Estimating the geocenter from GNSS data

Rolf Dach[1], Stefan Schaer[2], Urs Hugentobler[3], Carlos Rodriguez-Solano[3], Simon Lutz[1], Peter Steigenberger[3], Krzysztof Sośnica[1], Michael Meindl[4], Gerhard Beutler[1], Adrian Jäggi[1]

[1] *Astronomical Institute of the University of Bern, Bern, Switzerland*
[2] *Swiss Federal Office of Topography swisstopo, Wabern, Switzerland*
[3] *Fachgebiet Satellitengeodäsie, Technische Universität München, Germany*
[4] *Institute of Geodesy and Photogrammetry, ETH Zurich, Zurich, Switzerland*

IGS Workshop – Celebrating 20 Years of Service
Pasadena, California, June 23–27, 2014

Background

J Geod (2014) 88:65–85
DOI 10.1007/s00190-013-0669-5

ORIGINAL ARTICLE

A collinearity diagnosis of the GNSS geocenter determination

Paul Rebischung · Zuheir Altamimi · Tim Springer

Received: 25 June 2013 / Accepted: 21 October 2013 / Published online: 10 November 2013

Abstract The problem of observing geocenter motion from global navigation satellite system (GNSS) solutions through the network shift approach is addressed from the perspective of collinearity (or multicollinearity) among the parameters of a least-squares regression. A collinearity diagnosis, based on the notion of variance inflation factor, is therefore developed and allows handling several peculiarities of the GNSS geocenter determination problem. Its application reveals that the determination of all three components of geocenter motion with GNSS suffers from serious collinearity issues, with a comparable level as in the problem of determining the terrestrial scale simultaneously with the GNSS

1 Introduction

Geocenter motion is usually defined, with varying sign conventions, as the relative motion between the center of mass of the total Earth system (CM) and the center of figure of the solid Earth surface (CF). Its geophysical cause is the redistribution of masses within the Earth system, from daily and sub-daily periods (e.g. ocean tides) to secular time scales (e.g. post-glacial rebound, present-day ice melting) via seasonal and inter-annual periods (e.g. water mass exchanges). As Earth satellites orbit around CM, geocenter motion affects the measurements of surface processes

Background

J Geod (2014) 88:65–85
DOI 10.1007/s00190-013-0669-5

ORIGINAL ARTICLE

A collinearity diagnosis of the GNSS geocenter determination

Paul Rebischung · Zuheir Altamimi · Tim Springer

Receive

Summay

. . .

It can be concluded without much exaggerating that current GNSS are insensitive to any component of geocenter motion.

. . .

Abstra
from g
throug
perspe
param
nosis,
fore d
the GN
reveals that the determination of all three components of geocenter motion with GNSS suffers from serious collinearity issues, with a comparable level as in the problem of determining the terrestrial scale simultaneously with the GNSS

con-
mass
igure
se is
from
cular
time scales (e.g. post-glacial rebound, present-day ice melting) via seasonal and inter-annual periods (e.g. water mass exchanges). As Earth satellites orbit around CM, geocenter motion affects the measurements of surface processes

Estimating the geocenter from GNSS data

Part I:

Stability of GNSS–derived Geocenter Estimates

Part II:

Orbit Modelling Reflected by Geocenter Coordinate Series

Part I

Stability of GNSS–derived Geocenter Estimates

Stability of GNSS–derived Geocenter Estimates

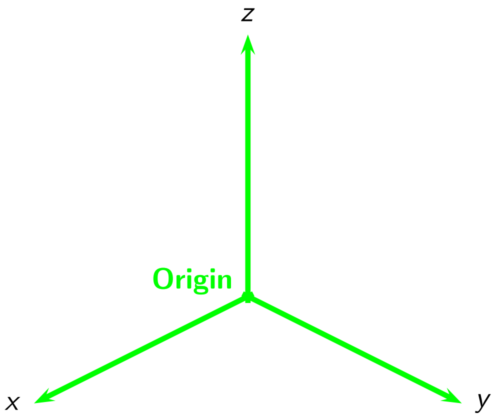
Description of the problem

Experiment 1: Shifting the Geocenter

Experiment 2: Geocenter with Simulated Data

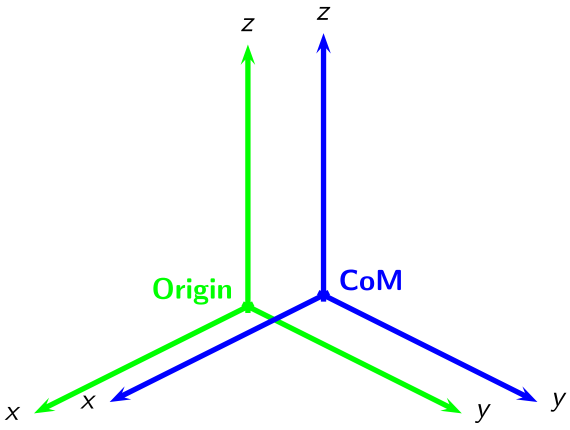
Geocenter Time Series from GNSS Solution

Origin and Geocenter



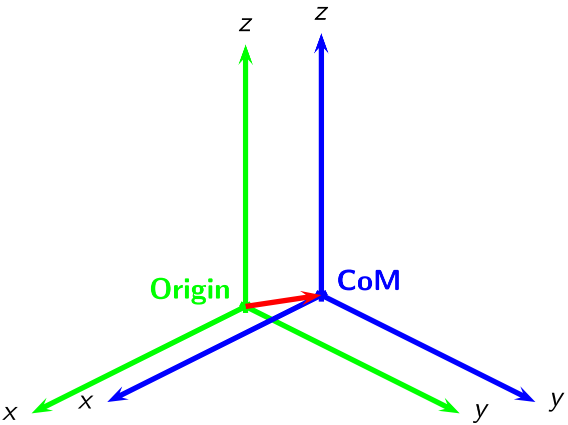
- Origin of the terrestrial reference system

Origin and Geocenter



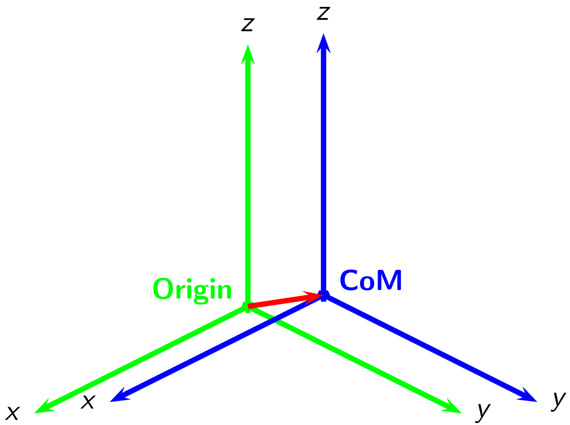
- Origin of the terrestrial reference system
- Center of mass of the Earth

Origin and Geocenter



- Origin of the terrestrial reference system
- Center of mass of the Earth
- Geocenter vector

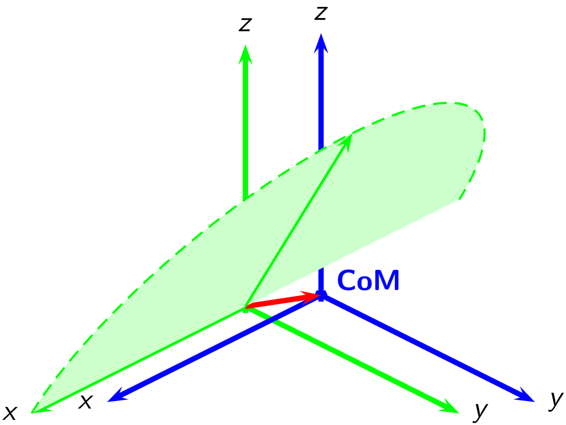
Origin and Geocenter



- Origin of the terrestrial reference system
- Center of mass of the Earth
- Geocenter vector

The instantaneous center of mass differs from the long–term averaged location that is supposed to be the origin of the terrestrial reference frame by the geocenter vector.

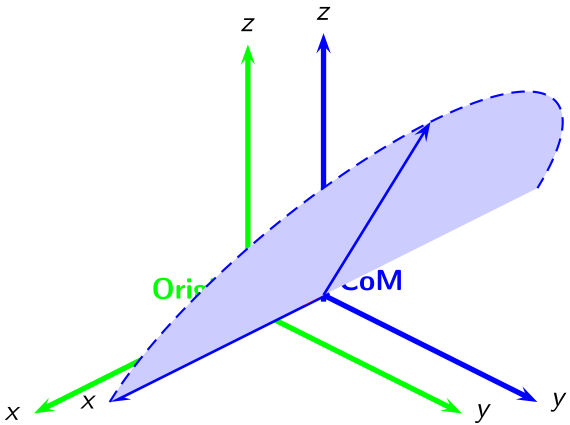
Origin and Geocenter



- Origin of the terrestrial reference system
- Center of mass of the Earth
- Geocenter vector

The satellite orbit refers to the origin of the terrestrial reference system because the transformation from the terrestrial into the quasi–inertial system contains only rotations (Earth rotation parameters).

