Combined Analysis of Observations from GPS and GLONASS

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Séminaires „Temps & Espace“

March 19, 2012, Paris

Outline

- Global Navigation Satellite Systems
  - Principle of navigation
  - Observation equation
  - System overview
  - Why multi-GNSS?

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- Combined GPS/GLONASS analysis
  - Motivation of study
  - Design and setup
  - Results

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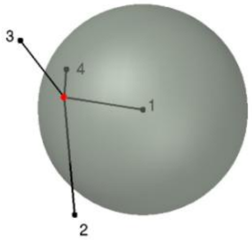
Principle of Navigation

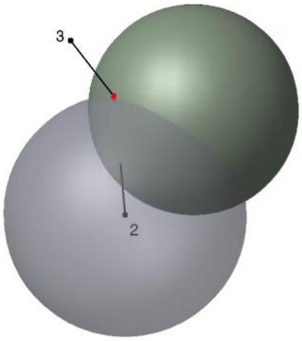
- Satellite as fixed point in space
- Distance satellite → observer
  - Measurement of signal travel time



- 1 satellite
  - Position: surface of sphere

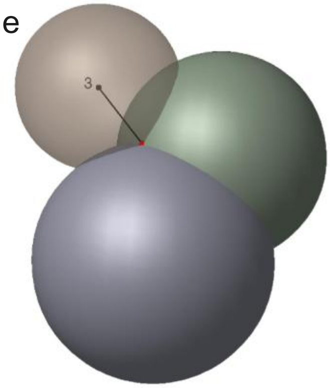
Principle of Navigation

- Satellite as fixed point in space
- Distance satellite → observer
  - Measurement of signal travel time
- 2 satellites
  - Position: circle



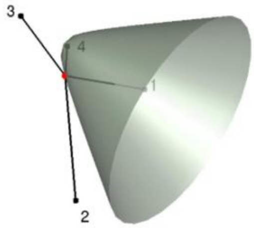
Principle of Navigation

- Satellite as fixed point in space
- Distance satellite → observer
  - Measurement of signal travel time
- 3 satellites
  - Position: point



Principle of Navigation

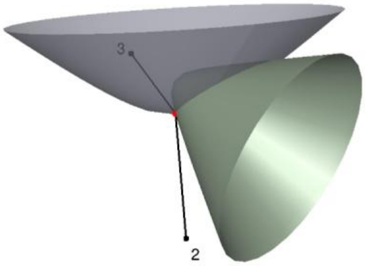
- Clocks not perfectly synchronized
- Biased distance satellite → observer
  - Difference of two distances free of receiver clock error



- 2 satellites
  - Position: hyperboloid

Principle of Navigation

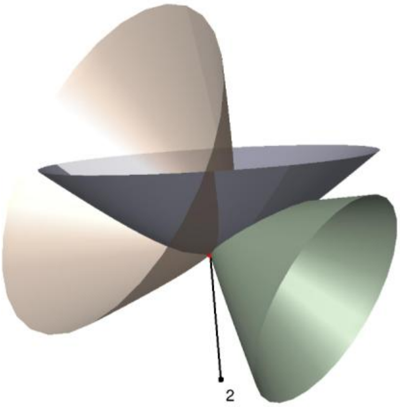
- Clocks not perfectly synchronized
- Biased distance satellite → observer
  - Difference of two distances free of receiver clock error



- 3 satellites
  - Position: intersection line

Principle of Navigation

- Clocks not perfectly synchronized
- Biased distance satellite → observer
  - Difference of two distances free of receiver clock error



- 4 satellites
  - Position: point

Observation Equation

- Modeling „distance“ satellite → observer

$$
\begin{aligned}
\mathcal{C} = {} & \left|(\boldsymbol{R}+\boldsymbol{E}+\boldsymbol{Y})-(\boldsymbol{r}+\boldsymbol{e}+\boldsymbol{y})\right| \\
& + c\,S - c\,s + c\,B - c\,b + \mathcal{T} + \mathcal{I} \\
& + \mathcal{U} + \mathcal{M} + \mathcal{E}
\end{aligned}
$$

Observation Equation

- Modeling „distance“ satellite → observer

$$\mathcal{C} = \left|\boxed{(\boldsymbol{R}+\boldsymbol{E}+\boldsymbol{Y})} - (\boldsymbol{r}+\boldsymbol{e}+\boldsymbol{y})\right| + c\,S - c\,s + c\,B - c\,b + \mathcal{T} + \mathcal{I} + \mathcal{U} + \mathcal{M} + \mathcal{E}$$

- Signal reception point
  - Position of observer
  - Antenna eccentricity
  - Antenna phase center

Observation Equation

- Modeling „distance“ satellite → observer

$$\mathcal{C} = \left|(\boldsymbol{R}+\boldsymbol{E}+\boldsymbol{Y}) - \boxed{(\boldsymbol{r}+\boldsymbol{e}+\boldsymbol{y})}\right| + c\,S - c\,s + c\,B - c\,b + \mathcal{T} + \mathcal{I} + \mathcal{U} + \mathcal{M} + \mathcal{E}$$

