GNSS Network-RTK
Today and in the Future
Concepts and RTCM Standards

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GNSS Basic Principle
GNSS Basic Principle

- Position Determination of a single ("Stand-Alone") GNSS Antenna
- Determine Position and Receiver Clock from
  - 4 or more Pseudoranges
    or Carrier Phase Observables
- Position Accuracy
  \[ s_p = \text{PDOP} \times s_R \]
  - good PDOP = 1-2
- \( s_R \) contains all Error Influences
- cm or dm accurate Positioning requires
  - precise Observations (Code / Carrier phase)
  - precise Knowledge of all Error Influences
GNSS Basic Principle

- >= 4 Pseudoranges
- 4 Unknowns (XYZ, t)
- $s_p = \text{PDOP} \times s_R$

ITRF/ETRF

X

Y

Z
GNSS Error Sources
GNSS Error Sources

Satellite HW Delay
Satellite Clock
Satellite Orbit
Satellite Antenna (PCV)

Ionosphere

Troposphere

Multipath

Antenna (PCV)
Receiver Clock
Receiver HW Delay

ITRF/ETRF
GNSS Error Sources

Geometric Distance between „Broadcast“ Satellite Position and Receiving Antenna required for Position Determination in a Global Coordinate Reference System.

Observed Pseudoranges and Carrier Phases are effected by several error components.
One of the key factors influencing the accuracy of GNSS positioning is the satellite orbit. The true satellite position is different from the "broadcast" satellite position. This difference affects the range measurements, which in turn impact the accuracy of the positioning solution. The ITRF/ETRF frame provides a reference for these satellite orbits and positions.
GNSS Error Sources

Satellite Clock

Satellite Orbit

Satellite Clock not perfectly synchronized with GNSS System Time

Ranging Error independent of Receiver/Satellite Geometry and identical for all Signals

ITRF/ETRF
GNSS Error Sources

Satellite HW Delay
Satellite Clock
Satellite Orbit

Different Signal Components are processed through different HW and SW

Ranging Error independent of Receiver/Satellite Geometry and different for different Signals
GNSS Error Sources

Satellite HW Delay
Satellite Clock
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GNSS Error Sources

Satellite HW Delay
Satellite Clock
Satellite Orbit
Satellite Antenna (PCV)

Ionosphere

Dispersive Effect
Carrier Phases Advanced Codes Delayed
(11-Year Solar Cycle)
GNSS Error Sources

- Satellite HW Delay
- Satellite Clock
- Satellite Orbit
- Satellite Antenna (PCV)

Ionosphere

Troposphere

Neutral Atmosphere
Non-Dispersive for GNSS all Signals Delayed

ITRF/ETRF
GNSS Error Sources

- Satellite HW Delay
- Satellite Clock
- Satellite Orbit
- Satellite Antenna (PCV)
- Ionosphere
- Troposphere
- Multipath
- Antenna (PCV)
- Local Effects

ITRF/ETRF
GNSS Error Sources

Satellite HW Delay
Satellite Clock
tropic
Ionosphere
Antenna (PCV)
Receiver Clock

Independent of Receiver/Satellite Geometry
Same Effect for all Satellites and Signals
(4th Unknown in Basic Operation)

ITRF/ETRF
**GNSS Error Sources**

Different Signal Components are processed through different HW and SW ==> Different Signal Delays

Ranging Error independent of Receiver/Satellite Geometry and different for different Signals

Satellite HW Delay
Satellite Clock
Satellite Orbit
Satellite Antenna (PCV)
Receiver Clock
Receiver HW Delay

Multipath
Troposphere
Ionosphere

Differential Signal Components
GNSS Error Sources (HW-Delays)

Signal HW-Delays are causing problems when

- mixing signals (L2P L2C)
- mixing GLONASS receiver types
The variety of available signals with modernized an new GNSS will intensify HW delay problems in the future. Interoperability of systems might suffer and algorithms like conventional Double Differencing will need modifications.
The variety of available signals with modernized new GNSS will intensify HW delay problems in the future. Data exchange between service providers and users will need additional or revised standards (RTCM) if tracking of the same signals cannot be assured.
### Order of Magnitude of some GNSS Error Sources