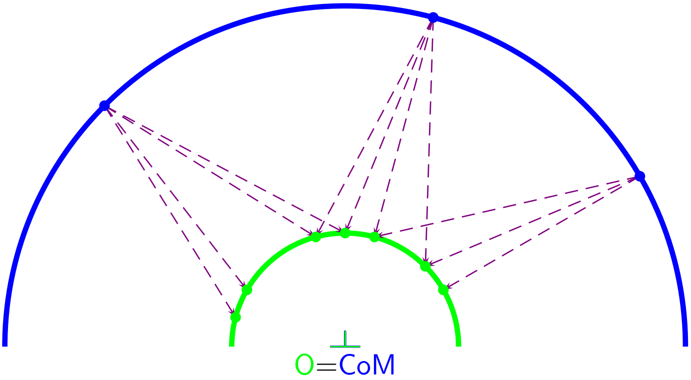
Origin and Geocenter



- Origin of the terrestrial reference system
- Center of mass of the Earth
- Geocenter vector

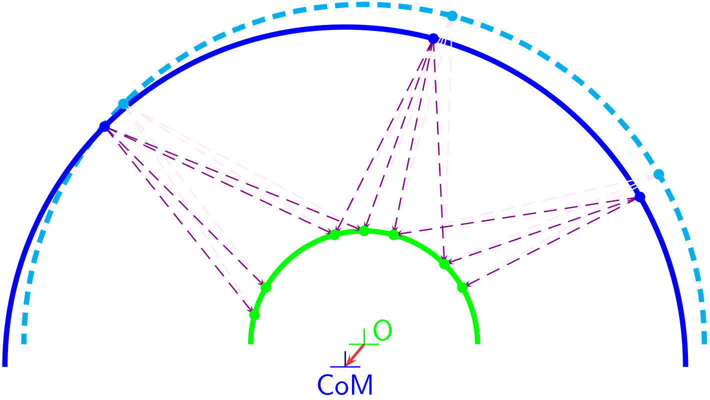
The satellite orbit refers to the center of mass of the Earth because the physics of celestial mechanics is based on the principle of gravitation.

Consequences for the Data Analysis



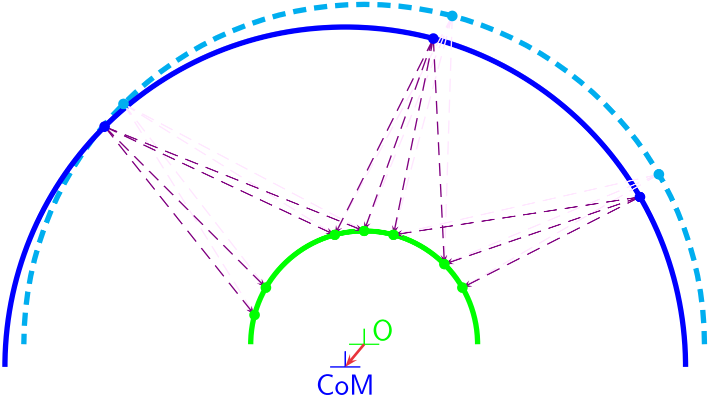
- In the processing model we typically assume that the origin of the terrestrial frame and the center of mass coincide in one and the same point.

Consequences for the Data Analysis



- If this is not true (geocenter vector $\neq 0$) we introduce an inconsistency between the processing model and the observations.

Consequences for the Data Analysis



- If this is not true (geocenter vector $\neq 0$) we introduce an inconsistency between the processing model and the observations.

Are there parameters in the GNSS–analysis capable of absorbing this discrepancy?

Experiment 1: Shifting the Geocenter

Parameters in the CODE–standard solution (GPS+GLONASS):

- Orbit: initial conditions,
  constant empirical SRP coefficients D_0, Y_0, X_0,
  once–per revolution for X–component;
  stochastic pulses at noon (constrained)
- ERP: offset and rates for polar motion and LOD; UT fixed
- Troposphere: vertical ZPD parameters every two;
  one set of gradient parameters per 24 hours
- Ambiguities: resolved for GPS and GLONASS
- Clocks: implicit; epoch–wise independent

Experiment 1: Shifting the Geocenter

Parameters in the CODE–standard solution (GPS+GLONASS):

- Orbit: initial conditions,
  constant empirical SRP coefficients D_0, Y_0, X_0,
  once–per revolution for X–component;
  stochastic pulses at noon (constrained)
- ERP: offset and rates for polar motion and LOD; UT fixed
- Troposphere: vertical ZPD parameters every two;
  one set of gradient parameters per 24 hours
- Ambiguities: resolved for GPS and GLONASS
- Clocks: implicit; epoch–wise independent
- Coordinates: minimum constrained solution
  with NNR+NNT condition on IGb08 for the reference sites

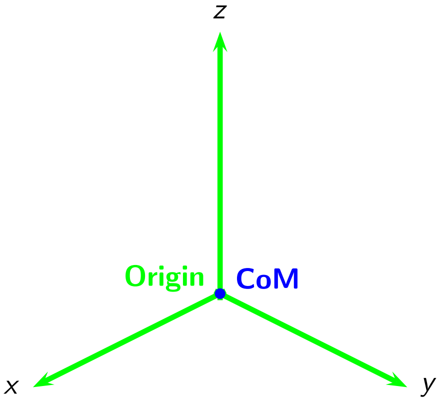
Experiment 1: Shifting the Geocenter

Parameters in the CODE–standard solution (GPS+GLONASS):

- Orbit: initial conditions,
  constant empirical SRP coefficients D_0, Y_0, X_0,
  once–per revolution for X–component;
  stochastic pulses at noon (constrained)
- ERP: offset and rates for polar motion and LOD; UT fixed
- Troposphere: vertical ZPD parameters every two;
  one set of gradient parameters per 24 hours
- Ambiguities: resolved for GPS and GLONASS
- Clocks: implicit; epoch–wise independent
- Coordinates: minimum constrained solution
  with NNR+NNT condition on IGb08 for the reference sites

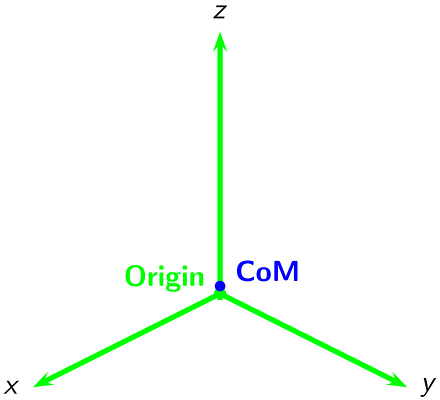
An arbitrarily choosen one–day solution has been selected for this experiment: January 21, 2014.

Experiment 1: Shifting the Geocenter



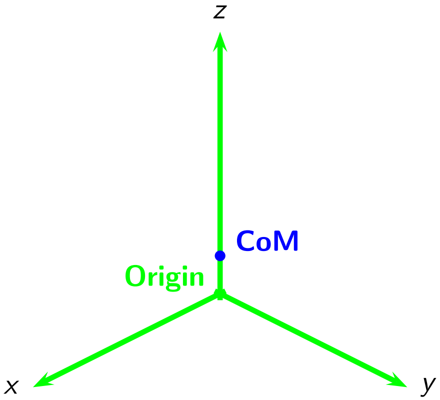
CoM wrt. Origin	RMS of adjustment
(0,0,0.00) m	1.59 mm

Experiment 1: Shifting the Geocenter



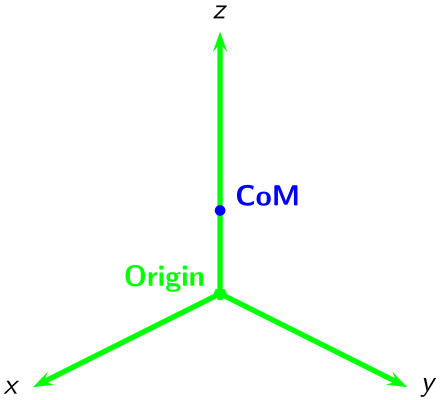
CoM wrt. Origin	RMS of adjustment
(0,0,0.00) m	1.59 mm
(0,0,0.01) m	1.59 mm

Experiment 1: Shifting the Geocenter



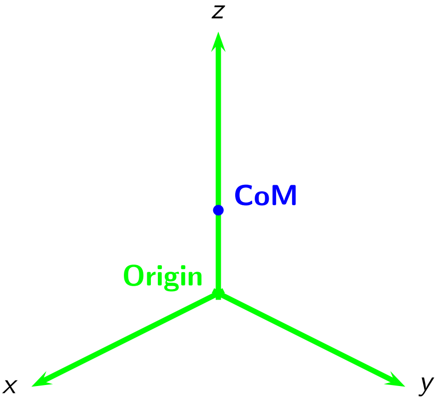
CoM wrt. Origin	RMS of adjustment
(0,0,0.00) m	1.59 mm
(0,0,0.01) m	1.59 mm
(0,0,0.10) m	1.60 mm

Experiment 1: Shifting the Geocenter



CoM wrt. Origin	RMS of adjustment
(0,0,0.00) m	1.59 mm
(0,0,0.01) m	1.59 mm
(0,0,0.10) m	1.60 mm
(0,0,1.00) m	2.01 mm

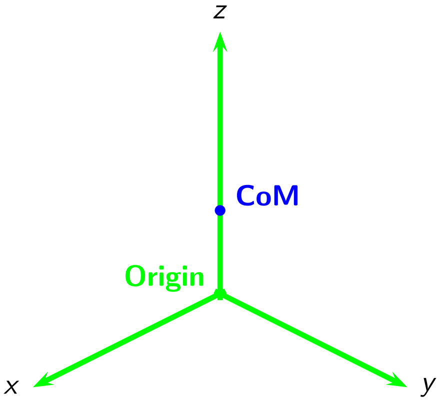
Experiment 1: Shifting the Geocenter



CoM wrt. Origin	RMS of adjustment
(0,0,0.00) m	1.59 mm
(0,0,0.01) m	1.59 mm
(0,0,0.10) m	1.60 mm
(0,0,1.00) m	2.01 mm

