Estimation of phase center variation and its effect on precise orbit determination

Akbar Shabanloui
Institute of Geodesy and Geoinformation
University of Bonn, Germany

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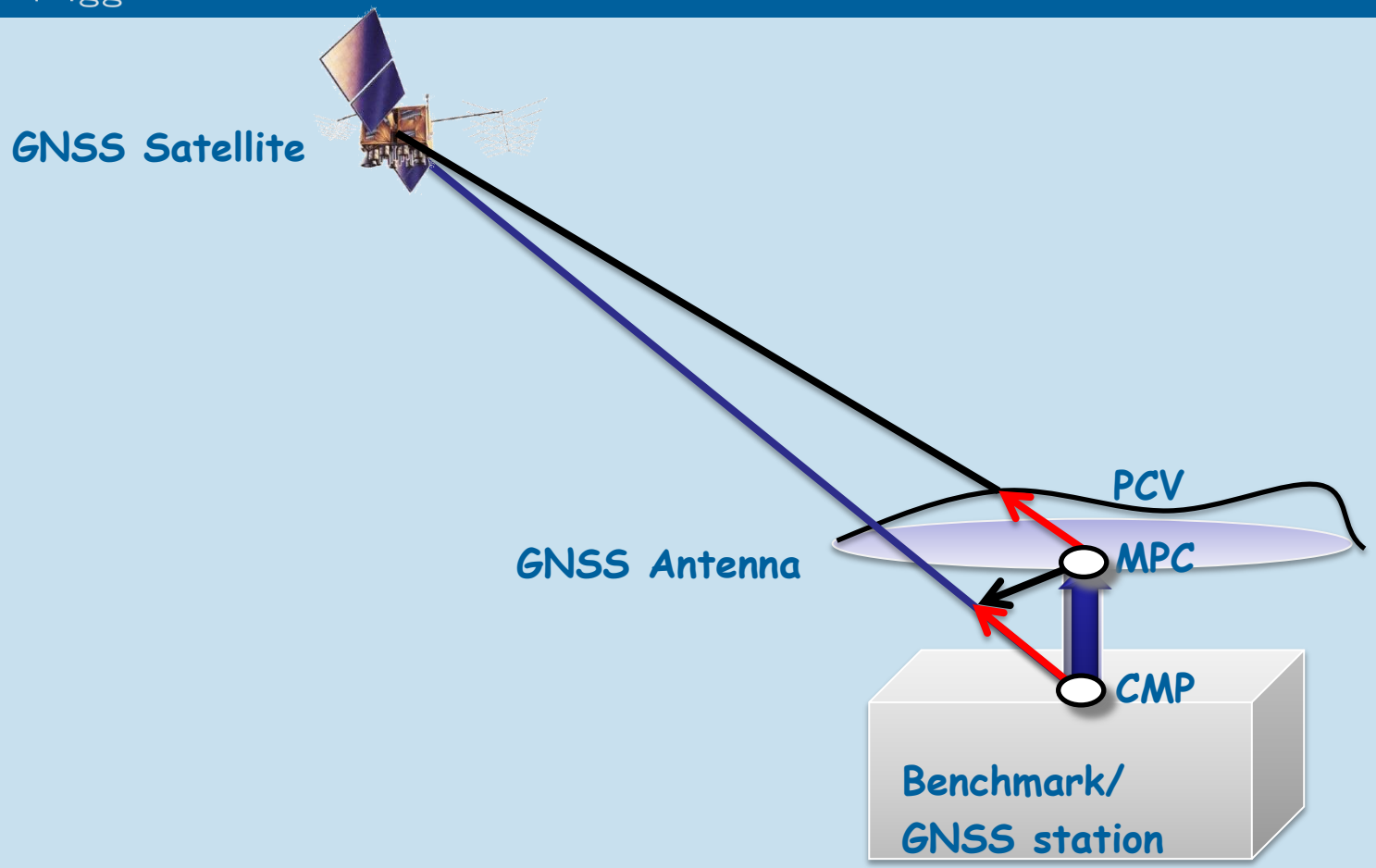
Outline

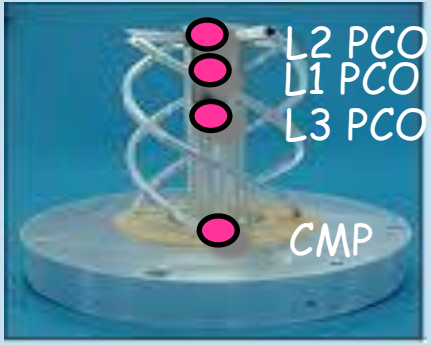
- Definition of phase center offset (PCO) and its variation (PCV)
- Modelling of Phase Center Varaition (PCV)
- Geometrical Precise Orbit Determination (GPOD)
- GPOD and PCV Results
  - ✓ GRACE
  - ✓ GOCE
- Conclusion

GNSS Antenna



GNSS Antenna offsets

- **CMP** (center of instrument's mounting plane): **frequency independent,** instrument offset, defined in the satellite (LEO) reference frame
- **PCO** (Phase center offset): **frequency dependent**, defined w.r.t **CMP** in the antenna reference frame (ARF)
- **PCV** (Phase center variations): **frequency dependent**, defined w.r.t **PCO** in the antenna reference frame (ARF), varying with the **direction** (azimuth and zenith) of incoming GNSS signal

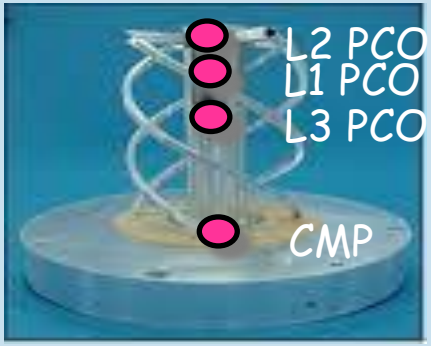


GOCE Antenna
Credit: ESA

Phase center offset & phase center variation

Carrier phase observation equation:

$$\Phi_{r,i}^{s}(t) = \rho_{r}^{s}(t) + c\delta t_{r}(t) - I_{r}^{s}(t) + T_{r}^{s}(t) +$$
$$+ \lambda_i A_{r,i}^{s_1} + O_{r,i}^{s}(t) + \varepsilon_{r,i}^{s}(t)$$



GOCE Antenna
Credit: ESA

Phase center offset and variation can be defined as:

$$O_{r,i}^{s}(t) = \mathbf{r}_0.\mathbf{e}_r^s + \Delta\Psi(\alpha, z)$$

According to Rothacher et al. (1995), phase center corrections (PCO and PCV) have some inherent degrees of freedom:

$$\mathbf{r}_0' \Rightarrow \mathbf{r}_0 + \Delta\mathbf{r}_0$$
$$\Delta\Psi'(\alpha, z) \Rightarrow \Delta\Psi(\alpha, z) - \Delta\mathbf{r}_0.\mathbf{e}_r^s + \Delta\Delta\Psi$$

PCO and PCV (cont.)

