Estimating the geocenter from GNSS data

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A collinearity diagnosis of the GNSS geocenter determination

Paul Rebischung · Zuheir Altamimi · Tim Springer

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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 satellite phase center offsets. The inability of current GNSS, therefore, is not only due to collinearity, but also due to the degradation of the network shift approach, as well as correction for non-linearities and other systematics.

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.
A collinearity diagnosis of the GNSS geocenter determination

Paul Rebischung · Zuheir Altamimi · Tim Springer

Summay

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

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

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- **Coordinates**: minimum constrained solution with NNR+NNT condition on IGb08 for the reference sites
Experiment 1: Shifting the Geocenter

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An arbitrarily choosen one–day solution has been selected for this experiment: January 21, 2014.
Experiment 1: Shifting the Geocenter

<table>
<thead>
<tr>
<th>CoM wrt. Origin</th>
<th>RMS of adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0,0,0.00) m</td>
<td>1.59 mm</td>
</tr>
</tbody>
</table>

Diagram shows the origin and center of mass (CoM) in a three-dimensional coordinate system with axes x, y, and z.
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
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CoM wrt. Origin | RMS of adjustment
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(0,0,0.10) m | 1.60 mm
(0,0,1.00) m | 2.01 mm
Experiment 1: Shifting the Geocenter

<table>
<thead>
<tr>
<th>Shifting the CoM wrt. Origin</th>
<th>Impact on coordinates dZ</th>
<th>RMS of adjustment</th>
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<tbody>
<tr>
<td>(0,0,0.00) m</td>
<td>0.03 mm</td>
<td>0.23 mm</td>
</tr>
<tr>
<td>(0,0,0.01) m</td>
<td>0.30 mm</td>
<td>2.32 mm</td>
</tr>
<tr>
<td>(0,0,0.10) m</td>
<td>3.00 mm</td>
<td>23.2 mm</td>
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<th>Shifting the CoM wrt. Origin</th>
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<tr>
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Experiment 1: Shifting the Geocenter

DZ

- Full RPR
- RPR w/o DO
- No RPR
- No RPR & no pulses
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

Description of the problem

Experiment 1: Shifting the Geocenter

- Experiment 2: Geocenter with Simulated Data
  - The simulation setup
  - Reference solutions
  - Correlations between the parameters

Geocenter Time Series from GNSS Solution
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

![Diagram showing reference solutions](image)

**Solution setup**

<table>
<thead>
<tr>
<th>Datum</th>
<th>GCC</th>
<th>Chi$^2$</th>
<th>CRD</th>
<th>GCC</th>
<th>ORB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NNR+NNT</td>
<td>estimate</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>NNR</td>
<td>fixed</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>NNR+NNT</td>
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- Original geometry from simulation
Modified reference solutions

- Original geometry from simulation
- Artificial geocenter shift: 10 cm
## Modified reference solutions

- Original geometry from simulation
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### Solution setup

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<tr>
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<td>NNR</td>
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Modified reference solutions

- Original geometry from simulation
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<table>
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<tr>
<th>Solution setup</th>
<th>Results</th>
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<td>NNR+NNT estimate</td>
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<td>NNR+NNT fixed</td>
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<td>☑️0.00</td>
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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.
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Correlations between the parameters

Correlations wrt geocenter X

Correlations wrt geocenter Y

Correlations wrt geocenter Z

Solution setup

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Correlations between the parameters

Correlations wrt X–coordinate of ZIM2

Correlations wrt Y–coordinate of ZIM2

Correlations wrt Z–coordinate of ZIM2

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Results

Astronomical Institute, University of Bern
Correlations between the parameters

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Astronomical Institute, University of Bern
Lesson learned from Experiment 2:

- (Even) in a global solution the **NNT condition must be applied** to complete the definition of the geodetic datum.
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- (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.
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→ In principle: the geocenter parameters can be estimated from GNSS solutions.
Experiment 2: Geocenter with Simulated Data

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- (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.

⇒ In principle: the geocenter parameters can be estimated from GNSS solutions.

- But what about their geodynamical interpretation?
Geocenter time series from the CODE repro2 solution
Geocenter Time Series from GNSS Solution

Geocenter time series from a LAGEOS solution

![Graph showing geocenter time series from a LAGEOS solution](image-url)
Geocenter time series from a LAGEOS solution
Geocenter time series from the CODE repro2 and a LAGEOS solution

MJD

Geocenter in mm

X-component
Y-component

50000 51000 52000 53000 54000 55000 56000

94 95 96 97 98 00 01 02 03 04 05 06 07 08 09 10 11 12 13
Geocenter time series from the CODE repro2 and a LAGEOS 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:
  \[
  \begin{align*}
  A & \quad \text{area of the surface} \\
  M & \quad \text{mass of the satellite} \\
  S_0 & \quad \text{solar irradiance at 1 AU (\approx 1367 \, \text{W/m}^2)} \\
  c & \quad \text{velocity of light in vacuum} \\
  \alpha & \quad \text{fraction of absorbed photons} \\
  \rho & \quad \text{fraction of reflected photons} \\
  \delta & \quad \text{fraction of diffusely scattered photons} \\
  \vec{e}_D & \quad \text{direction of the Sun from the satellite} \\
  \vec{e}_N & \quad \text{normal to the satellite surface}
  \end{align*}
  \]

- Satellite properties

- Well known

- Satellite attitude, orientation in space
  \[ \cos \theta = \vec{e}_D \cdot \vec{e}_N, \text{ valid only if } \cos \theta \geq 0. \]
Solar Radiation Pressure Modeling

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

- **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)

- 3 stochastic pulses per day
  - radial
  - along-track
  - cross-track
Solar Radiation Pressure Modeling

- Physically based model:
  Simple box-wing model for SRP

- Four main surfaces:
  \[
  \begin{align*}
  &\text{Solar panels front} \\
  &\text{Bus } +X \text{ side} \\
  &\text{Bus } +Z \text{ side} \\
  &\text{Bus } -Z \text{ side}
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Solar Radiation Pressure Modeling

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  \end{align*}
  \]

- Model capable of fitting the GNSS tracking data
  \[\Rightarrow\text{adjusting the optical properties of the satellite’s surfaces}\]

- Additionally adjustment of:
  \[\begin{align*}
  &\text{Stochastic pulses} \\
  &\text{Y-bias acceleration} \\
  &\text{Solar panel rotation lag angle}
  \end{align*}\]
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)

- Following results from:
Impact on Satellite Orbits

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

![Graphs showing orbit prediction error for Block IIA vs Sun elevation](image-url)
Impact on the Geocenter Z-component

**Time series**

- **Box-wing**:
  - Nominal Attitude

- **CODE + Nominal Attitude**

- **Box-wing + Yaw Attitude Modeled**

**Draconitic harmonics**

- **Solution 1**
  - Power Spectrum

- **Solution 2**
  - Power Spectrum

- **Solution 3**
  - Power Spectrum
Impact on the Geocenter Z-component

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

- 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

- 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 does not 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?