Shifting the CoM wrt. Origin	Impact on coordinates dZ	RMS
(0,0,0.00) m		
(0,0,0.01) m	0.03 mm	0.23 mm
(0,0,0.10) m	0.30 mm	2.32 mm
(0,0,1.00) m	3.00 mm	23.2 mm

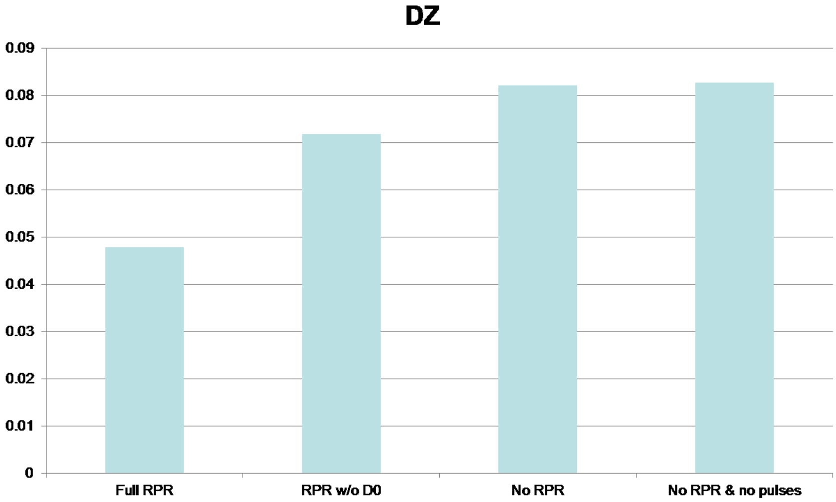
Experiment 1: Shifting the Geocenter



CoM wrt. Origin	RMS of adjustment
(0,0,0.00) m	1.59 mm
(0,0,0.01) m	1.59 mm
(0,0,0.10) m	1.60 mm
(0,0,1.00) m	2.01 mm

Shifting the CoM wrt. Origin	Impact on coordinates dZ	Impact on coordinates RMS	Impact on orbits dZ	Impact on orbits RMS
(0,0,0.00) m				
(0,0,0.01) m	0.03 mm	0.23 mm	−0.53 cm	0.2 cm
(0,0,0.10) m	0.30 mm	2.32 mm	−5.23 cm	1.5 cm
(0,0,1.00) m	3.00 mm	23.2 mm	−52.1 cm	14.9 cm

Experiment 1: Shifting the Geocenter



Experiment 1: Shifting the Geocenter

Lessons learned from Experiment 1:

- If the ground network is not geocentric (and the geocenter is kept fixed) the network will be deformed.

Experiment 1: Shifting the Geocenter

Lessons learned from Experiment 1:

- If the ground network is not geocentric (and the geocenter is kept fixed) the network will be deformed.
- Some orbit parameters (in particular D_0) may absorb a significant part of the geocenter shift. The amount depends on the orientation of this component (direction to the Sun) w.r.t. the orbital plane.

Experiment 1: Shifting the Geocenter

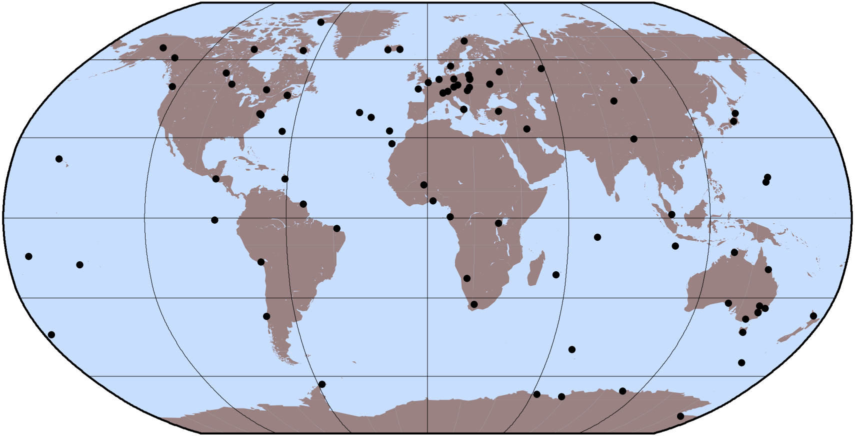
Lessons learned from Experiment 1:

- If the ground network is not geocentric (and the geocenter is kept fixed) the network will be deformed.
- Some orbit parameters (in particular D_0) may absorb a significant part of the geocenter shift. The amount depends on the orientation of this component (direction to the Sun) w.r.t. the orbital plane.
- The GNSS analysis system is stable and able to reconstruct the geometry between orbits and station coordinates – even if other parameters like troposphere or (satellite) clocks have to be estimated (the ambiguities are assumed to be resolved).

Experiment 2: Geocenter with Simulated Data

The simulation setup

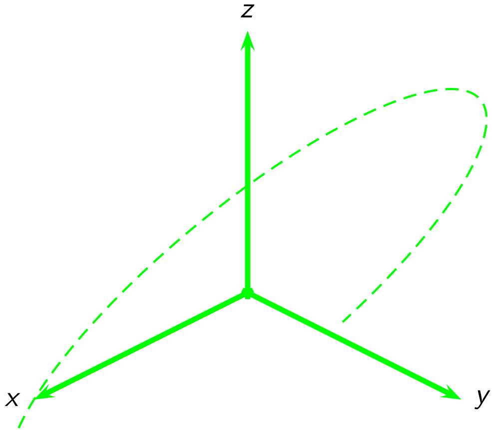
A network of 90 globally distributed stations has been selected:



The simulation setup

- Geometry has been introduced from a CODE final solution.
- GPS observations have been generated for all stations.
- Code measurements without noise may be used for a solution where all ambiguities are fixed to their correct integer values.
- The standard parametrization is used for the analysis (see Experiment 1).

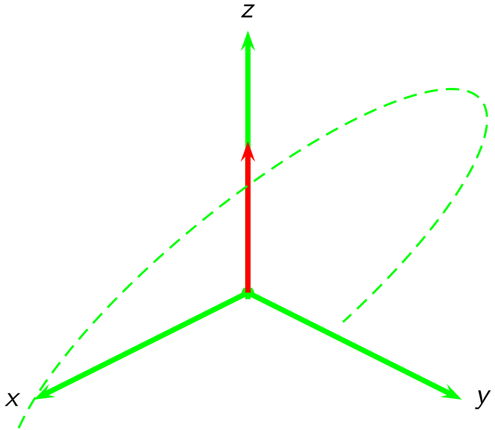
Reference solutions



- Original geometry from simulation

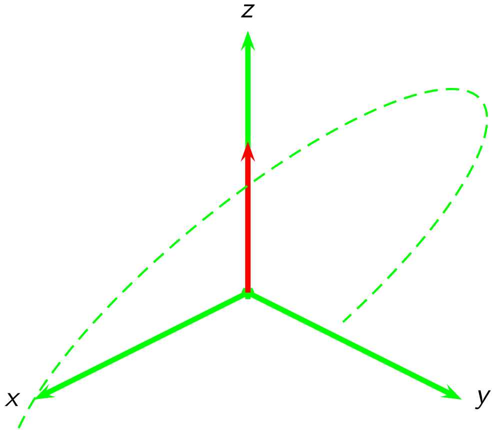
Solution setup		Results			
Datum	GCC	Chi^2	CRD	GCC	ORB
NNR+NNT	estimate	0.00	0.00	0.00	0.00
NNR	fixed	0.00	0.00		0.00
NNR+NNT	fixed	0.00	0.00		0.00
NNR	estimate	0.00	0.00	0.00	0.00

Modified reference solutions



- Original geometry from simulation
- Artificial geocenter shift: 10 cm

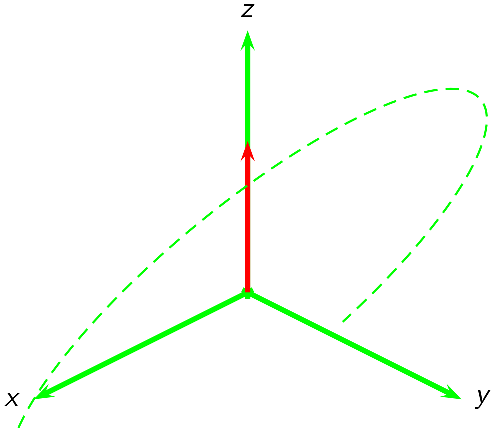
Modified reference solutions



- Original geometry from simulation
- Artificial geocenter shift: 10 cm

Solution setup		Results			
Datum	GCC	Chi^2	CRD	GCC	ORB
NNR+NNT	estimate	0.00	0.00	0.10	0.00

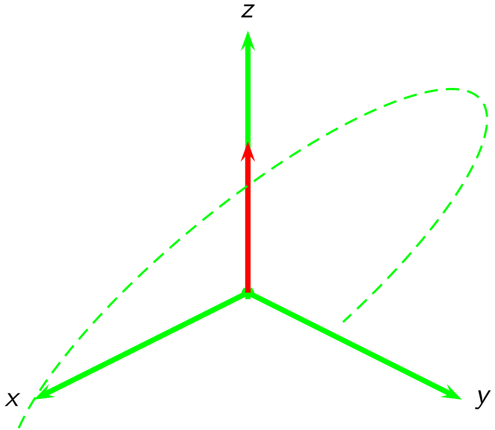
Modified reference solutions



- Original geometry from simulation
- Artificial geocenter shift: 10 cm

Solution setup		Results			
Datum	GCC	Chi^2	CRD	GCC	ORB
NNR+NNT	estimate	0.00	0.00	0.10	0.00
NNR	fixed	0.00	-0.10		0.00