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$$\Delta\Psi'(\alpha, z) \Rightarrow \Delta\Psi(\alpha, z) - \Delta\mathbf{r}_0.\mathbf{e}_r^s + \Delta\Delta\Psi$$

$\Delta\mathbf{r}_0, \Delta\Psi_0$: arbitrary location of mean phase center and arbitrary phase offset for all directions

To avoid singularity we assume:

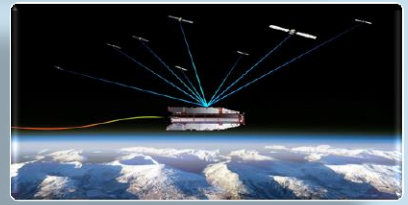
- ✓ Summation over all azimuth and zenith angles to zero (zero mean)
- ✓ Bore-sight to zero
- ✓ Other constrains…

PCO & PCV Determination

- Anechoic Test Chamber (Chamber measurements, relative PCO and PCV)

- Absoulte phase center offset and variation based on robot calibration

- Empirical estimation of PCV based on GNSS carrier phase residuals (in-flight calibration)



Modelling of PCV

PCV can be modelled based on spherical harmonic coefficients as:

$$\Delta\Psi(\alpha,z)=\sum_{n=0}^{n_{\max}}\sum_{m=0}^{n} c_{nm}C_{nm}(\alpha,z)+s_{nm}S_{nm}(\alpha,z)$$

with

$$C_{nm}(\alpha,z)=\bar{P}_{nm}(\cos z)\cos m\alpha$$

$$S_{nm}(\alpha,z)=\bar{P}_{nm}(\cos z)\sin m\alpha$$

With unknowns as $(n_{\max}=8-10)$: c_{nm}, s_{nm}

✓To prevent the normal equation systems from becoming singular, a priori constraint has to be added on each parameter (because of arbitrary phase shift!)

✓ With least squares method, the unknown parameters can be estaimated based on post-fit GNSS carrier phase residuals.

Generate Antenna PCV Map

✓After empirically estimation of spherical harmonics coefficients, the antenna PCO and PCV map can be generated as tabular correctios (e.g. ANTEX, Antenna Exchange Format).

✓The generated antenna PCO and PCV map can be used to future GNSS estimation procedure as a systematical error.

Advantages & Disadvantages

GNSS residual approach compared to other methods:

Advantages

- ✓Smaller effort
- ✓A large number of GNSS antennas in a short time period
- ✓A small accurate network with fixed positions can be used to calibrate and determine antenna PCO and PCV map

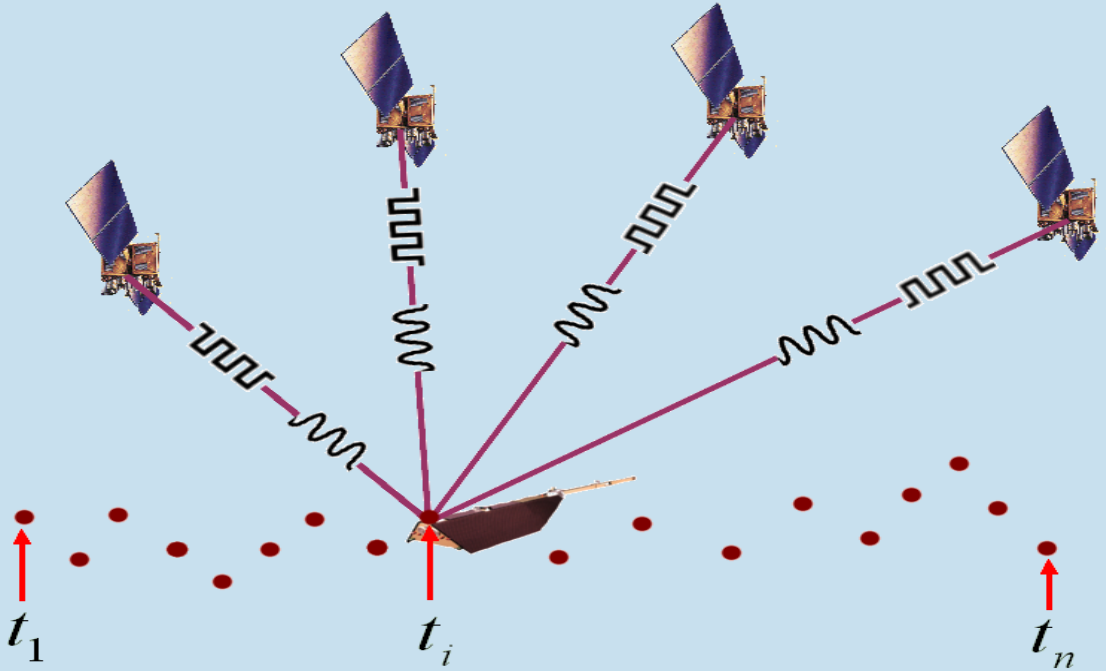
Disadvantages

- ✓Some iterations are needed to absorbe all residuals and estimate final antenna map
- ✓It denepends on the data availibity and data volume!

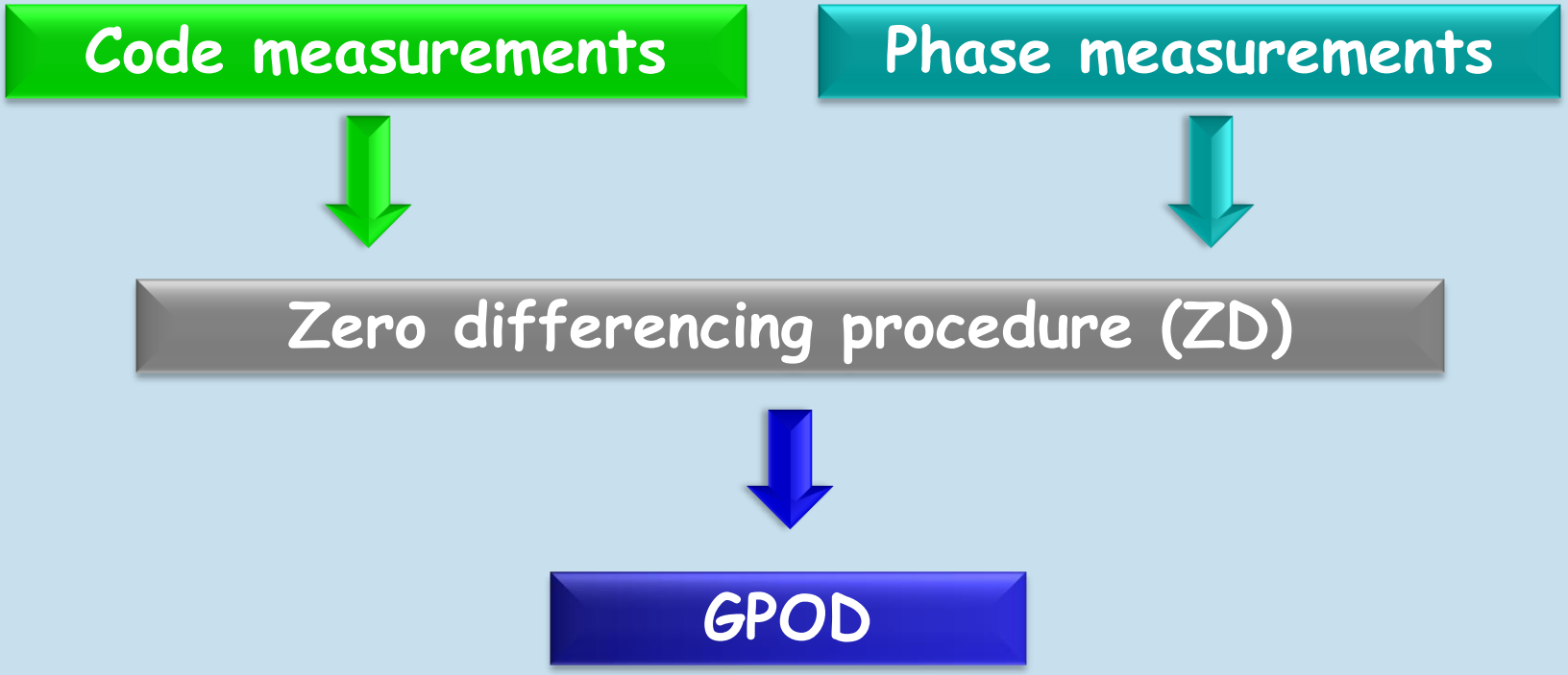
Precise Orbit Determination (POD)

Credit: European Space Agency (ESA)

Zero Differenced Geometrical POD



Processing concept



Zero differenced Geometrical POD

Zero Difference

Only connection between LEO and GPS satellites

Geometrical

Only pure geometrical relations between LEO and the GPS satellites have to be used, no force models and no constraints