- Signal transmission point
  - Position of satellite
  - Antenna eccentricity
  - Antenna phase center

Observation Equation

- Modeling „distance“ satellite → observer

$$\mathcal{C} = \left|(\boldsymbol{R}+\boldsymbol{E}+\boldsymbol{Y}) - (\boldsymbol{r}+\boldsymbol{e}+\boldsymbol{y})\right| + c\,S - c\,s + c\,B - c\,b + \mathcal{T} + \mathcal{I} + \mathcal{U} + \mathcal{M} + \mathcal{E}$$

- Reception and transmission point
  - Given in same system
  - Transformation Earth-fixed ↔ inertial
  - Earth orientation parameters

Observation Equation

- Modeling „distance“ satellite → observer

$$\mathcal{C} = \left|(\boldsymbol{R}+\boldsymbol{E}+\boldsymbol{Y}) - (\boldsymbol{r}+\boldsymbol{e}+\boldsymbol{y})\right| + c\,S - c\,s + c\,B - c\,b + \mathcal{T} + \mathcal{I} + \mathcal{U} + \mathcal{M} + \mathcal{E}$$

- Clock synchronization errors
  - Station and satellite
  - Order of magnitude: < milliseconds

Observation Equation

- Modeling „distance“ satellite → observer

$$\mathcal{C} = \left|(\boldsymbol{R}+\boldsymbol{E}+\boldsymbol{Y})-(\boldsymbol{r}+\boldsymbol{e}+\boldsymbol{y})\right| + c\,S - c\,s + \boxed{c\,B - c\,b} + \mathcal{T} + \mathcal{I} + \mathcal{U} + \mathcal{M} + \mathcal{E}$$

- Biases
  - Caused by station and satellite hardware
  - Order of magnitude: nanoseconds

Observation Equation

- Modeling „distance“ satellite → observer

$$\mathcal{C} = \left|(\boldsymbol{R}+\boldsymbol{E}+\boldsymbol{Y})-(\boldsymbol{r}+\boldsymbol{e}+\boldsymbol{y})\right| + c\,S - c\,s + c\,B - c\,b + \boxed{\mathcal{T} + \mathcal{I}} + \mathcal{U} + \mathcal{M} + \mathcal{E}$$

- Atmospheric effects
  - Troposphere, ionosphere
  - Order of magnitude: meters

Observation Equation

- Modeling „distance“ satellite → observer

$$\begin{aligned}\mathcal{C} = &\left|(\boldsymbol{R}+\boldsymbol{E}+\boldsymbol{Y})-(\boldsymbol{r}+\boldsymbol{e}+\boldsymbol{y})\right| \\ &+c\,S-c\,s+c\,B-c\,b+\mathcal{T}+\mathcal{I} \\ &+\boxed{\mathcal{U}+\mathcal{M}}+\mathcal{E}\end{aligned}$$

- Other effects
  - Relativistic effects
  - Multipath, reflected signals
  - ...

Observation Equation

- Modeling „distance“ satellite → observer

$$\begin{aligned}\mathcal{C} = &\left|(\boldsymbol{R}+\boldsymbol{E}+\boldsymbol{Y})-(\boldsymbol{r}+\boldsymbol{e}+\boldsymbol{y})\right| \\ &+c\,S-c\,s+c\,B-c\,b+\mathcal{T}+\mathcal{I} \\ &+\mathcal{U}+\mathcal{M}+\mathcal{E}\end{aligned}$$

- Combined analysis of different GNSS
  - GNSS-specific parameters
  - Models fitting the different GNSS
  - Consideration of all bias parameters

System Overview

- Global systems
  - USA — Global Positioning System
  - Russia — GLObal NAvigation Satellite System
  - EU — Galileo
  - China — Compass

- Regional and augmentation systems
  - Quasi-Zenith Satellite System
  - Indian Regional Navigation Satellite System
  - WAAS, EGNOS, MSAS, GAGAN, SDCM

System Overview

- GNSS satellites
  - Weight ~ 1 ton
  - Size ~ 2 x 2 x 2 meters
  - Panel span ~ 10 meters


GPS (Block IIF)

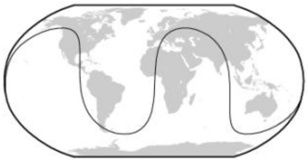

GLONASS (K)


Galileo (IOV

System Overview - GPS

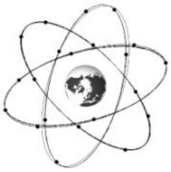
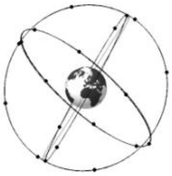
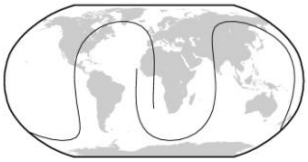
- 32 operational satellites
- 6 orbital planes
- Semi-major axis: 26'560 km
- Inclination: 55°
- Revolution period: 1/2 sidereal day (11h 58min)
- 2 (3) frequencies, CDMA