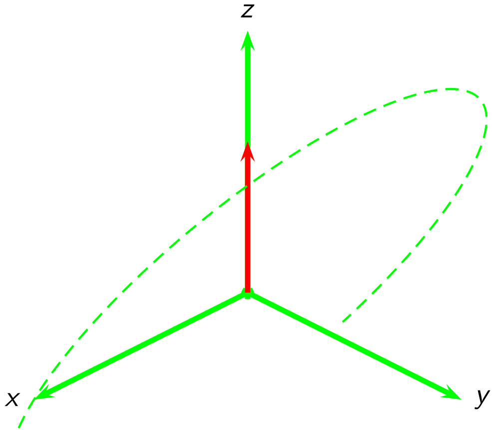
Modified reference solutions



- Original geometry from simulation
- Artificial geocenter shift: 10 cm

Solution setup		Results			
Datum	GCC	Chi^2	CRD	GCC	ORB
NNR+NNT	estimate	0.00	0.00	0.10	0.00
NNR	fixed	0.00	-0.10		0.00
NNR	estimate	0.00	0.00	0.10	0.00

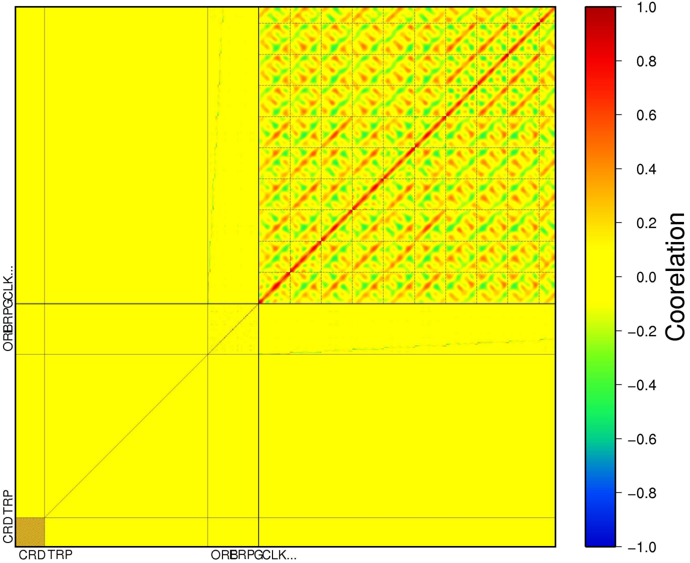
Modified reference solutions



- Original geometry from simulation
- Artificial geocenter shift: 10 cm

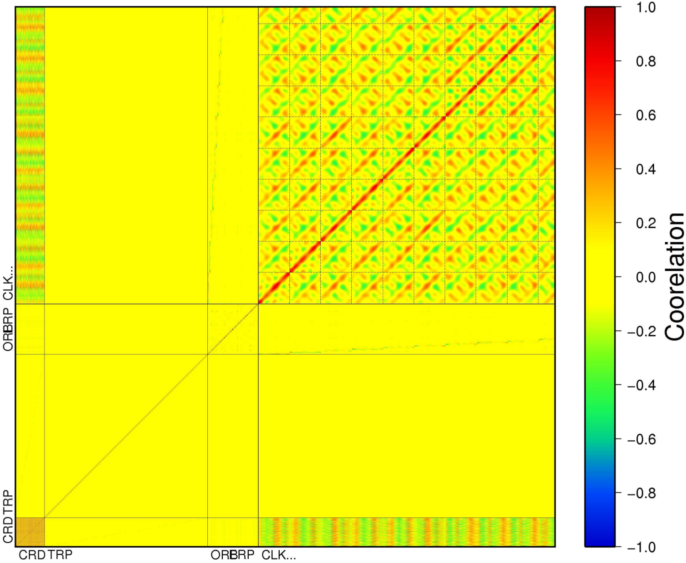
Solution setup		Results			
Datum	GCC	Chi^2	CRD	GCC	ORB
NNR+NNT	estimate	0.00	0.00	0.10	0.00
NNR	fixed	0.00	-0.10		0.00
NNR	estimate	0.00	0.00	0.10	0.00
NNR+NNT	fixed	$\neq$0.00	$\neq$0.00		$\neq$0.00

Correlations between the parameters



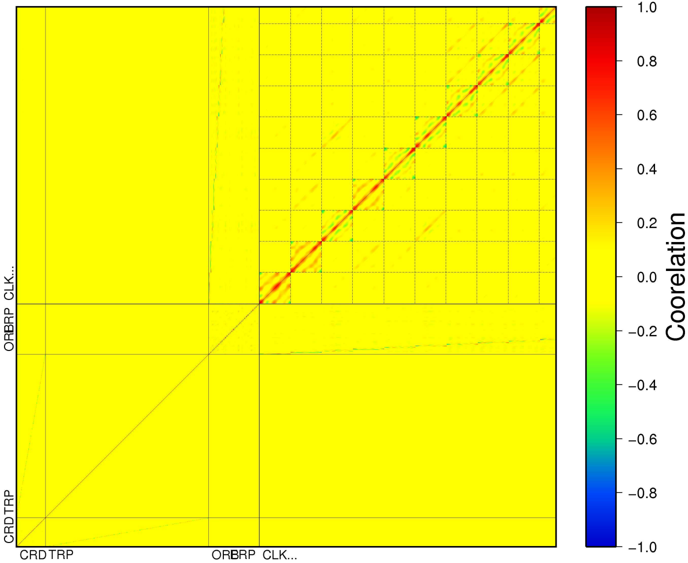
GPS-only solution
based on code mea.
Datum: NNR
GCC: estimated
(10 cm GCC shift)

Correlations between the parameters



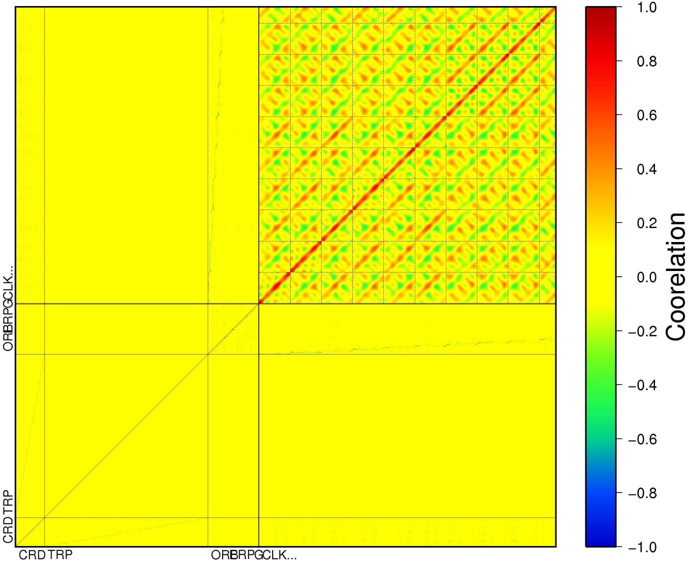
GPS-only solution
based on code mea.
Datum: NNR
GCC: fixed
(10 cm GCC shift)

Correlations between the parameters



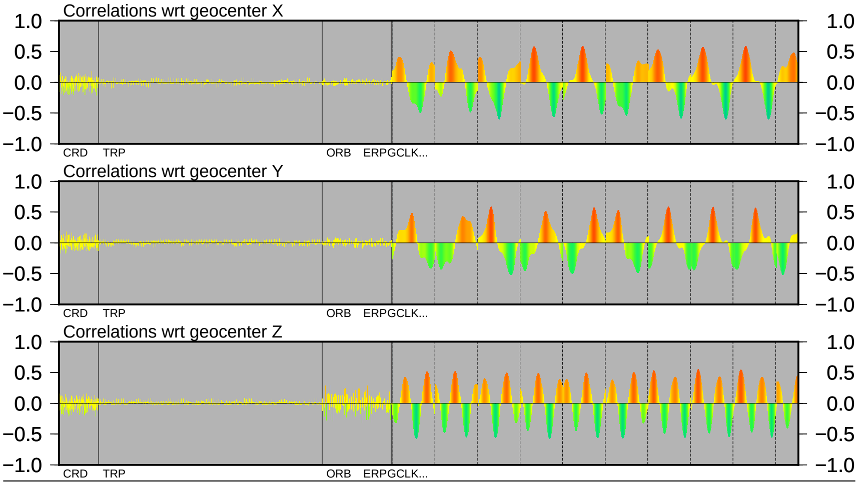
GPS-only solution
based on code mea.
Datum: NNR+NNT
GCC: fixed
(10 cm GCC shift)

Correlations between the parameters



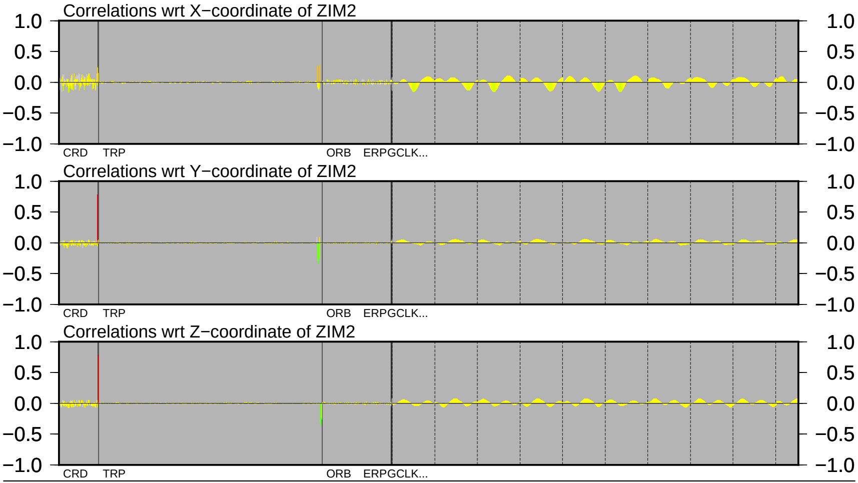
GPS-only solution
based on code mea.
Datum: NNR+NNT
GCC: estimated
(10 cm GCC shift)