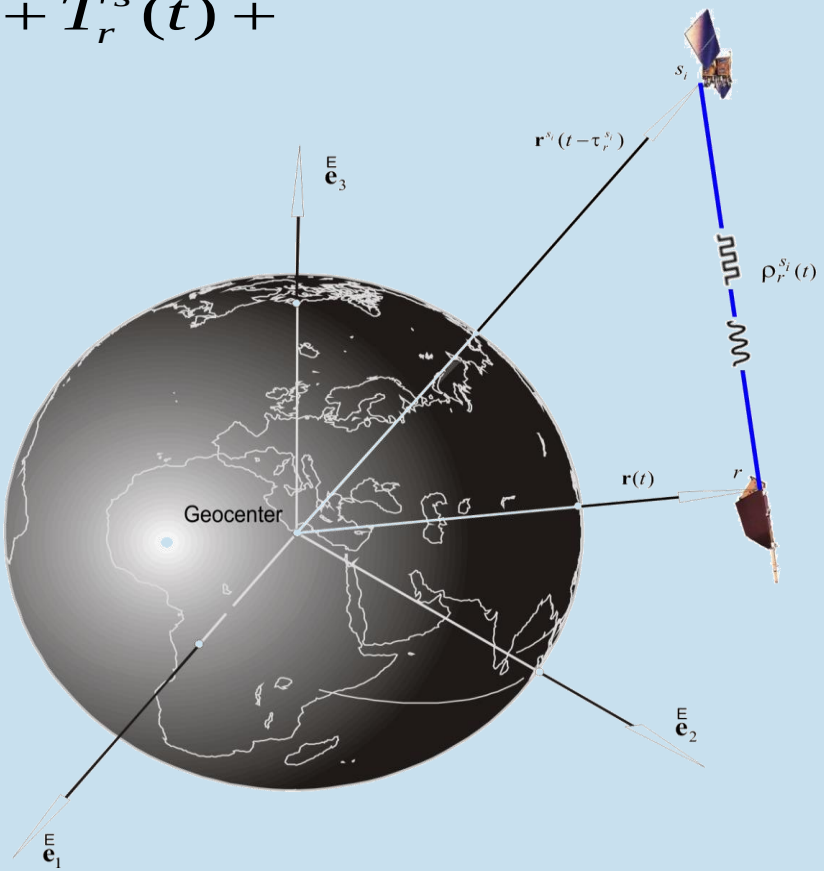
Precise

Consideration of all effects on SST observations, using precise GNSS ephemerides and clocks

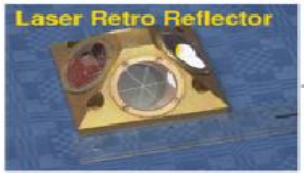
Precise Orbit Determination (POD)

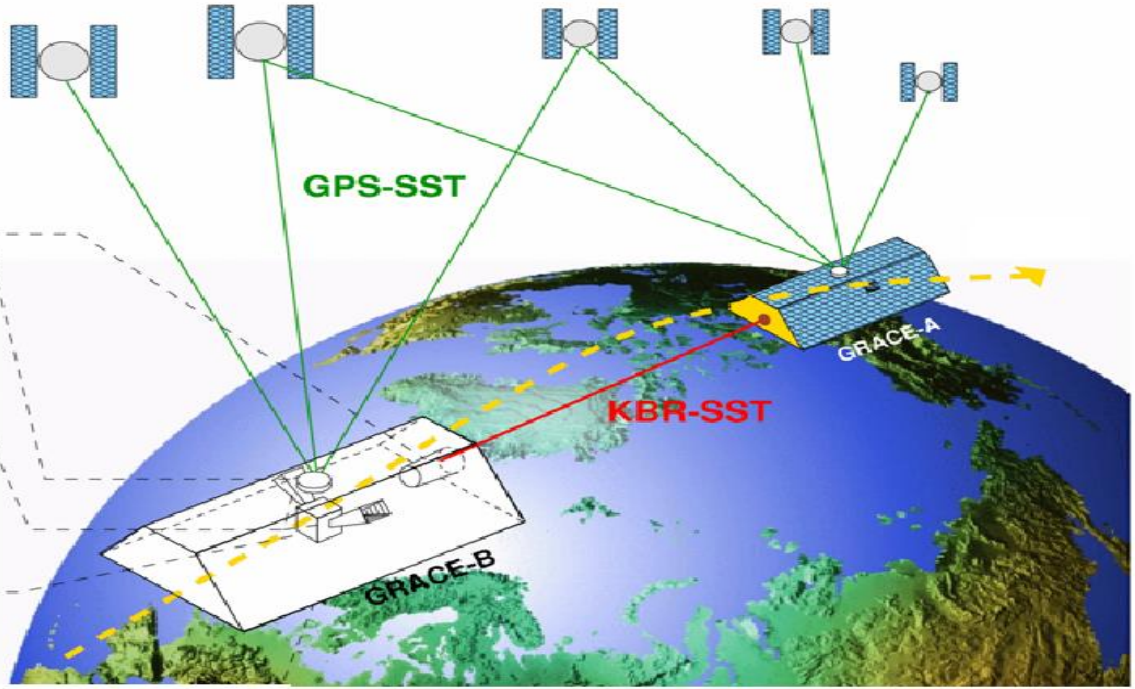
$$\Phi_{r,i}^{s}(t) = \rho_r^s(t) + c\delta t_r(t) - I_r^s(t) + T_r^s(t) + \\ + \lambda_i A_{r,i}^{s_1} + O_{r,i}^{s}(t) + \varepsilon_{r,i}^{s}(t)$$

- No tropospheric effect at LEO altitude (~250-1000 km)
- First order ionospheric effect eliminated with Ion-free linear combination
- Ambiguity term cannot be solved as integer (real)!
- GPS precise orbits (at 15 minutes) and clocks at 30 sec



GRACE (Gravity Recovery And Climate Explorer)