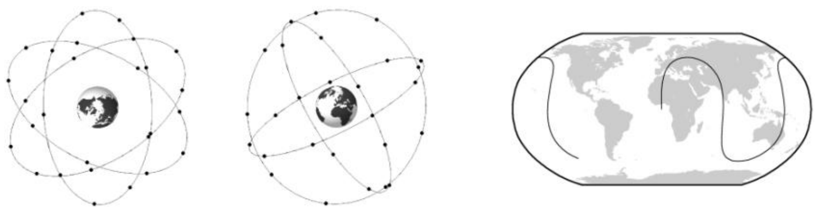
System Overview - GLONASS

- 24 operational satellites
- 3 orbital planes
- Semi-major axis: 25'510 km
- Inclination: 64.8°
- Revolution period: 8/17 sidereal days (11h 16min)
- 2 reference frequencies, FDMA

System Overview - Galileo

- 2 test satellites, 2 IOV satellites
- 3 orbital planes
- Semi-major axis: 29'600 km
- Inclination: 56°
- Revolution period: 10/17 sidereal days (14h 05min)
- 5 frequencies, CDMA

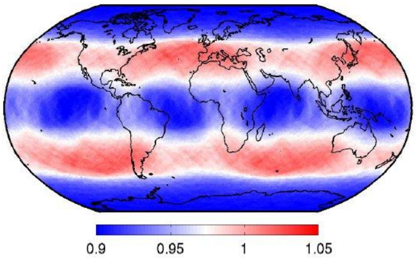


System Overview - Comparison

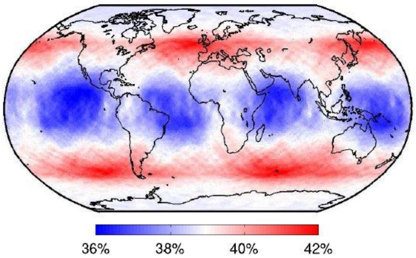
Constellation characteristic	GPS	GLONASS	Galileo
Walker designation	–	64.8°: 24/3/1	56°: 27/3/1
Orbital planes	6	3	3
Spacing of planes	60°	120°	120°
Number of satellites (nominal)	32 (24)	24 (24)	2 IOV (27)
Semi-major axis	26 500 km	25 510 km	29 600 km
Inclination	55°	64.8°	56°
Nodal drift per day	−0.0384°	−0.0336°	−0.0260°
Length of GNSS year	351.5 days	353.2 days	355.6 days
Revolution period	11 h 58 min 1/2 sidereal days	11 h 16 min 8/17 sidereal days	14 h 05 min 10/17 sidereal days
Repeat cycle (sidereal days)	1	8	10
Repeat cycle (orbital revolutions)	2	17	17

Why Multi-GNSS?

- Position Dilution Of Precision (PDOP)
  - Quality indicator for navigation solution
  - Smaller = better



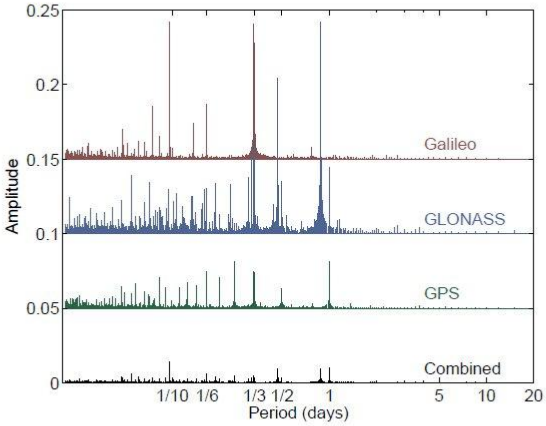
Mean daily PDOP
(GPS-only)



Mean PDOP improvement
(when adding GLONASS and Galileo)

Why Multi-GNSS?

- PDOP spectrum for a mid-latitude station



Why Multi-GNSS?

- Increased number of satellites, improved orbit geometry
  - Major improvement for kinematic applications
  - Especially in mid-latitude regions
  - In difficult environment (restricted view of sky)
- Main benefits for scientific-grade applications
  - Additional signals and frequencies
  - Different orbit characteristics of GNSS

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Motivation of the Study

- Data analyzed in post-processing mode for high-accuracy applications
  - Data recorded over a certain amount of time
  - Joint data analysis in processing batches
  - 24-hour session length widely used
- All GNSS show specific periods
- Batch length close to system-specific repeat cycles may effect solution
  - E.g., averaging or amplification of umodelled errors
  - A GNSS may be „favored“ or „penalized“

Motivation of the Study

- Examine the impact of the session length on estimated parameters
- Quality assessment of GPS-only, GLONASS-only, and combined GPS/GLONASS solutions