<table>
<thead>
<tr>
<th>Error Source</th>
<th>Absolute Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite Orbit</td>
<td>2 ... 50m</td>
</tr>
<tr>
<td>Satellite Clock</td>
<td>2 ... 100m</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>0.5 ... &gt;100 m</td>
</tr>
<tr>
<td>Troposphere</td>
<td>0.01 ... 0.5 m</td>
</tr>
<tr>
<td>Multipath Code</td>
<td>m</td>
</tr>
<tr>
<td>Multipath Phase</td>
<td>mm ... cm</td>
</tr>
<tr>
<td>Antenna</td>
<td>mm ... cm</td>
</tr>
</tbody>
</table>

-> total: 5 ... 20 m
Precise Position Determination

- precise position determination requires knowledge of “Sum of all Errors” at the Rovers position with corresponding accuracy \( s_p = \text{PDOP} \times s_R \)
- cm-accuracy requires cm accurate knowledge of “Sum of all Errors”
- Different solution techniques
  - Determination and representation of errors in Observation Space (OS)
    - describes effect of error sources in Range measurements
    - “Observation Space Representation” (OSR)
    - Technique used with current RTCM standards
  - Determination and representation of errors in State Space (SS)
    - Modelling of error source in a „State Space Model“ (SSM) and
    - Representation as State Space Parameters
      - „State Space Representation“ (SSR)
    - Technique used in Postprocessing “Precise Point Positioning” (PPP)
    - and Real-Time (SBAS (WAAS/Egnos), Geo++ GNSMART als PPP-RTK)
Differential GNSS
Differential („DGNSS“) Positioning

- Determine “Sum of Errors”
  at known reference station (XYZ) through
  Subtraction of „known“ Distance to satellites
  → „Corrections“

- transmit corrections
to Rover

- Apply corrections at Rover
  → Reduction of error influences

- Determine position from corrected measurements
  - with Codes („DGNSS“) or
  - with Carrier Phase („RTK“) (resolve Ambiguities)
Differential („DGNSS“) Positioning

Pseudorange:

\[ PR_{\text{gem.}} = R_0 + \epsilon_S + \epsilon_B + \epsilon_I + \epsilon_T + \Delta t + \epsilon_L \]

Error Sources:
- SV Clock+Delays \( \epsilon_S \)
- Satellite(SV) Orbit \( \epsilon_B \)
- Ionosphere \( \epsilon_I \)
- Troposphere \( \epsilon_T \)
- Multipath, Antenna, Noise: \( \epsilon_L = \epsilon_M + \epsilon_A + \epsilon_\phi \)

Reference station => \( R_0 + \Delta t \)

Pseudorange-correction:

\[ PRC = PR - R_0 - \Delta t \]

Receiver Clock + Delay(s)
Using Corrections or Raw Data for Single Rover Positioning

- Positioning of a single rover with GNSS can be done with
  - Corrections to observables (Codes and Carrier Phases) determined at the reference station
  - Baseline processing of raw data (Codes and Carrier Phases) using
    - undifferenced observables
    - single or double differenced observables

- All processing strategies in principle yield equivalent results

- Problem with Corrections and Differencing:
  - Same signal must be tracked by both receivers
DGNSS Error Sources – Spatial Variations

short distance → similar effect of station independent errors 
→ high correlation
DGNSS Error Sources – Spatial Variations

increased distance → increasing differential effect of station independent errors
→ low correlation
DGNSS Error Sources – Station Dependency

lokale effects $\rightarrow$ correction (Calibration), Averaging, Weighting, ... partially systematic influence!
DGNSS/RTK Distance Dependency

“true” Error (lump sum)