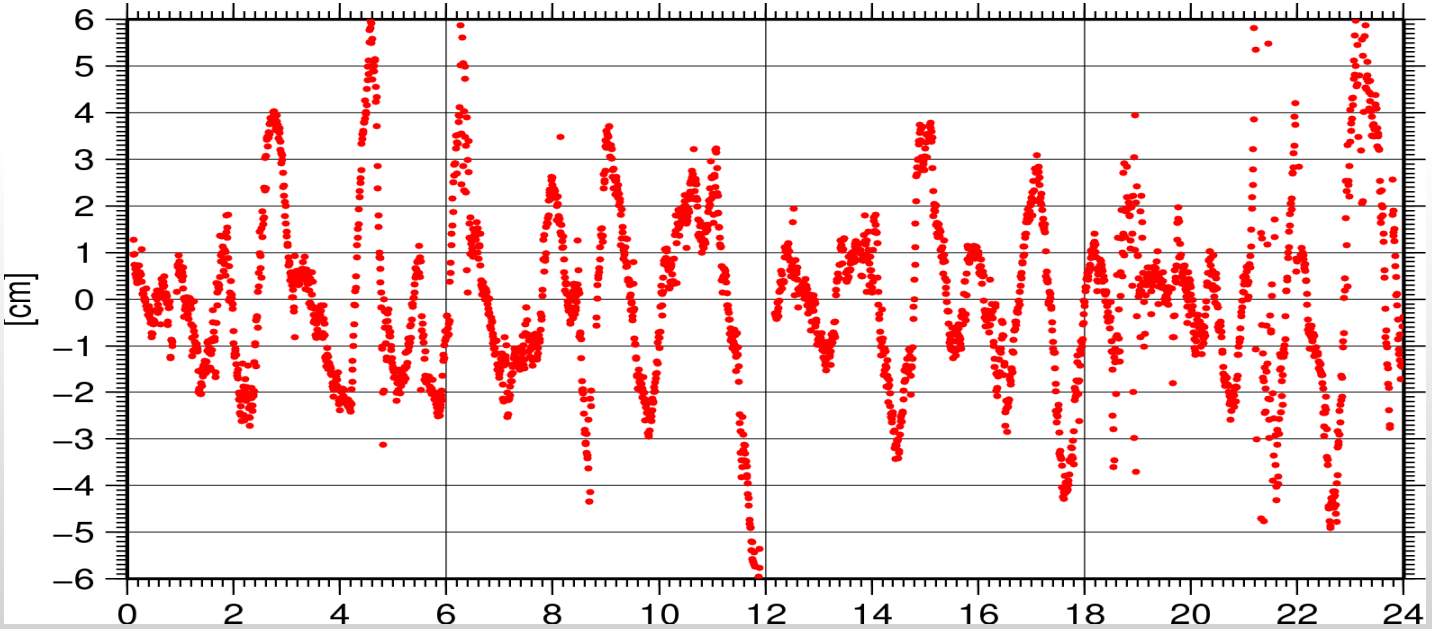


Start: 17 March 2002
Altitude: 500 km
Inclination: 89.5 deg

Excentricity: 0.002
Low-low SST: 220 km

GPS Processing of GRACE

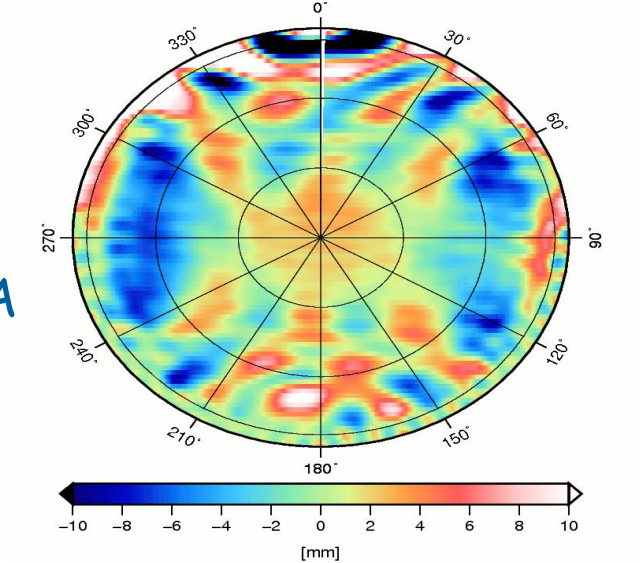
Comparison of GPS derived geometrical orbits and K-Band ranges



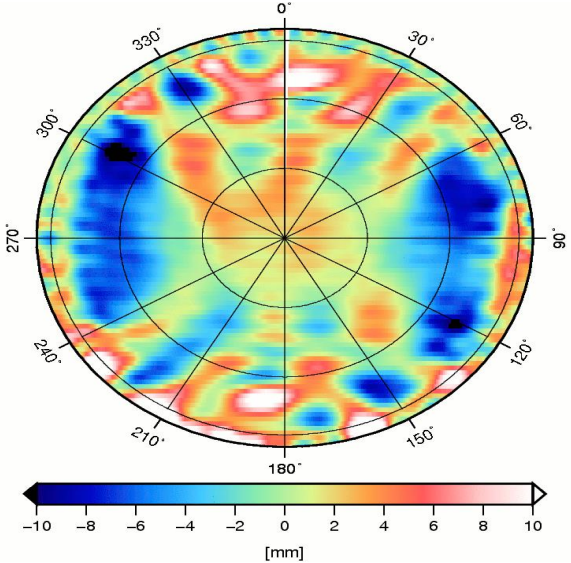
GNSS GRACE data processing

- More than 85 months of GNSS GRACE data have been used to estimated geometrical precise orbit of twin satellites
- Based on spherical harmonics, the phase center variations for twin satellites have been estimated as:

GRACE A

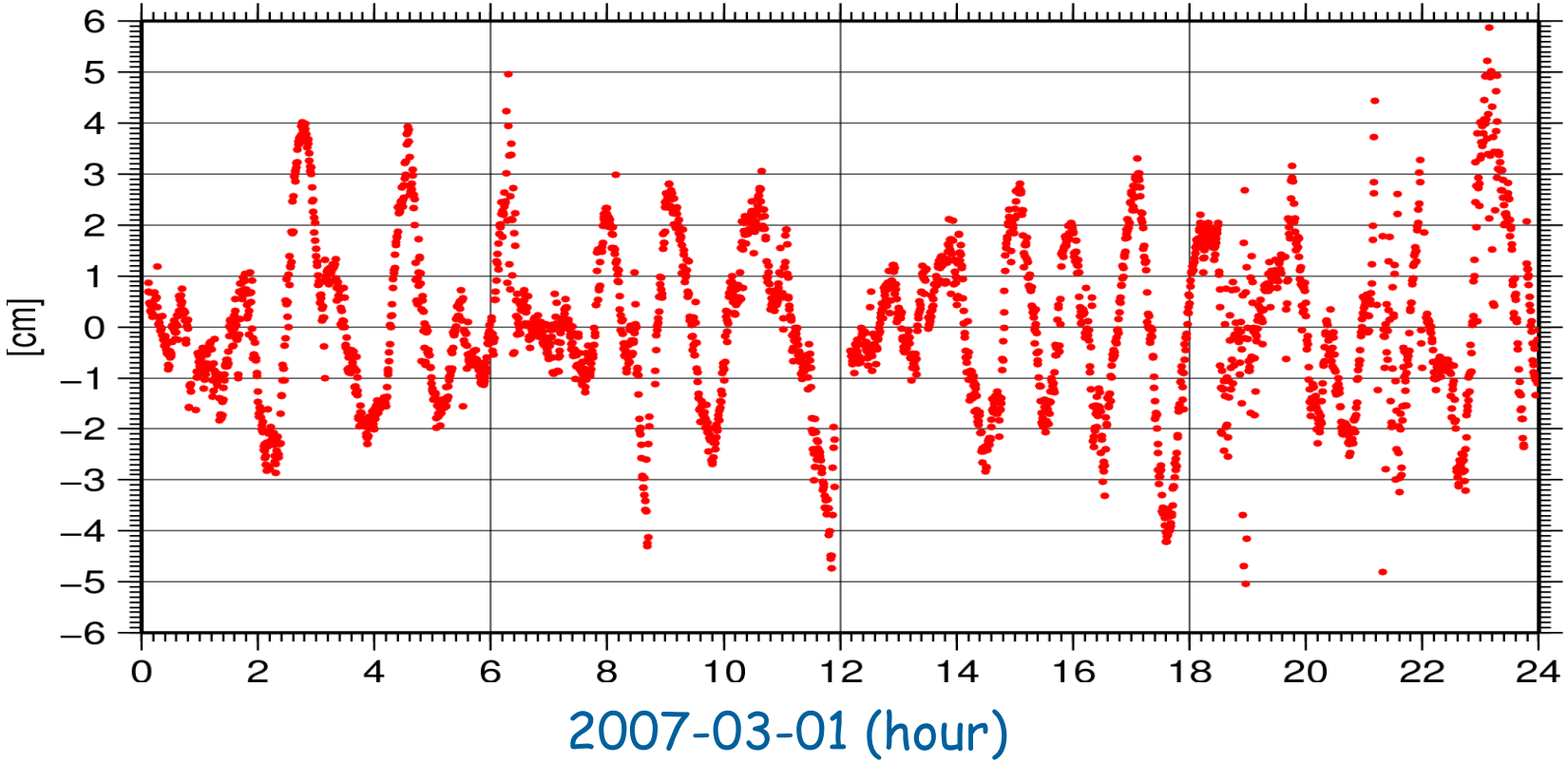


GRACE B

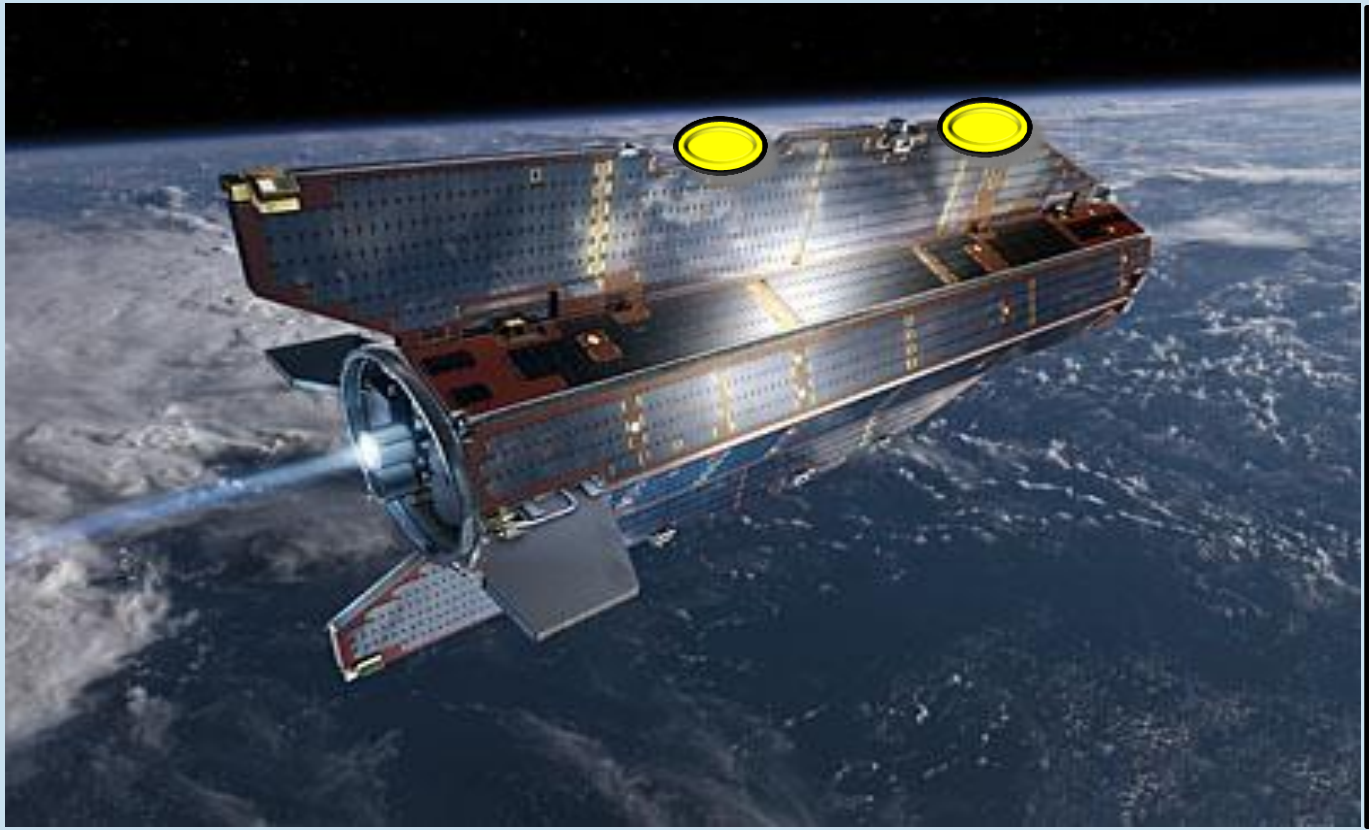


GPOD of GRACE after applying PCV

Comparison of GPS derived geometrical orbits and K-Band ranges



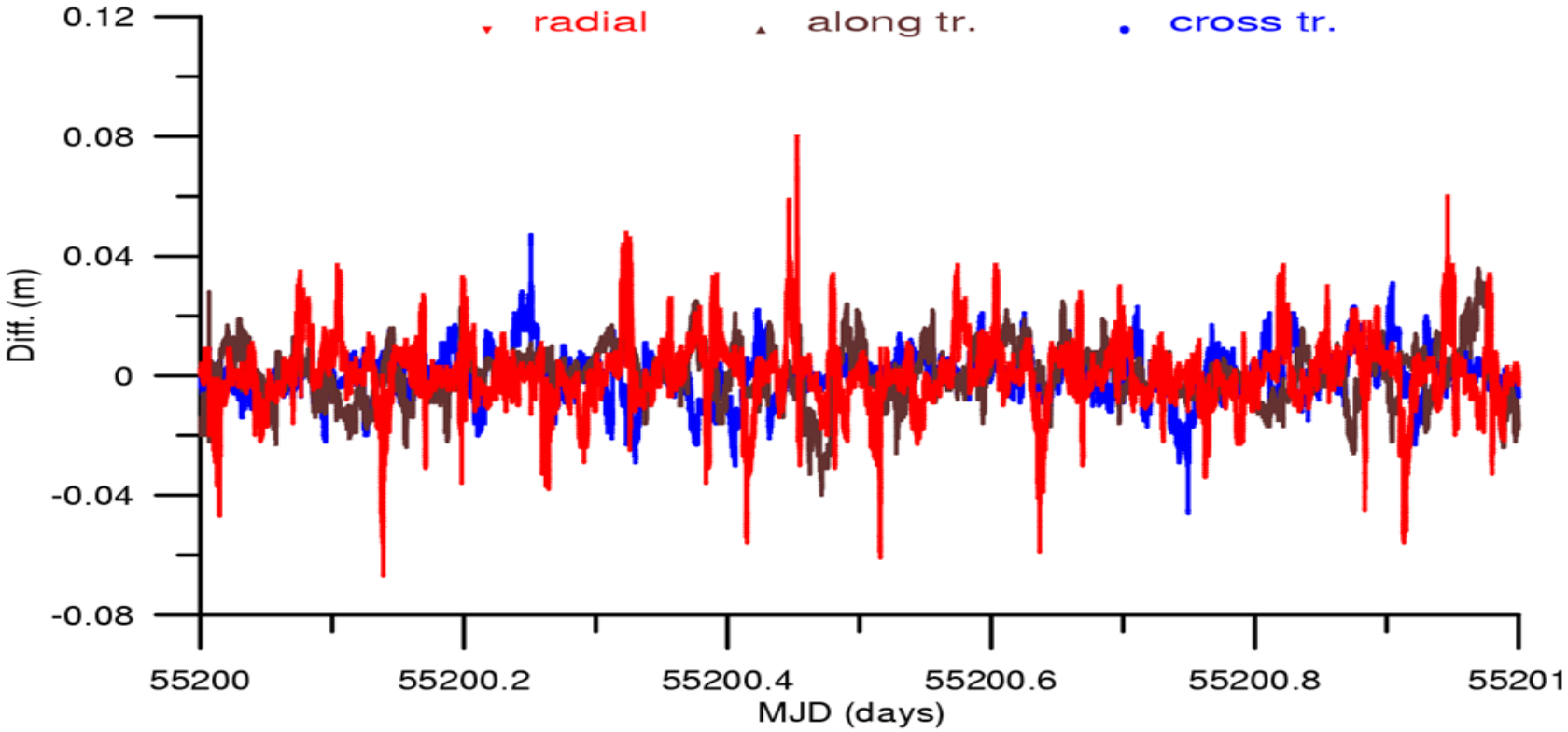
GOCE (Gravity & Ocean Circulation Explorer)



- Start: 17 Mar. 2009
- Altitude: 254 km
- Sun Synchronize
- Inclination: 96.5 deg