Correlations between the parameters



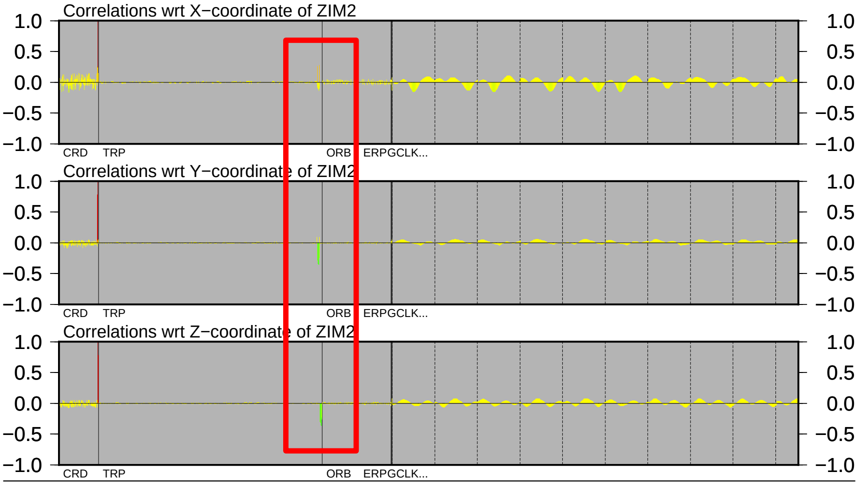
Solution setup		Results			
Datum	GCC	Chi^2	CRD	GCC	ORB
NNR+NNT	estimate	0.00	0.00	0.10	0.00

Correlations between the parameters



Solution setup		Results			
Datum	GCC	Chi^2	CRD	GCC	ORB
NNR+NNT	estimate	0.00	0.00	0.10	0.00

Correlations between the parameters



Solution setup		Results			
Datum	GCC	Chi^2	CRD	GCC	ORB
NNR+NNT	estimate	0.00	0.00	0.10	0.00

Experiment 2: Geocenter with Simulated Data

Lessons learned from Experiment 2:

- (Even) in a global solution the NNT condition must be applied to complete the definition of the geodetic datum.

Experiment 2: Geocenter with Simulated Data

Lessons learned from Experiment 2:

- (Even) in a global solution the NNT condition must be applied to complete the definition of the geodetic datum.
- The correlations between geocenter parameters and the satellite clock parameters derived from the a posteriori covariance matrix are of the same order of magnitude as the correlations between station height and troposphere ZPD parameters.

Experiment 2: Geocenter with Simulated Data

Lessons learned from Experiment 2:

- (Even) in a global solution the NNT condition must be applied to complete the definition of the geodetic datum.
- The correlations between geocenter parameters and the satellite clock parameters derived from the a posteriori covariance matrix are of the same order of magnitude as the correlations between station height and troposphere ZPD parameters.

$\Longrightarrow$ In principle: **the geocenter parameters can be estimated from GNSS solutions.**

Experiment 2: Geocenter with Simulated Data

Lessons learned from Experiment 2:

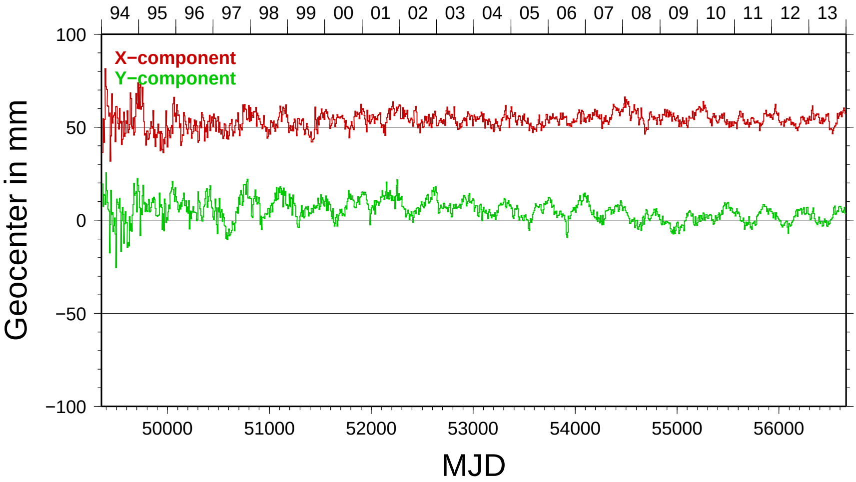
- (Even) in a global solution the NNT condition must be applied to complete the definition of the geodetic datum.
- The correlations between geocenter parameters and the satellite clock parameters derived from the a posteriori covariance matrix are of the same order of magnitude as the correlations between station height and troposphere ZPD parameters.

$\Longrightarrow$ In principle: **the geocenter parameters can be estimated from GNSS solutions.**

- *But what about their geodynamical interpretation?*

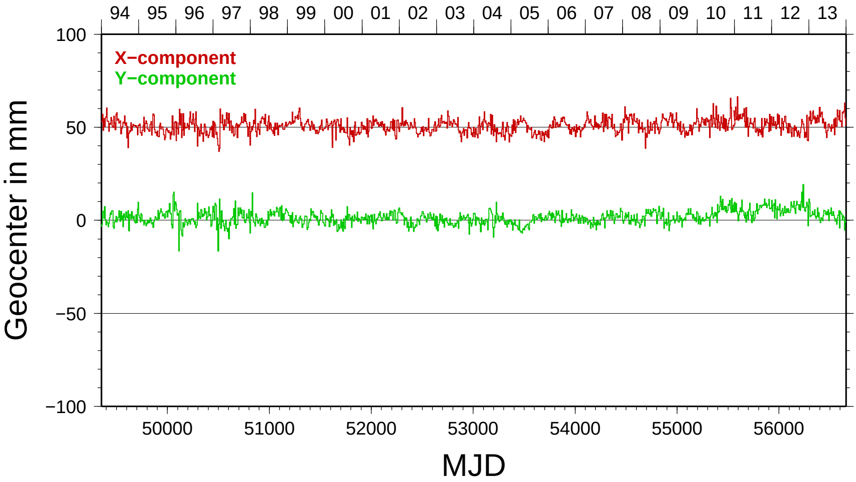
Geocenter Time Series from GNSS Solution

Geocenter time series from the CODE repro2 solution



Geocenter Time Series from GNSS Solution

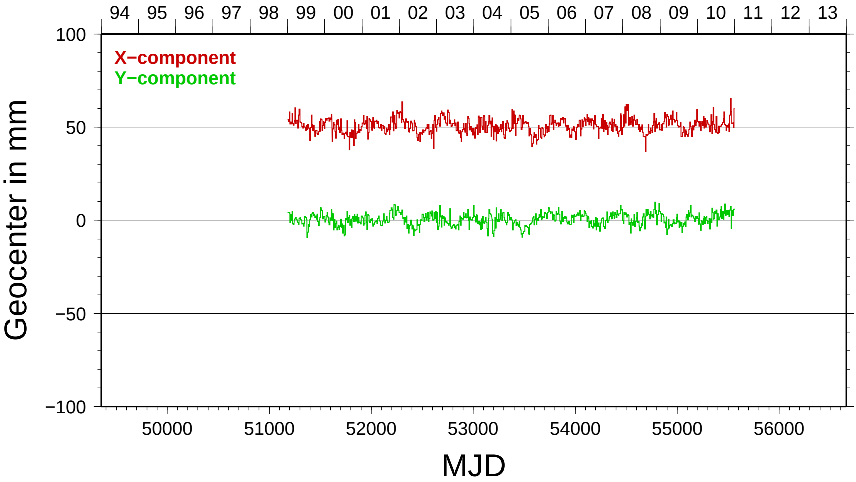
Geocenter time series from a LAGEOS solution



R. Dach et al.: Estimating the geocenter from GNSS data
IGS Workshop: Pasadena, June 23–27, 2014

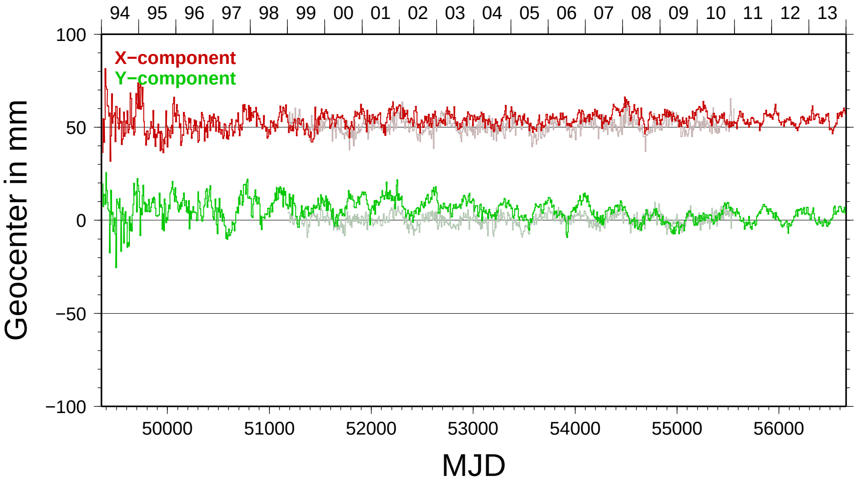
Geocenter Time Series from GNSS Solution