Distance dependent Error
(Quality degradation with increasing Distance)

transmitted correction

PRC

Reference

Rover

Distance
## Order of Magnitude of some GNSS Errors

<table>
<thead>
<tr>
<th>Error source</th>
<th>Absolute influence</th>
<th>Relative influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite Orbit</td>
<td>2 ... 50m</td>
<td>0.1 ... 2 ppm</td>
</tr>
<tr>
<td>Satellite Clock</td>
<td>2 ... 100m</td>
<td>0.0 ppm</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>0.5 ... &gt;100 m</td>
<td>1 ... 50 ppm</td>
</tr>
<tr>
<td>Troposphere</td>
<td>0.01 ... 0.5 m</td>
<td>0 ... 3 ppm</td>
</tr>
<tr>
<td>Multipath Code</td>
<td>m</td>
<td>m</td>
</tr>
<tr>
<td>Multipath Phase</td>
<td>mm ... cm</td>
<td>mm ... cm</td>
</tr>
<tr>
<td>Antenna</td>
<td>mm ... cm</td>
<td>mm ... cm</td>
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</table>

-> total:  1...2 cm  +  1...20 ppm

- High spatial correlation
- Local (Calibration)
RTK Networks
Network - RTK

- Principle:
  - Determination of **Sum of Errors** for Observations of Reference Stations for all observed Signals
  - **Interpolation** of Sum of Errors for Position of Rover

- Requirements for RTK:
  - Resolution of *carrier phase ambiguities* between reference stations

- Implementations:
  - Initial: **Simple Models** for resolution of *Ambiguities*
  - sophisticated: **complete state model** for the determination of *individual error components*. 
Determination of distance dependent Errors in RTK Networks

"true" Error-Sum

"Interpolated“ Error for the Rover Position

Error-Sum Ref 1

Error-Sum Ref 2

Location
Network RTK Representation Techniques OSR
Rover receives Raw Data/Corrections for Ref1 and FKP (Flächenkorrekturparameter)
Virtual Reference Station (VRS)

Problem 1: moving VRS?

Rover sends its own Position to Server und receives „Raw Data“/“Corrections“ of the VRS

Problem 2: non-expected Representation Error

Rover sends its own Position to Server und receives „Raw Data“/“Corrections“ of the VRS
MAC Representation
Master Auxiliary Concept

Rover receives Raw Data of the Master Station and Correction-differences for the Aux-Stations (min. 2)
„State Space“ Representation
State Space Repräsentation

- **OSR Dis-Advantages:**
  - No Reduction of reference station dependent Errors (MP, Biases)
  - Only satellites and signals that are tracked at the „Master“-station are usable.
  - necessary update rate of corrections dependent on the error component with highest dynamics (satellite clocks, ionosphere)
    - $\Rightarrow$ bandwidth of communication link
  - Limited spatial validity of corrections

- **Alternative concept: SSR**
  - Transmission of individual error components to the rovers
  - Requirement: Determination of the complete state vector
„State Space“ Representation

SSR Advantages:

- Elimination or high reduction of reference station dependent errors (noise, MP, Biases) through high redundancy within the networks
- better Modeling and Interpolation for individual errors (more realistic physical models)
- independent from single reference stations, i.e. all satellites and signals are usable, which are tracked from a sufficient number of stations.
- The data rate for corrections can be optimized for different state parameters. (i.e.. 10 seconds instead of 1 second)
  - Optimization of communication bandwidth
- Broadcast of Parameters
- Scalability of derived services

SSR Disadvantages

- Higher implementation efforts
- Higher standardization efforts
Standardization
Standardization - RTCM

- RTCM SC104 standards for RTK Applications
  („Radio Technical Commission For Maritime Services“):
  - RTCM 2.0 – 1990 – DGPS
  - RTCM 2.1 – 1994 – RTK Extension
  - RTCM 2.2 – 1998 – DGLONASS + GLONASS RTK
  - RTCM 2.3 – 2001 – Improvements: mm-Coordinates, Antenna-ARP,...
  - RTCM 3.0 – 2004 – compressed Raw Data Format (Bandwidth) (RTK)
  - RTCM 3.1 – 2006 – Network-RTK MAC (GPS only)
  - RTCM 3.1 (Amendment 1) – 2007 – Transformation Messages
  - RTCM 3.1 (Amendment 2) – 2007 – Network RTK Residual Messages, Non-Physical Reference Station (VRS)
  - NTRIP 1.0 – 2004 – „Networked Transport of RTCM via Internet Protocol“
RTCM SC104