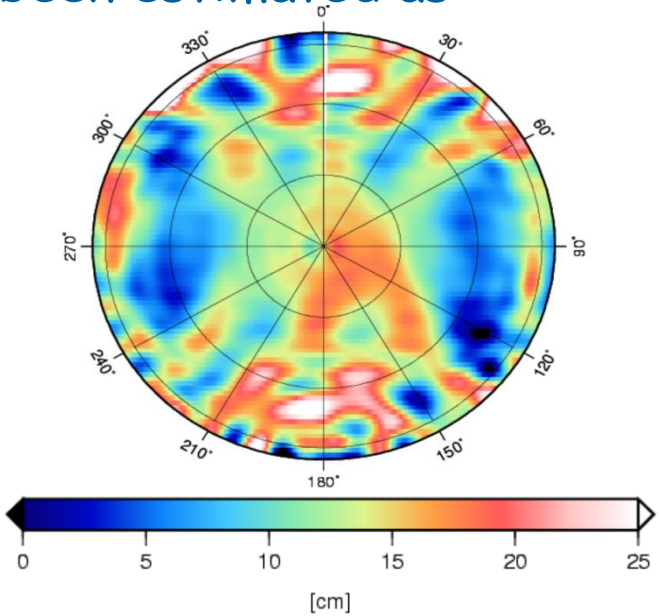
Geometrical POD of GOCE

Comparison of GPS derived geometrical POD and PSO orbit



Modelling of PCV

- More than 72 days of GNSS GOCE data have been used to estimated geometrical precise orbit of GOCE satellite
- Based on GNSS residuals, the phase center varaition of GOCE has been estimated as:



=>Estimated PCV should be used as a systematical effect on GPOD estimation procedure.

GPOD of GOCE after applying PCV

Comparison of GPS derived geometrical POD and PSO orbit

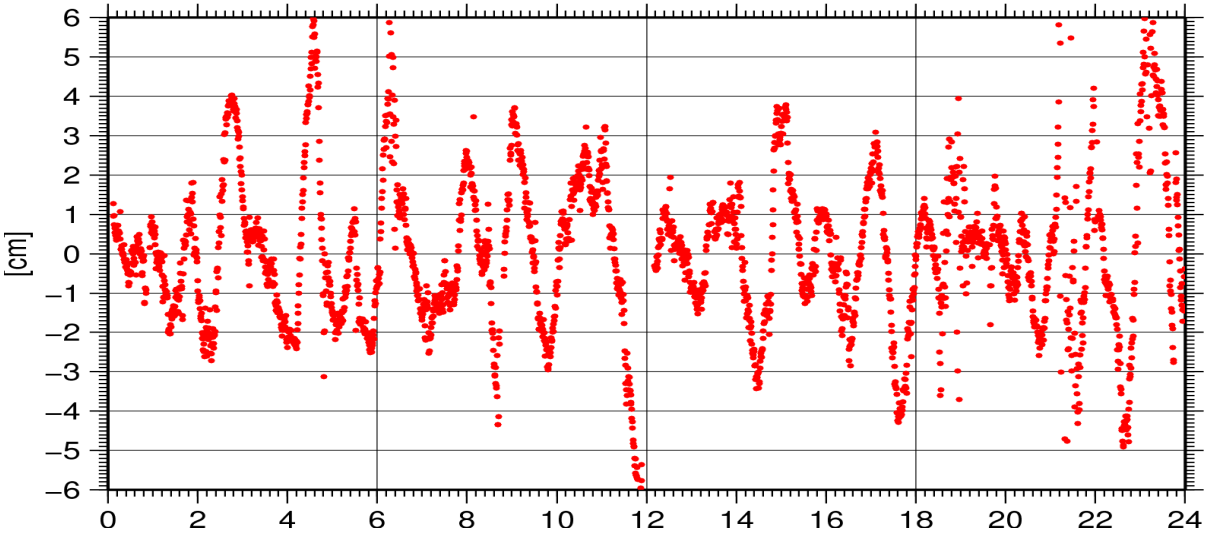
Conclusion

- ✓ GNSS-LEO satellites configuration and geometrical strength play an important role in Geometrical POD, subsequently in PCV
- ✓ PCV based on GNSS carrier phase observation residuals successfully implemented and affects Geometrical POD
- ✓ To estimate reliable phase center variation, long period of GNSS data should be used as pseudo-observations.
- ✓ No gravity field and no force models have been used in the Geometrical POD. Therefore, it can be directly used to recover of the Earth's gravity field.

Thank you
for your attention

GPS Processing

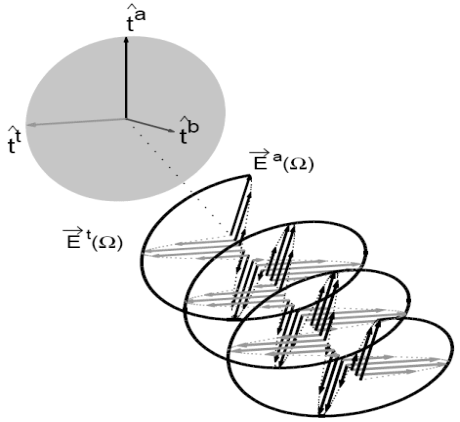
Comparison of
GPS derived kinematic orbits - K-Band ranges



2007-03-01 [hour]

- **Improvements in the GPS processing**

- F



G. Beyerle 2008

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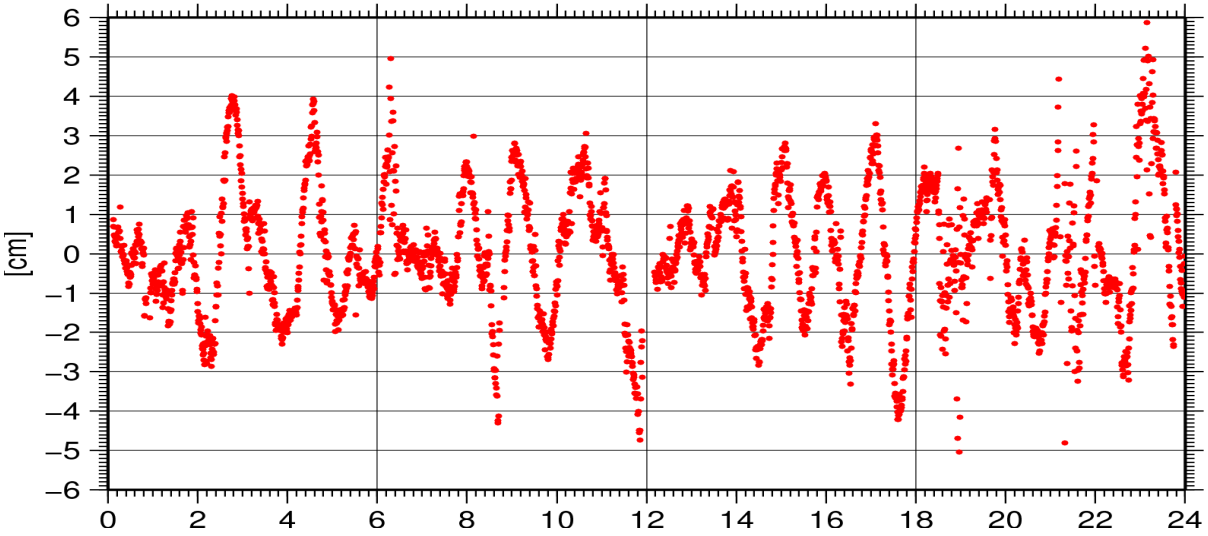

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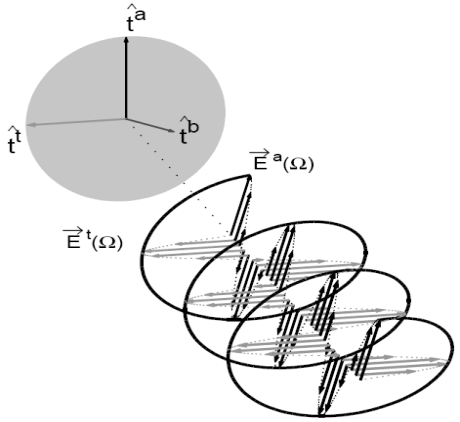