Design and Setup

- Data from 2008–2010
- 92 GPS/GLONASS stations
  - Globally distributed
  - Availability at least 75% of the three years
- GPS and GLONASS fully consistent and comparable
  - in particular concerning station selection

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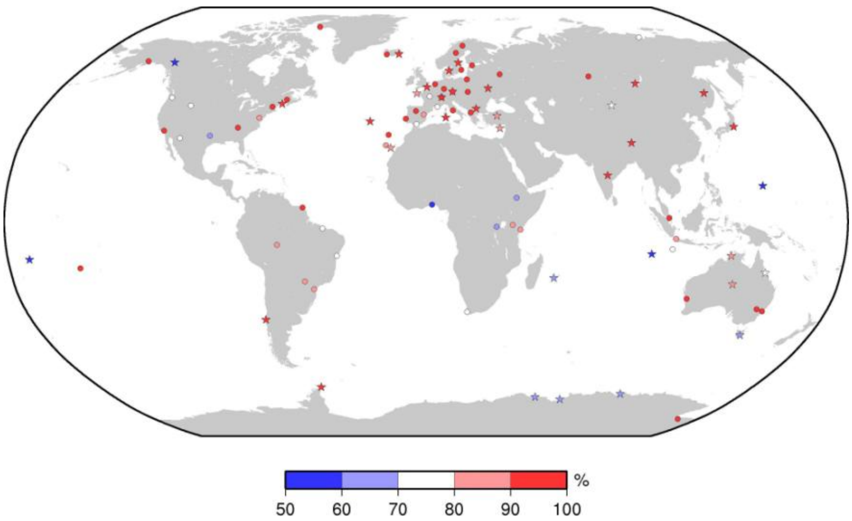
Design and Setup



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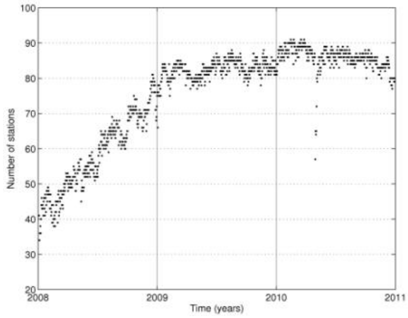
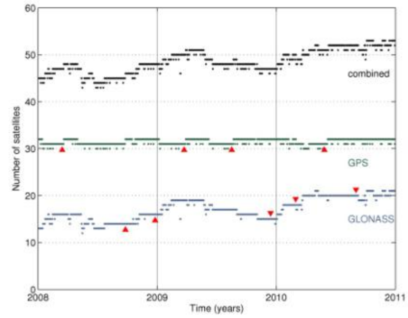
Design and Setup



Number of stations



Number of satellites

Design and Setup

- Batch length specification

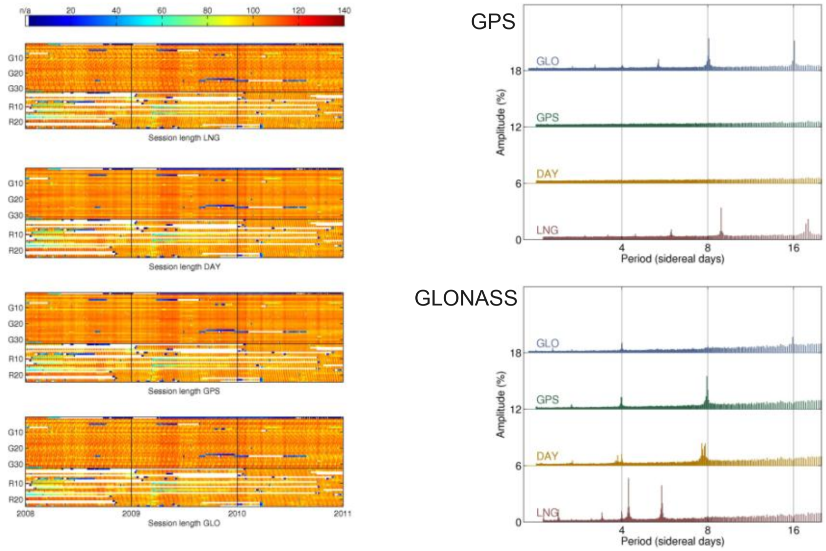
ID	Adapted to	Batch length in sid. days	Batch length in hr:min:sec	# Sessions
LNG	–	18/17	25 h 21 min 00 s	1037
DAY	1 day	–	24 h 00 min 00 s	1096
GPS	GPS	17/17	23 h 56 min 30 s	1097
GLO	GLONASS	16/17	22 h 32 min 00 s	1166

Design and Setup

- Solution type specification

ID	Charakteristic
GPS	GPS-only
GLO	GLONASS-only
CMB	GPS/GLONASS combined on observation level
NEQ	GPS/GLONASS combined on normal equation level