Geocenter time series from a LAGEOS solution



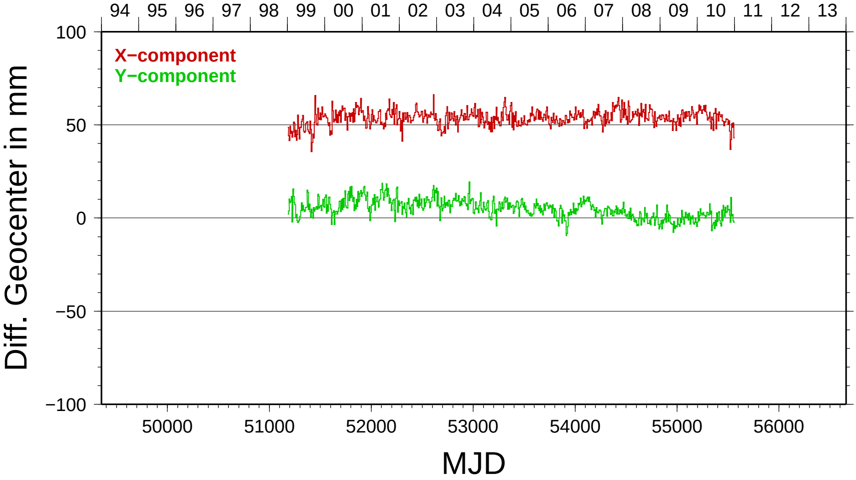
Geocenter Time Series from GNSS Solution

Geocenter time series from the CODE repro2 and a LAGEOS solution



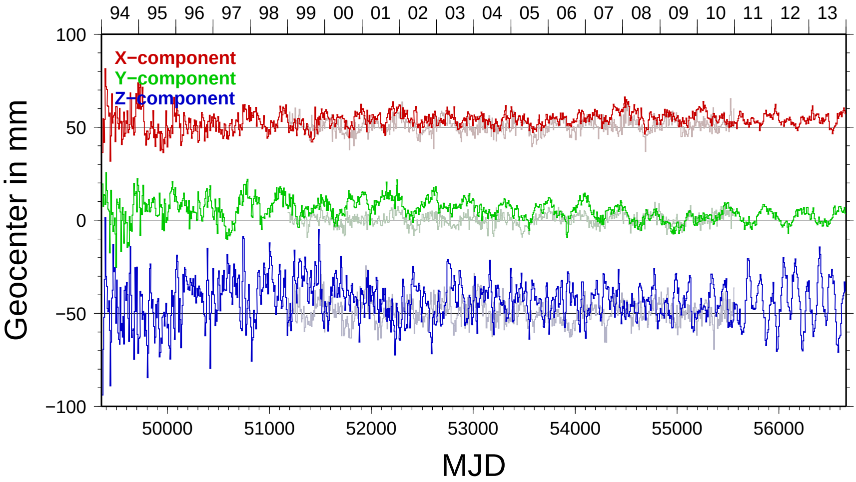
Geocenter Time Series from GNSS Solution

Geocenter time series from the CODE repro2 and a LAGEOS solution



Geocenter Time Series from GNSS Solution

Geocenter time series from the CODE repro2 and a LAGEOS solution



Estimating the Geocenter from GNSS data

Part II

Orbit Modeling Reflected by Geocenter Coordinate Series

GNSS Orbit Modeling

- For **GNSS satellites**, at an **altitude of ~20,000 km**,
  - ➔ non-conservative forces are very important for precise orbit determination and prediction
  - ➔ mismodelling issues or no models are used
  - ➔ gravitational forces have a low contribution to the orbit error budget

- Main non-conservative force ➔ **solar radiation pressure**

- Smaller non-conservative forces:
  - ➔ Earth radiation pressure
  - ➔ thermal radiation pressure

- Basically two types of models:
  - ➔ empirical models, based on in-orbit behavior
  - ➔ analytical/physical models, based on pre-launch information

Solar Radiation Pressure Modeling

- Modeling of non-conservative forces is a complex task!

- Acceleration due to solar radiation pressure

$$\vec{f} = -\frac{A}{M}\frac{S_0}{c}\cos\theta\left[(1-\rho)\vec{e}_D + 2\left(\frac{\delta}{3} + \rho\cos\theta\right)\vec{e}_N\right],$$

with:

$$\alpha + \rho + \delta = 1,$$

where:

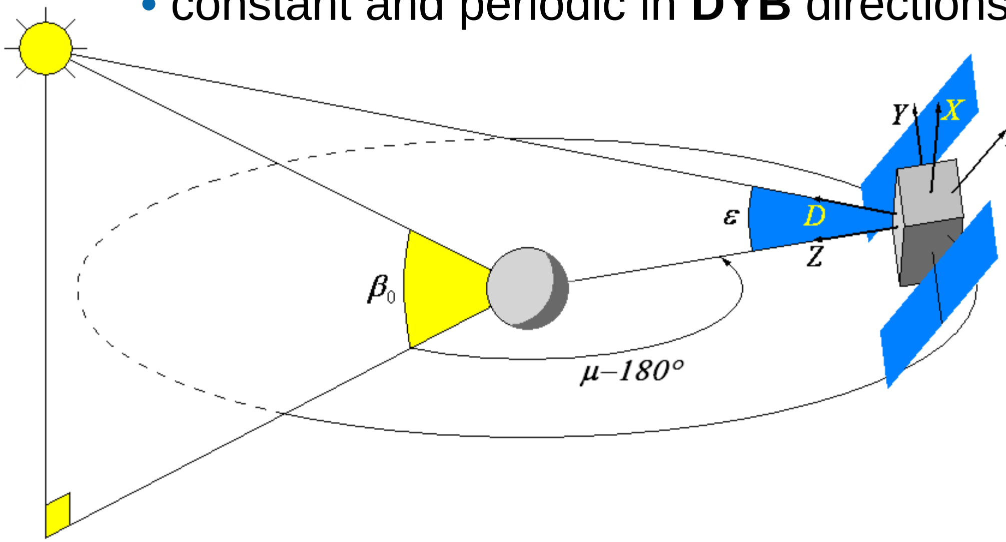
- Satellite properties
- Well known
- Satellite attitude, orientation in space

A	area of the surface
M	mass of the satellite
S_0	solar irradiance at 1 AU (≈ 1367 W/m^2)
c	velocity of light in vacuum
α	fraction of absorbed photons
ρ	fraction of reflected photons
δ	fraction of diffusely scattered photons
$\vec{e}_D$	direction of the Sun from the satellite
$\vec{e}_N$	normal to the satellite surface

$\cos\theta = \vec{e}_D \cdot \vec{e}_N$, valid only if $\cos\theta \geqslant 0$.

Solar Radiation Pressure Modeling

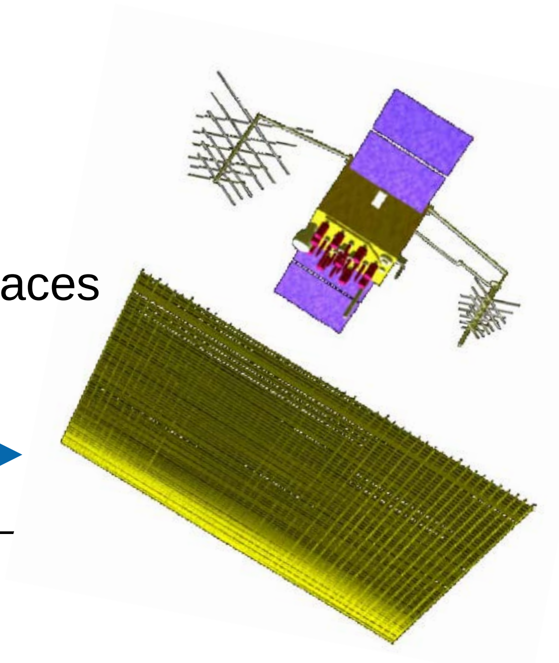
- **CODE empirical model:**
  - 5 empirical acceleration parameters [m/s²] per arc
  - constant and periodic in **DYB** directions



  - 3 stochastic pulses per day
    - radial
    - along-track
    - cross-track

- **Analytical models:**
  - knowledge e.g. from satellite manufacturers
  - nominal attitude
  - physical interaction between radiation and satellite surfaces

- Examples: **T20/T30** (Fliegel et al., 1992, 1996)
  UCL (Ziebart et al., 2005)

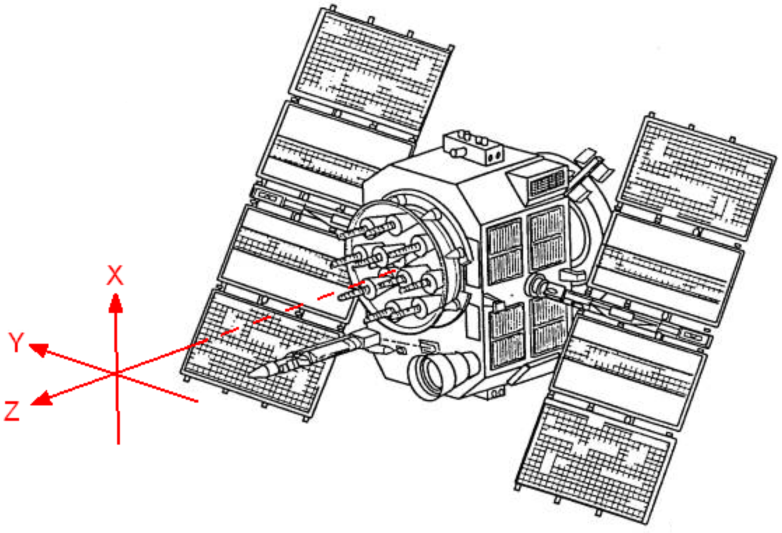


Solar Radiation Pressure Modeling

- **Physically based model:**

  Simple box-wing model for SRP

- Four main surfaces:
  - Solar panels front
  - Bus +X side
  - Bus +Z side
  - Bus –Z side