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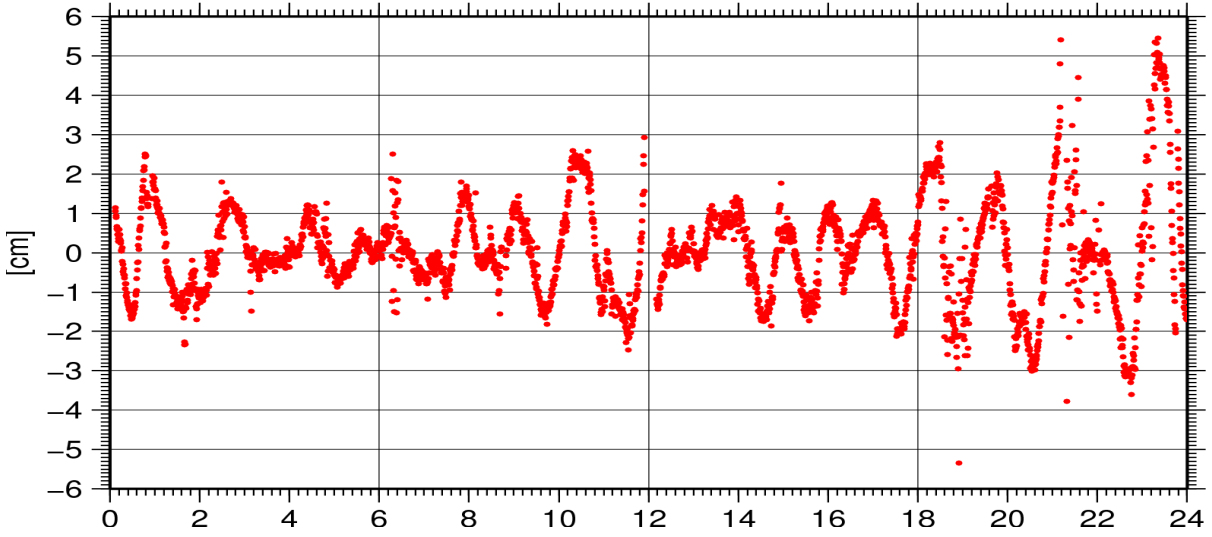
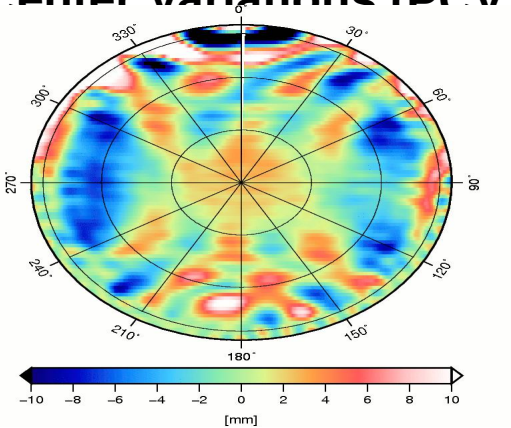


2007-03-01 [hour]

Improvements in the GPS processing

- Phase wind-up

•- Empirical Phase Center Variations (PCV)



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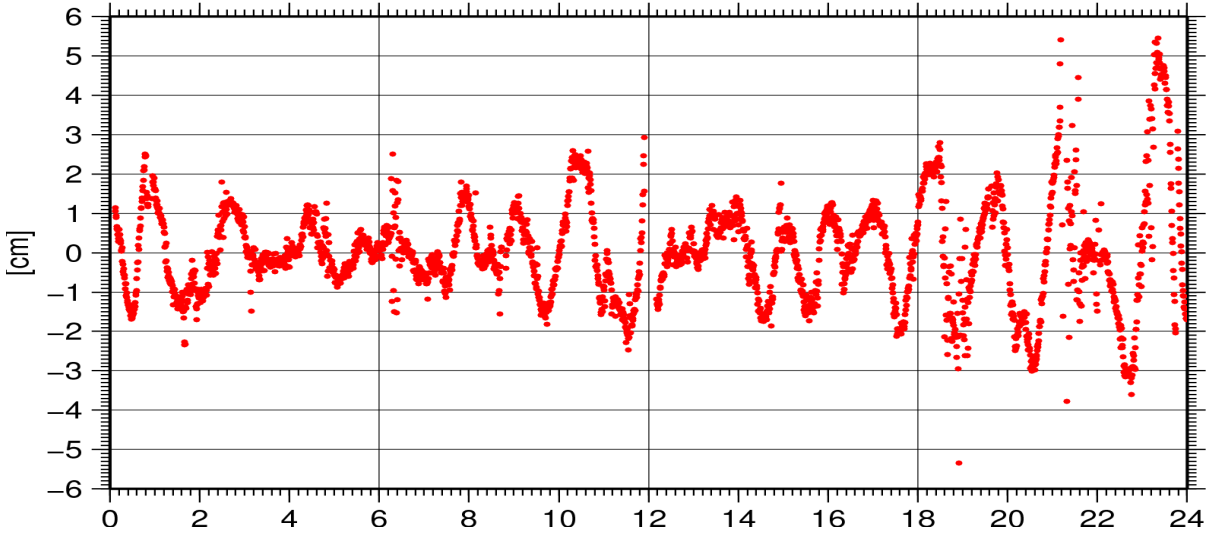


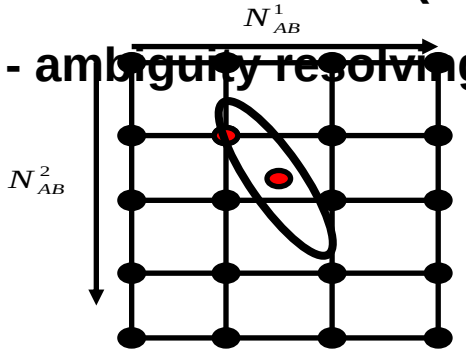
2007-03-01 [hour]

Improvements in the GPS processing

- Phase wind-up

- Empirical Phase Center Variations (PCV)

- ambiguity resolving



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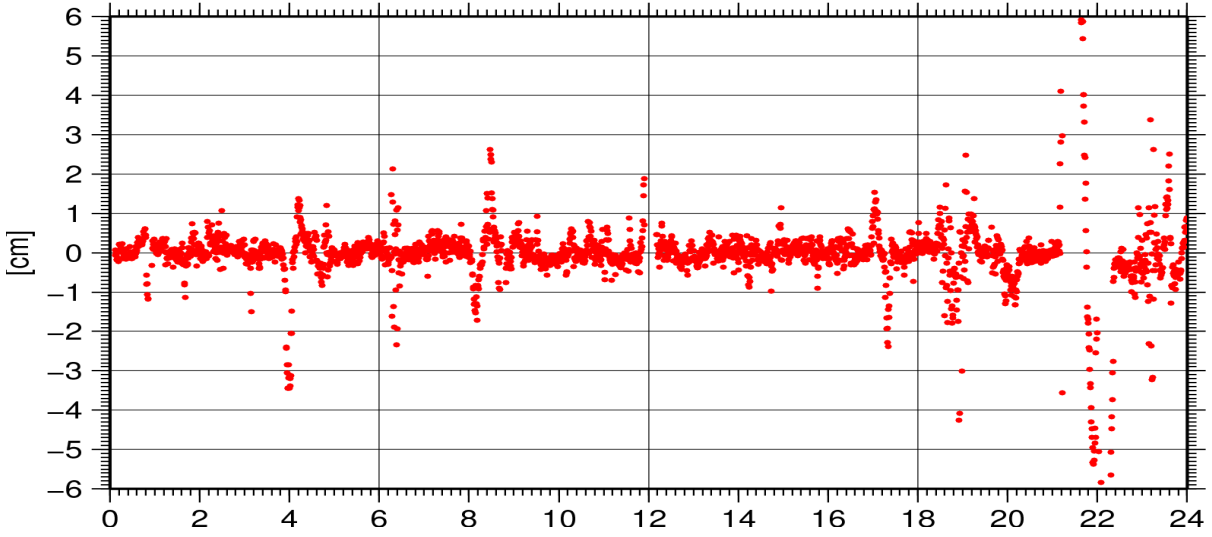