Available Observations



Results

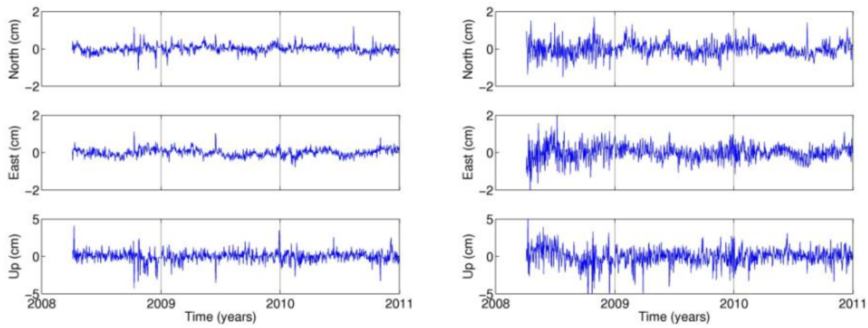
- Quality of solutions
- Time series of parameters
- Parameter types
  - Station coordinates
  - Satellite orbits
  - Geocenter coordinates

Results – Station Coordinates

- Coordinate time series
  - 3-year solution coordinates/velocities
  - 3 translation and 3 rotation conditions
  - Comparison to session-specific results
- RMS of residuals → repeatability
- Realistic accuracy measure

Results – Station Coordinates

- Repeatability: one station, batch length DAY (24 hours)



GPS GLONASS

Results – Station Coordinates

- Repeatability: all stations, median

	Session LNG				Session DAY			
Solution	N	E	U	Total	N	E	U	Total
CMB	2.2	2.1	5.4	3.6	2.1	2.1	5.6	3.6
NEQ	2.1	2.1	5.5	3.7	2.1	2.1	5.6	3.6
GPS	2.2	2.1	5.7	3.9	2.2	2.2	5.8	4.0
GLO	4.5	5.4	9.9	7.1	4.6	5.7	9.7	7.3
	Session GPS				Session GLO			
Solution	N	E	U	Total	N	E	U	Total
CMB	2.1	2.1	5.6	3.7	2.2	2.1	5.6	3.7
NEQ	2.1	2.1	5.6	3.7	2.2	2.1	5.6	3.8
GPS	2.2	2.2	5.8	3.9	2.3	2.1	6.0	4.0
GLO	4.7	5.5	10.2	7.5	4.8	5.7	10.6	7.7

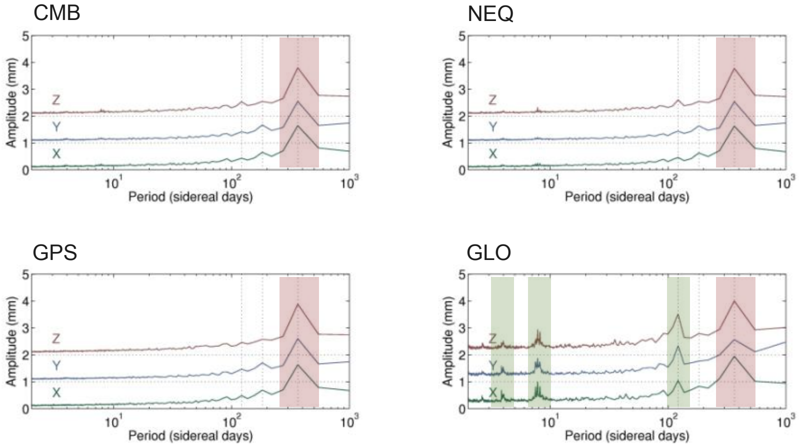
Results – Station Coordinates

- Expected improvement
  - $\sqrt{n}$ -law
  - with number of satellites: 31 GPS, 16 GLONASS

	CMB/GPS	CMB/GLO	GPS/GLO
Expected	25%	80%	45%
Observed	10%	100%	80%

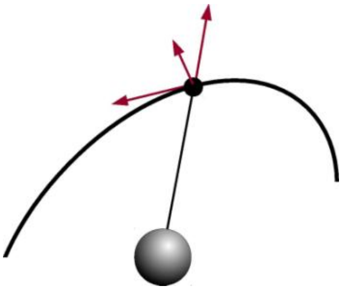
Results – Station Coordinates

- Periodic variations, batch length DAY (24 hours)



Results – Orbits

- Orbit overlap differences
  - Position difference at session boundaries computed from two subsequent orbits
  - Absolute or in radial, along-track, cross-track direction
- Good quality measure