- Working Groups
  - Network-RTK: GLONASS MAC, FKP (Interoperability Testing)
  - „Version 3“: new Raw Data Messages for multiple GNSS Signals
  - GLONASS: Interoperability Problems, Biases
  - Galileo: Galileo Raw Data Messages
  - Private Services: Encryption (Interoperability Testing)
  - RSIM: Integrity of Single Reference Stations
  - Internet Protocol: NTRIP2.0 (UDP, full HTTP-Compatibility)
  - State Space: 1st Step: Satellite Clock/Orbit/Bias Messages (Interoperability Testing)
RTCM SC104 – State Space Parameter

Satellite signal delay
Satellite clock error
Satellite orbit error
Satellite antenna PCV
Ionosphere
Troposphere
Multipath
Antenna (PCV)
Rcvr clock error
Rcvr signal delay
RTCM SC104 - State Space WG – Schedule

- Start May 2007 - Goal: Development of
  - Concepts and Messages for all Accuracies:
    - DGNSS and RTK (Single- and Multi-Frequency)
  - Step 1: DF-RT-PPP („Dual Frequency – Real Time - PPP)
    - Message(s) for precise Satellite-Orbits and -Clock (incl. Biases)
  - Step 2: SF-RT-PPP („Single Frequency – Real Time - PPP)
    - Messages for the vertical Ionospheric effect (VTEC)
  - Step 3: RTK-PPP („Real Time Kinematic - PPP)
    - Slant Ionospheric influence (STEC),
    - Troposphere, Satellite Phase-Delays,
    - Carrier Phasen Ambiguities („Integer Nature“)
- (PPP = Precise Point Positioning)
State Space Representation

Application/Transition

- conventional OSR with RTCM Rover
- SSR with conventional

**OSR Rover**

- Conversion of SSR into standardized OSR format (RINEX, RTCM)
  - in Service Center
  - or at Rover

- Direct usage of SSR in **SSR rover**

- SSR concept operationally applied with Geo++ GNSMART
Reverse / Inverse
DGNSS
RTK
Reverse/Inverse DGNSS/RTK

- **Principle:**
  - Position Determination at Server instead of Rover
    - Rover sends Raw Data (Pseudoranges, Carrier Phases) to Server
    - Server computes DGNSS or RTK Position while using Information (SSR) from a RTK-Network
    - Server sends Position back to the Rover and/or other applications

- **Requirements:**
  - Duplex Communication
  - Reverse/Inverse Server
  - Rover with Reverse/Inverse Client Functionality (PDA, Mobile Phone,...)
Reverse/Inverse DGNSS/RTK

• Advantages:
  – Optimum „Performance“
    • Consistency of Algorithms with Networking Software
    • Rover-Receiver just a „Sensor“
      – No sophisticated algorithms required
        • Simple Single Frequency Receivers
        • „old“ Receivers (no firmware updates anymore)
        • Save Software Options
  • Requirements:
    – Duplex Communications
    – Reverse/Inverse Server
    – Rover with Reverse/Inverse Client Functionality (PDA, Handy)
New GNSS and Modernization

- **GPS**: 3 Carrier-frequencies and new (civil) Codes (L2C, L5, L1C)
- **GLONASS**: „full Constellation“ in 2009/2010
- **GLONASS**: 5 Frequencies L3 (FDMA), $f_{L3}(i) = 94/125 \cdot f_{L1}(i)$ and
  - GPS-L1 (CDMA) GPS-L5 (CDMA)
- **Galileo**: operational in 201?
- **Galileo** up to 5 Frequencies with different signals
- **China**: Compass GNSS 30(?) MEO's und 3 GEO's
- In total there will be **75-105 GNSS Satellites**!
- **RINEX 3.0** defines 40+ different Code Signals and Combinations on 7+ Carrier-Frequencies
- **SBAS Systems** with L1/L5 (Egnos, WAAS, MSAS, QZSS...)
Geo++® GNSMART

thank you for your attention

... artist view of Geo++® building in Garbsen