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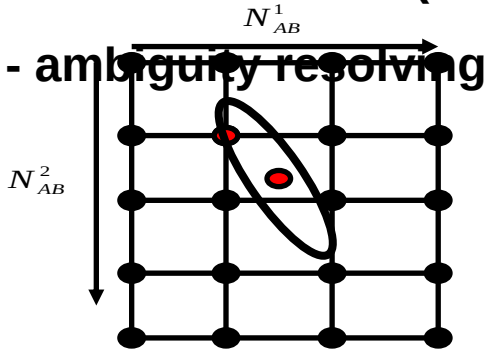
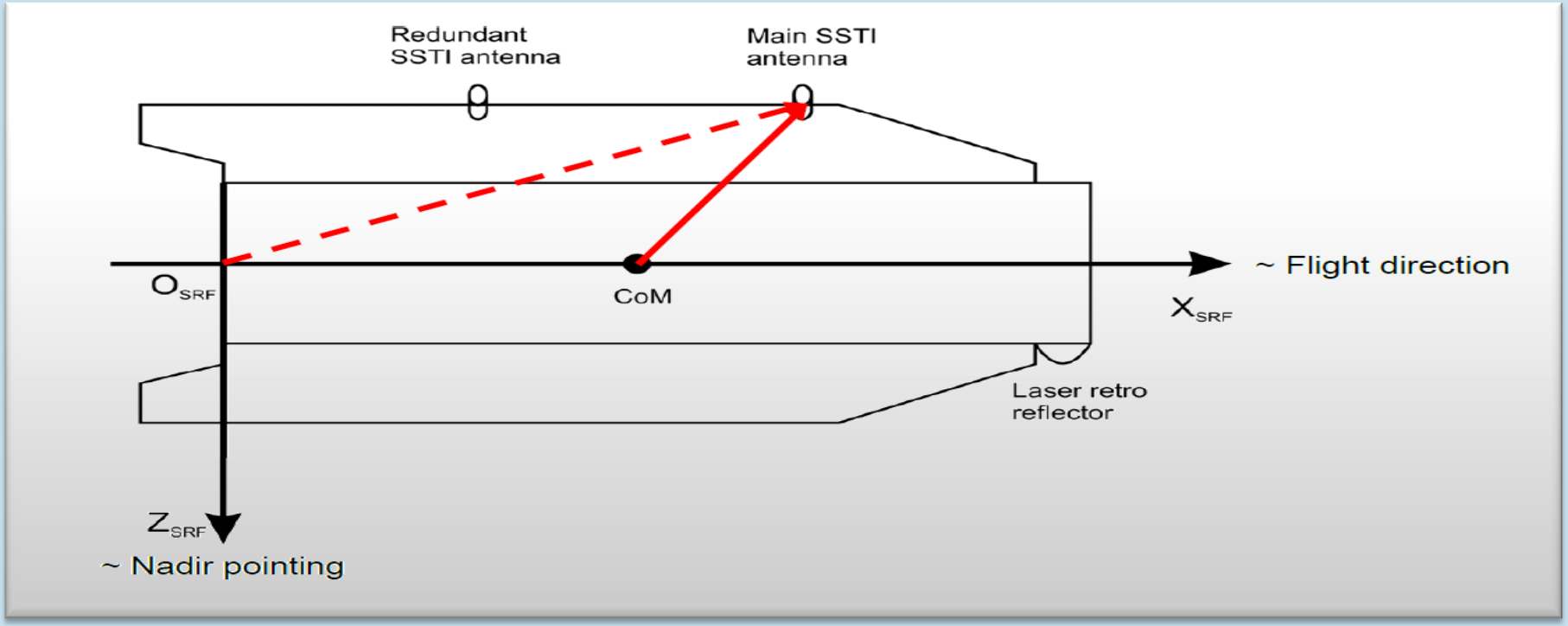
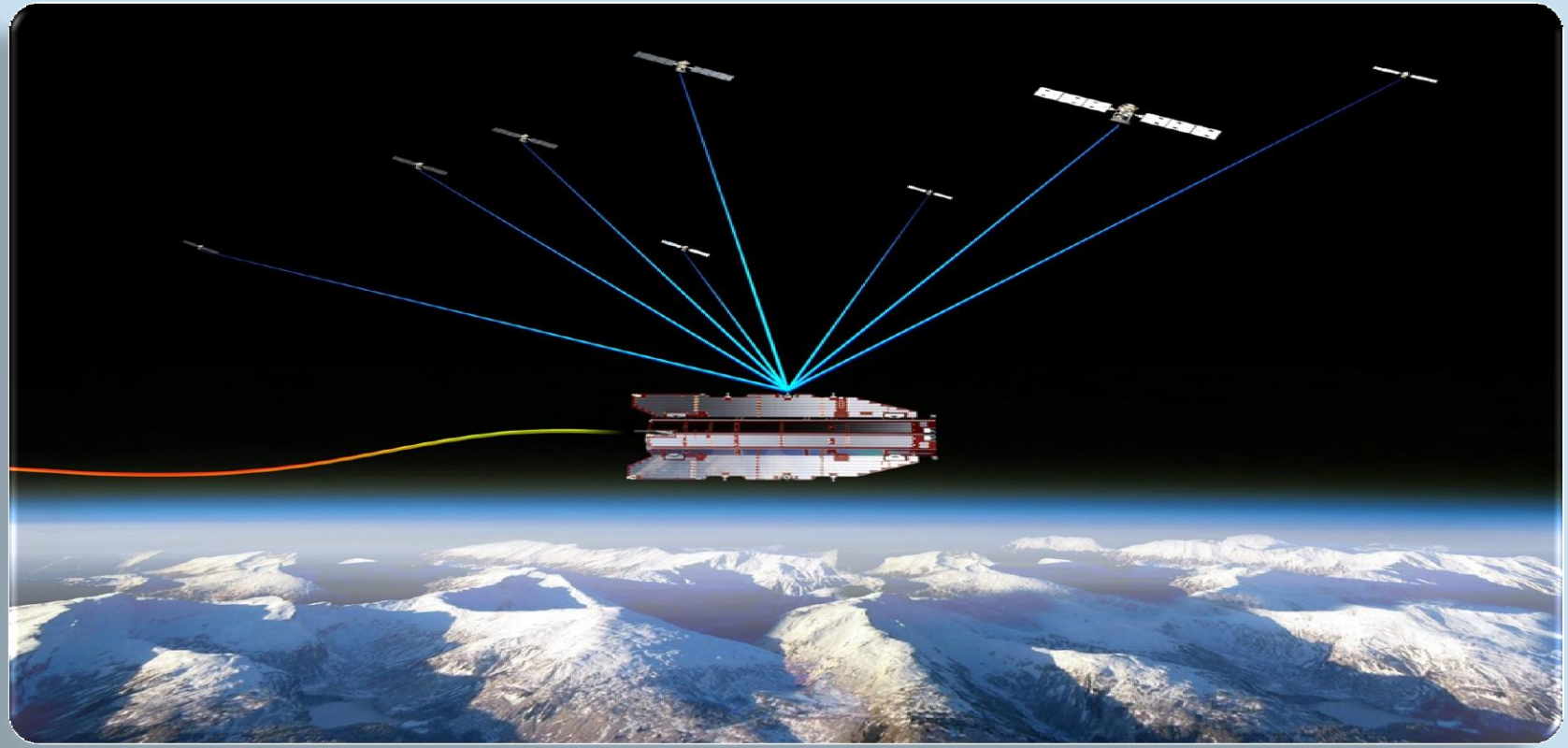


GOCE GNSS Antenna offsets



Precise Orbit Determination (POD)



Credit: European Space Agency (ESA)