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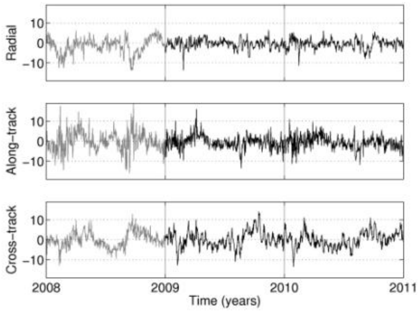
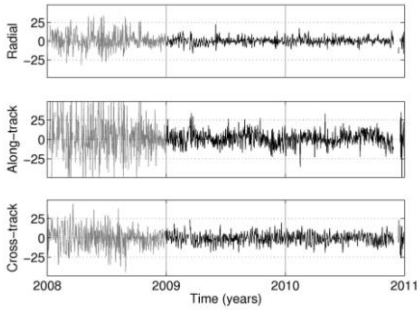
Results – Orbits

- Orbit overlap differences (cm), batch length DAY



G03



R17

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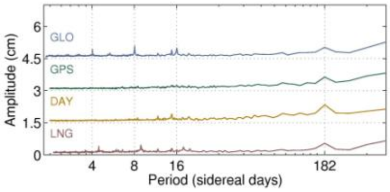
Results – Orbits

- Orbit overlap differences (cm), mean values

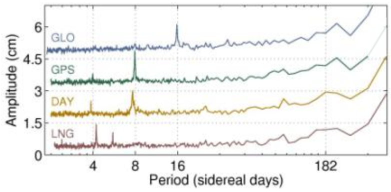
	GPS satellites			GLONASS satellites		
Session	CMB	NEQ	GPS	CMB	NEQ	GLO
LNG	5.2	5.3	5.5	8.7	10.2	10.9
DAY	5.4	5.5	5.6	8.8	10.6	11.6
GPS	5.2	5.3	5.5	8.9	10.7	11.6
GLO	5.3	5.4	5.6	9.3	11.3	12.2

Results – Orbits

- Periodic variations



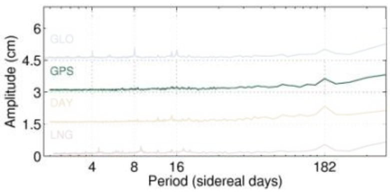
GPS-only



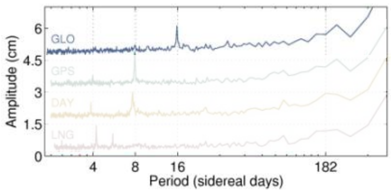
GLONASS-only

Results – Orbits

- Periodic variations



GPS-only



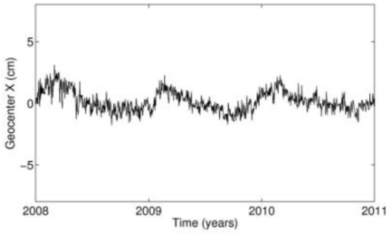
GLONASS-only

Results – Geocenter Coordinates

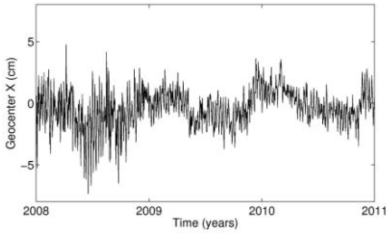
- Geocenter
  - Center of mass of the Earth
  - Reference point for satellite orbits
  - Moves wrt reference frame due to geophysical effects
  - Can be estimated with satellite geodetic methods
- Geocenter coordinates
  - Offset of geocenter wrt origin of the reference frame