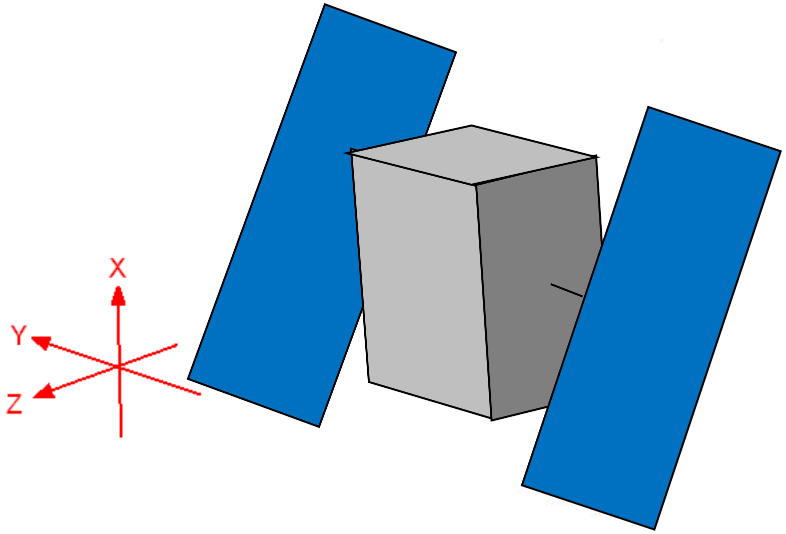


Solar Radiation Pressure Modeling

- **Physically based model:**

  Simple box-wing model for SRP

- Four main surfaces:
  - Solar panels front
  - Bus +X side
  - Bus +Z side
  - Bus –Z side



- Model capable of fitting the GNSS tracking data

  ➔ adjusting the optical properties of the satellite's surfaces

- Additionally adjustment of:
  - Stochastic pulses
  - Y-bias acceleration
  - **Solar panel rotation lag angle**

Three Different Solutions

- Reprocessing of 8 years (2004-2011) of GNSS tracking data
  - ➔ 3 solutions differing only on the non-conservative force modeling
  - ➔ GPS+GLONASS global solutions (up to 254 ground stations used)

- Solutions:

1) CODE (5-parameter) model + nominal yaw attitude (Beutler et al. 1994)

2) Adjustable box-wing model + nominal yaw attitude (Rodriguez-Solano et al. 2012)

3) Adjustable box-wing model + yaw attitude models (Rodriguez-Solano et al. 2013)

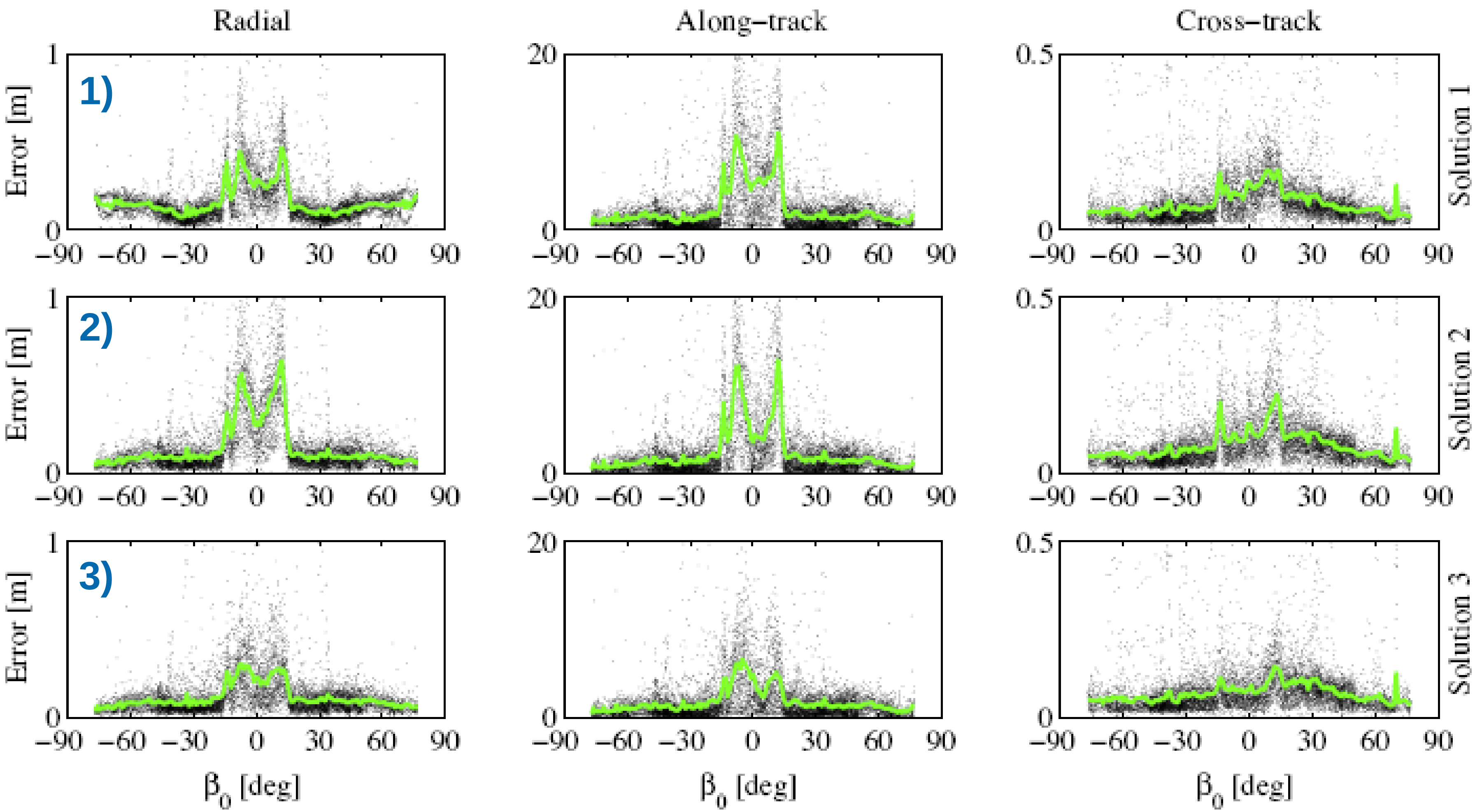
→ GPS-IIA (Bar-Sever 1996)
GPS-IIR (Kouba 2009)
GLONASS-M (Dilssner et al. 2011)

- Following results from:

Rodriguez-Solano CJ, Hugentobler U, Steigenberger P, Bloßfeld M, Fritsche M (2014) **Reducing the draconitic errors in GNSS geodetic products.** Journal of Geodesy 8(6): 559-574, doi:10.1007/s00190-014-0704-1

