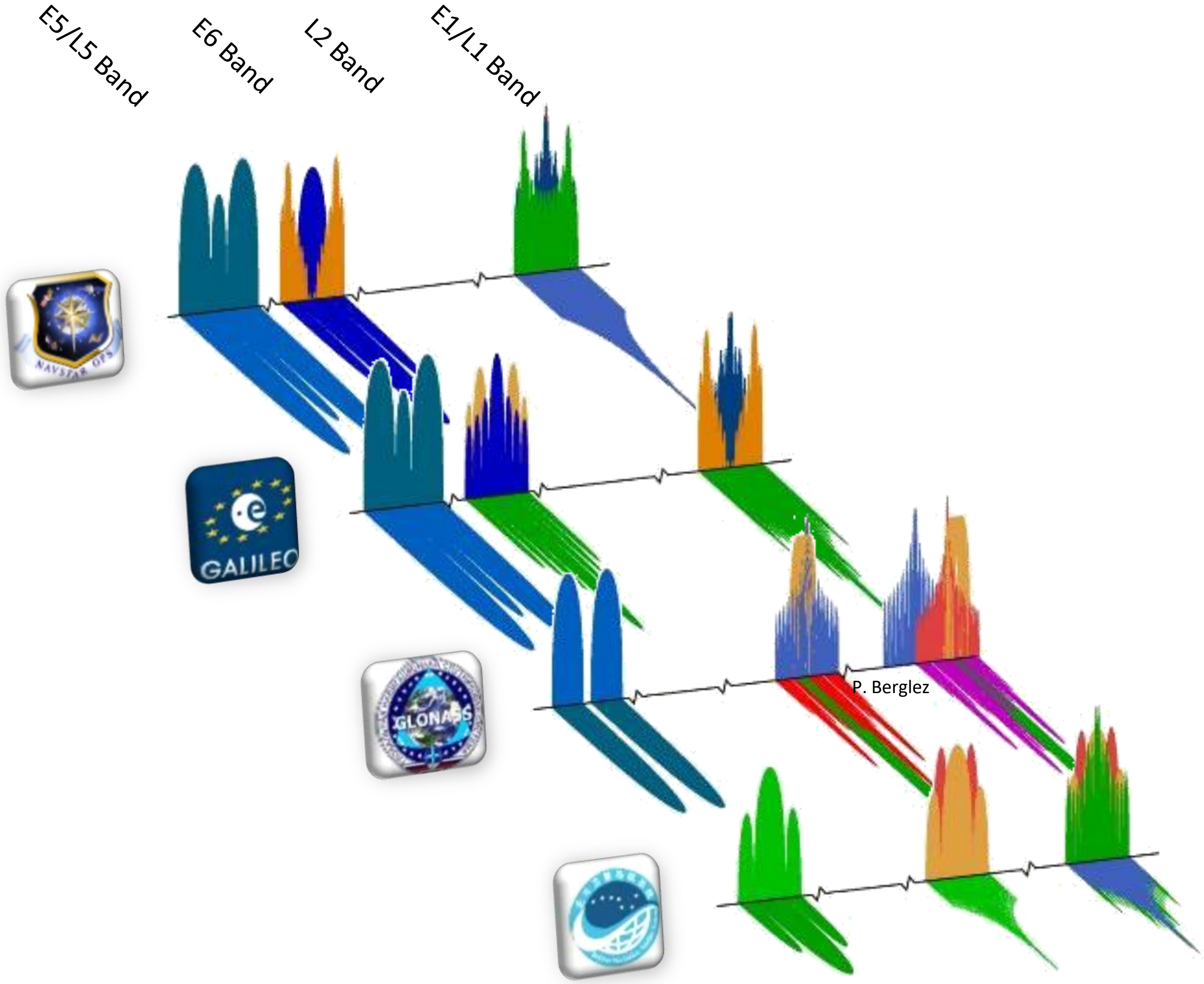
- Different data types
  - GPS, GLONASS and EGNOS GEO observations and navigation data collected by entire network
  - EGNOS augmentation message
  - Differential GNSS and RTK messages (via NTRIP)

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

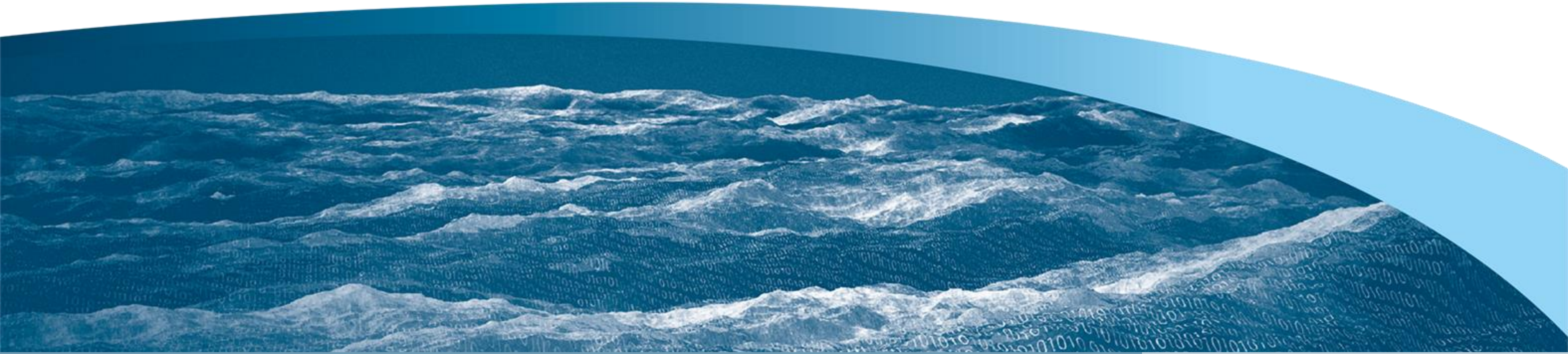
Conclusions

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!

OHB Digital Solutions GmbH
Dr. Philipp Berglez, CTO
Graz, November 25th 2019



GNSS Short and Crisp

An introduction into Global Navigation Satellite Systems

New2Space Workshop

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