Results – Geocenter Coordinates

- Geocenter coordinates, batch length DAY



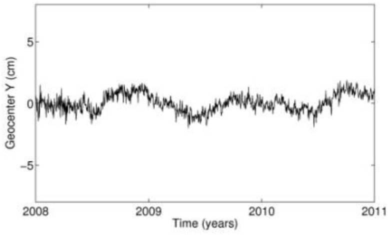
GPS X-component



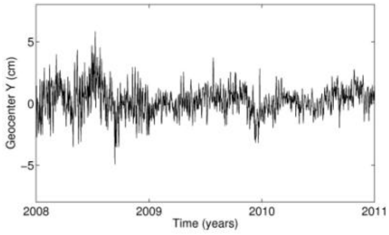
GLONASS X-component

Results – Geocenter Coordinates

- Geocenter coordinates, batch length DAY



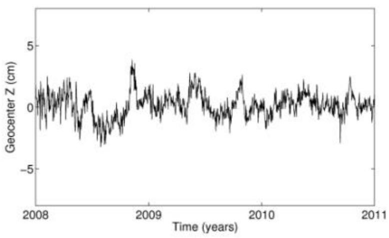
GPS Y-component



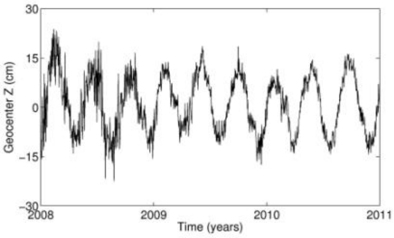
GLONASS Y-component

Results – Geocenter Coordinates

- Geocenter coordinates, batch length DAY



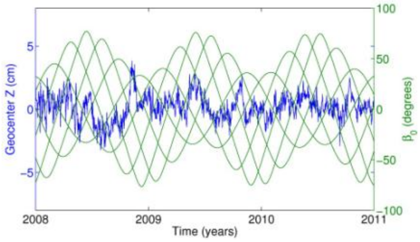
GPS Z-component



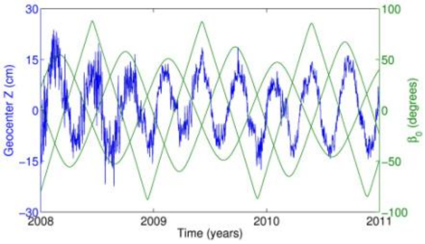
GLONASS Z-component

Results – Geocenter Coordinates

- Geocenter coordinates, batch length DAY



GPS Z-component



GLONASS Z-component

Results – Geocenter Coordinates

- Large variations in the GLONASS-only geocenter Z-component
  - 30 cm peak-to-peak
  - Absolutely unexpected
- Striking correlation with the elevation of the Sun above the orbital planes
  - Implies a correlation with orbital parameters
  - in particular with the radiation pressure parameters

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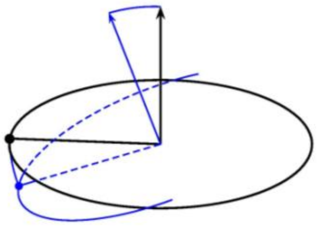
Results – Geocenter Coordinates

- From perturbation theory (Gerhard's presentation)
  - W-component causes a tilting of the orbital plane



$$\delta i(t) = \frac{W}{n^2 a} \sin u$$

$$\delta \Omega(t) = \frac{W}{n^2 a \sin i} \cos u$$

$$\delta u(t) = \frac{W}{n^2 a \tan i} \sin u$$

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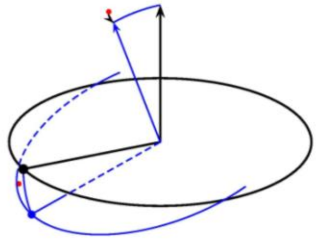
Results – Geocenter Coordinates

- From perturbation theory (Gerhard's presentation)
  - W-component causes a tilting of the orbital plane



$$\delta i(t) = \frac{W}{n^2 a} \sin u$$

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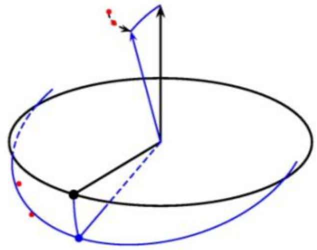

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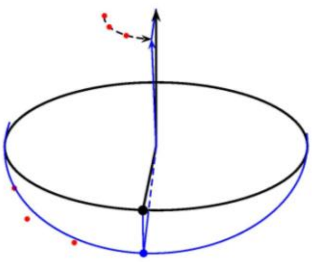

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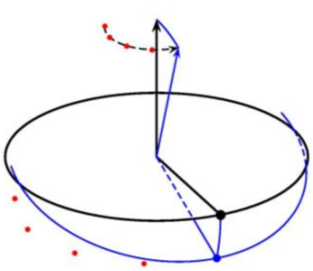

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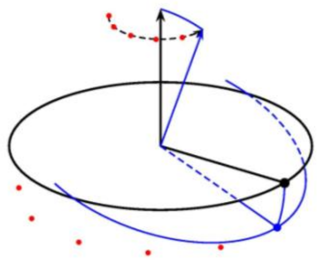
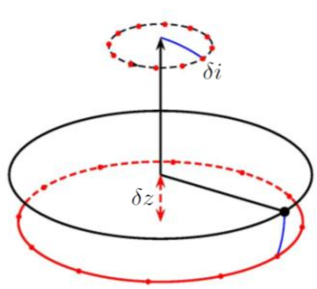


$$\delta i(t) = \frac{W}{n^2 a}\sin u$$
$$\delta\Omega(t) = \frac{W}{n^2 a \sin i}\cos u$$
$$\delta u(t) = \frac{W}{n^2 a \tan i}\sin u$$

Results – Geocenter Coordinates

- From perturbation theory (Gerhard's presentation)
  - W-component causes a tilting of the orbital plane
- Satellite seemingly moves on a parallel shifted plane with



$$\delta i = W/n^2 a$$
$$\delta z = W/n^2$$

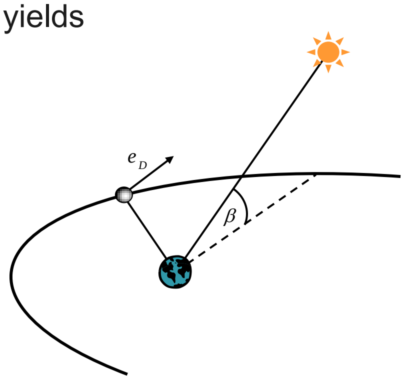
$$\delta i(t) = \frac{W}{n^2 a}\sin u$$
$$\delta\Omega(t) = \frac{W}{n^2 a \sin i}\cos u$$
$$\delta u(t) = \frac{W}{n^2 a \tan i}\sin u$$