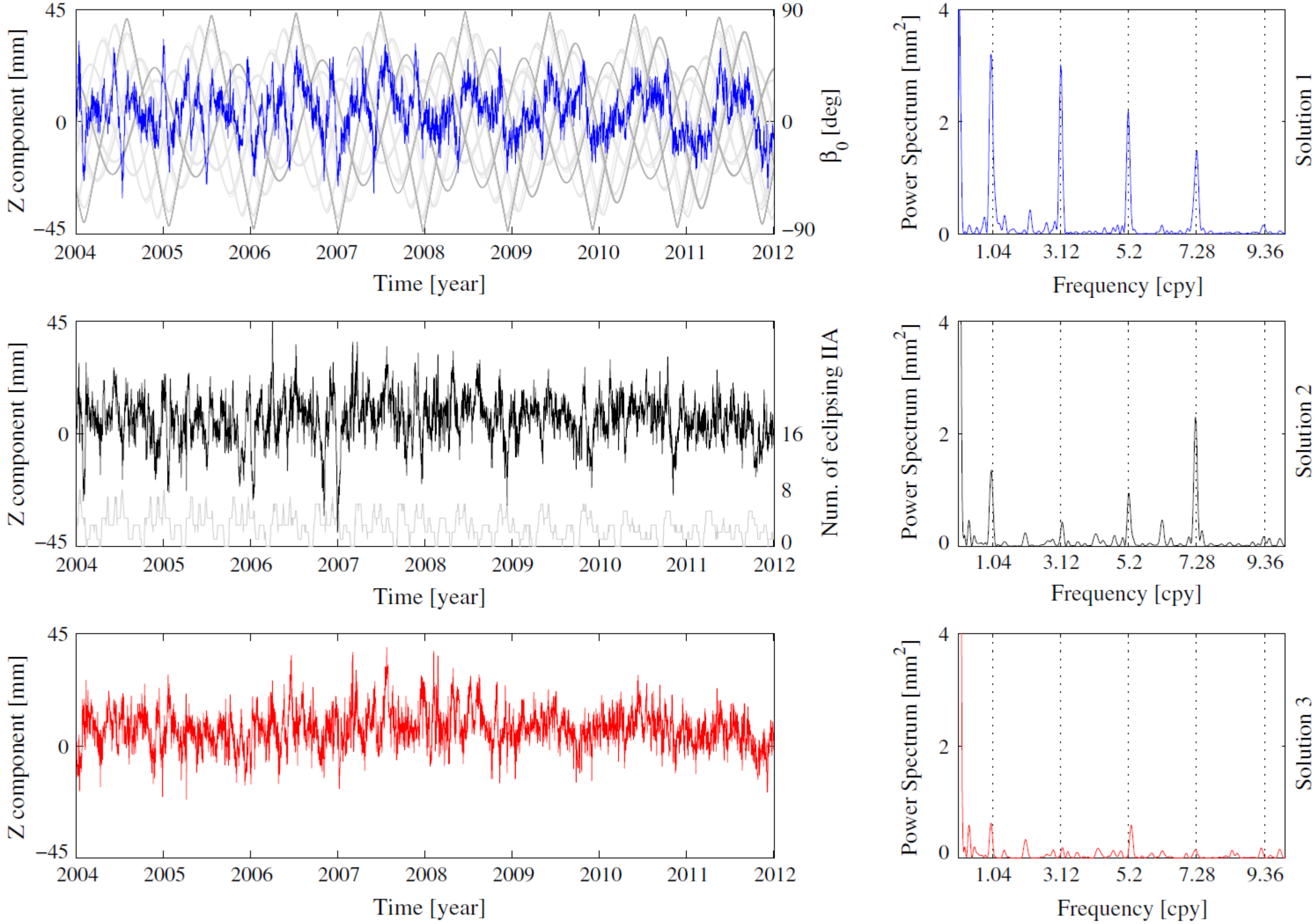
Impact on Satellite Orbits

- Orbit prediction error for Block IIA vs Sun elevation above the orbital plane



Impact on the Geocenter Z-component

Time series | Draconitic harmonics

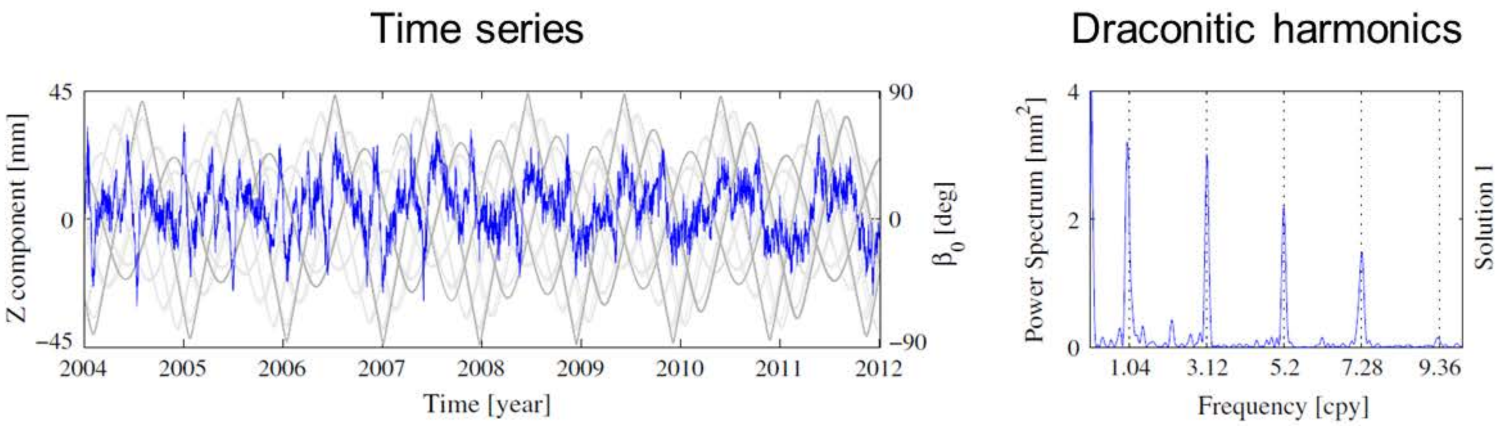


CODE + Nominal Attitude

Box-wing + Nominal Attitude

Box-wing + **Yaw Attitude Modeled**

Impact on the Geocenter Z-component

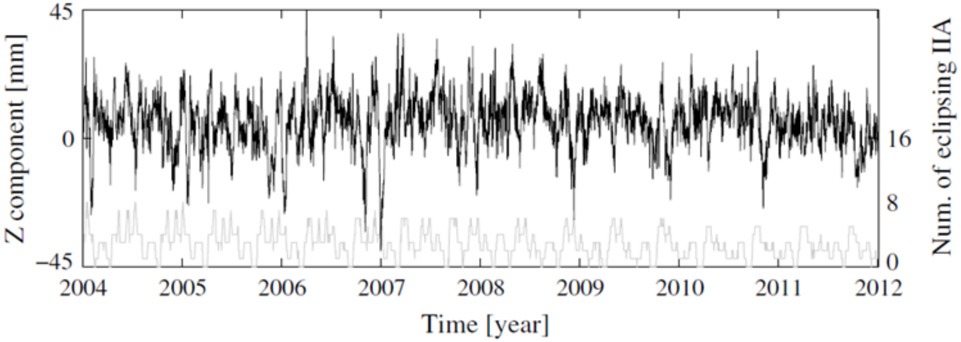


CODE + Nominal Attitude

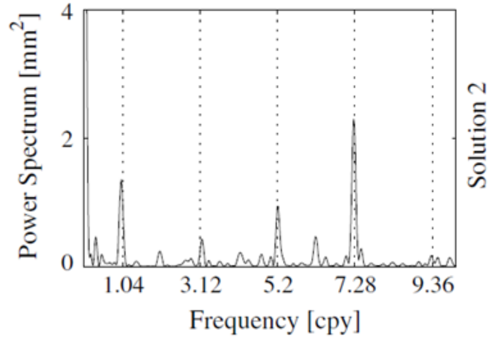
- Why the CODE model (solution 1) shows mainly odd draconitic harmonics?
  ➔ not yet an explanation

Impact on the Geocenter Z-component

Time series



Draconitic harmonics



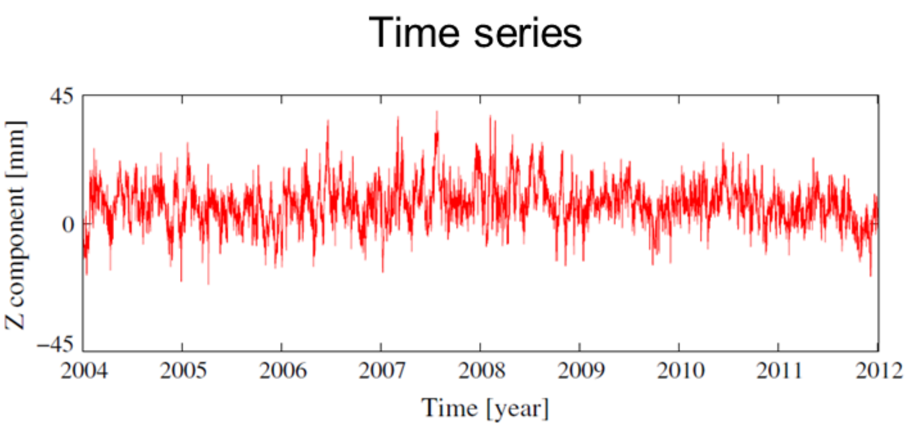
Box-wing +
Nominal
Attitude

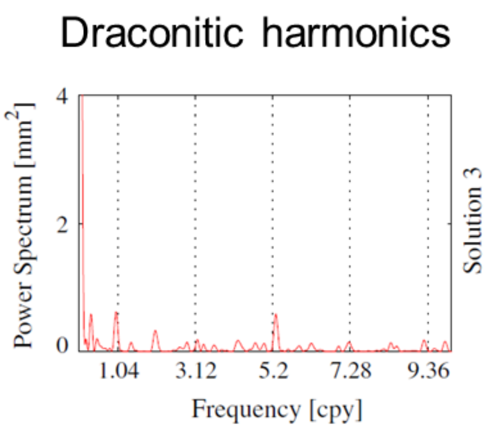
- Why the box-wing model with nominal attitude (solution 2) shows mainly errors at the 7th draconitic harmonic? ➔ explanation:

  ➔ The box-wing model with nominal attitude shows a degradation in the orbits (compared to the CODE model) during eclipse seasons, especially for GPS-IIA satellites

  ➔ The differences in days between consecutive GPS orbital planes along the ecliptic (not the equator) shows a peak close to 50 days ➔ 7th draconitic harmonic

Impact on the Geocenter Z-component





Box-wing +
Yaw Attitude Modeled

- Why the box-wing model combined with the yaw attitude models (solution 3) reduces significantly the 7th draconitic harmonic? ➔ explanation:

  ➔ The use of the yaw attitude models shows a significant improvement in the orbits (compared to the two previous models) during eclipse seasons, especially for GPS-IIA satellites

Conclusions

- Geocenter Z-component draconitic errors:
  ➔ **In total 92% reduction** from solution 1 to solution 3

- Despite a large reduction of the draconitic errors obtained for the geocenter *Z*-component ➔ not yet obtained the expected geophysical annual signal

- The geocenter Z-component is very sensitive to orbit modeling errors

- The box-wing model combined with the yaw attitude models <u>does not</u> remove completely the draconitic errors in the GNSS orbits
  ➔ other modeling problems remain, especially during eclipse seasons

- How the geocenter Z-component time series would look like if the remaining draconitic errors in the GNSS orbits could be corrected?