Results – Geocenter Coordinates

- Direct (constant) radiation pressure D_0 is estimated in the orbit determination process
- Decomposition of D_0 in RSW yields

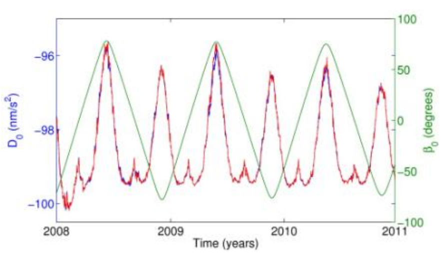
$$W = -D_0 \sin\beta$$

$$\delta z = -\frac{D_0 \sin\beta}{n^2 \cos i}$$

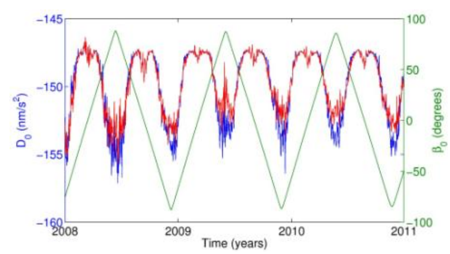


Results – Geocenter Coordinates

- D_0 estimates with GCC (blue) and without GCC (red)



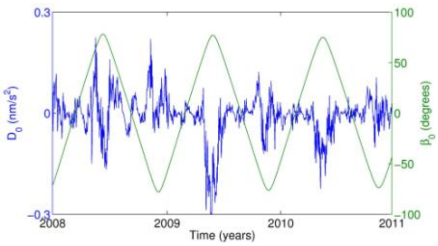
GPS (G29)



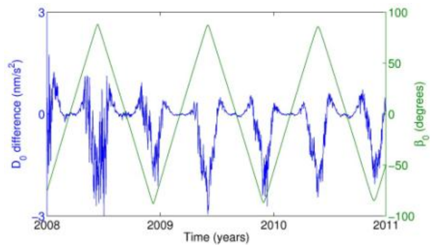
GLONASS (R20)

Results – Geocenter Coordinates

- D_0 difference (with GCC minus without GCC)



GPS (G29)



GLONASS (R20)

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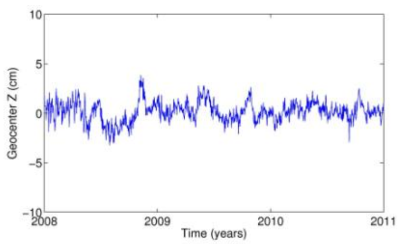
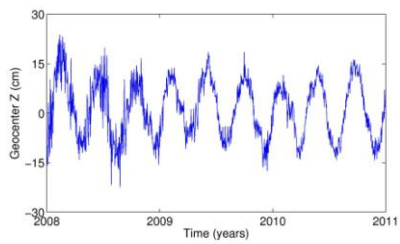
Results – Geocenter Coordinates

- GCC Z-component: estimated (blue)



GPS



GLONASS

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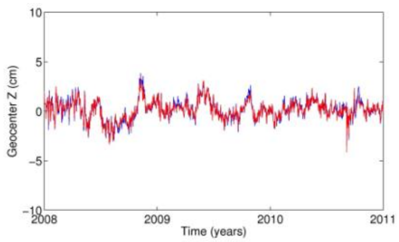
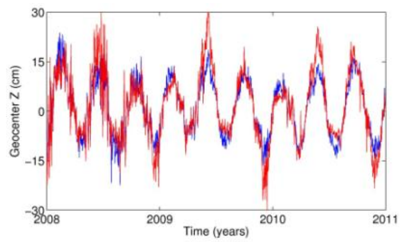
Results – Geocenter Coordinates

- GCC Z-component: estimated (blue), reconstructed (red)



GPS



GLONASS

Outline

- Global Navigation Satellite Systems
- Combined GPS/GLONASS analysis
- Summary

Summary

- GNSS
  - Are based on the same principles
  - Differences: frequencies, signals, orbit characteristics
  - In a few years: at least 4 GNSS and several regional systems
- Multi-GNSS will be a major issue
- Combined multi-GNSS analysis is non-trivial
  - Especially correct bias handling is important

Summary

- Combined multi-GNSS analysis example
  - 4 different batch lengths
  - GPS-only, GLONASS-only, combined solutions
- Coordinates and orbits
  - Combined solution always gives the best results
  - Especially GLONASS profits
  - GNSS-specific periods are visible
  - Selection of batch length is not trivial

Summary

- Geocenter
  - Large variations of Z-component for GLONASS
  - Highly correlated with the elevation of the Sun wrt the orbital planes
  - No geophysical interpretation
- Explained by perturbation theory
  - Variations are caused by a constant force in W-direction → direct solar radiation pressure
  - Experimental results impressively confirm theory