Present and Future Impact of GNSS on Spaceborne Scientific Applications – *in particular on Orbit and Gravity Field Determination*

G. Beutler, A. Jäggi

Astronomical Institute, University of Bern (AIUB)

U. Hugentobler

Institut für Astronomische und Physikalische Geodäsie (IAPG)

24th European Frequency and Time Forum (EFTF)

ESTEC/ESA,

Noordwijk, the Netherlands

April 11-16, 2010

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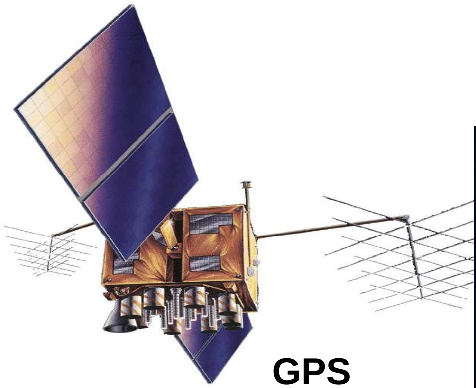
Global Navigation Satellite Systems 2010

Global Positioning System (GPS): **USA , ~ 30 satellites**

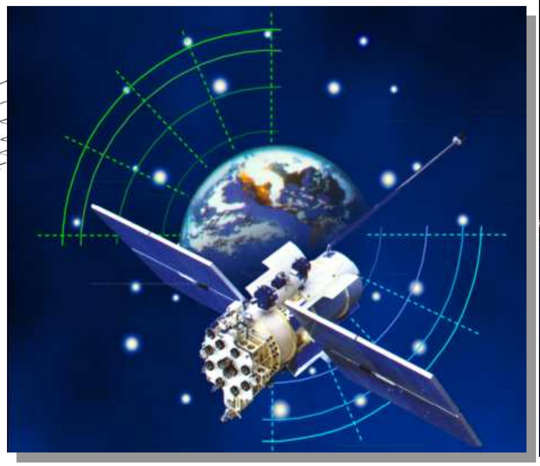
Global Navigation Satellite System (GLONASS): **Russia, ~ 20 satellites**

GALILEO: **Europe, 2 satellites**

... Currently, GPS and GLONASS are routinely used for science and other demanding applications



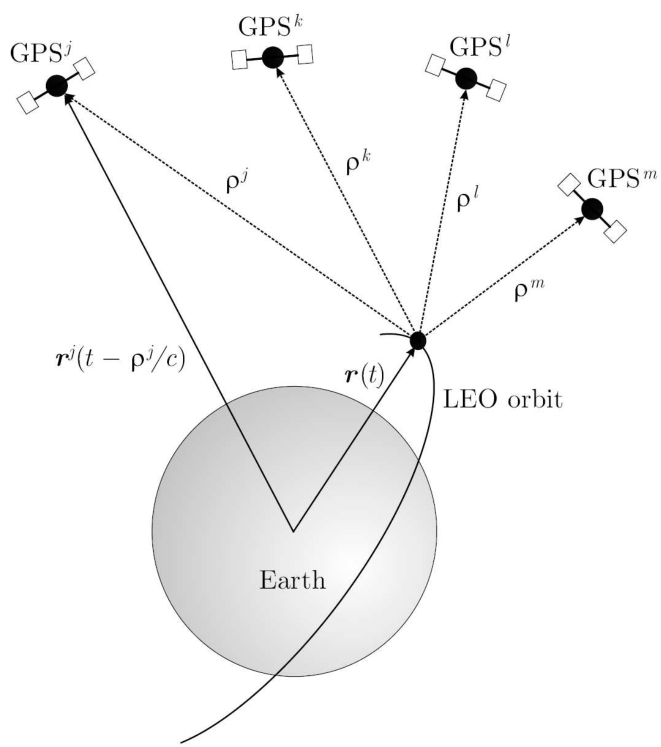
GPS



GLONASS

GALILEO

Global Navigation Satellite Systems 2010



GNSS have been designed for use on the Earth's surface or in the Earth-near space.

Each satellite is equipped with a stable oscillator generating at least two coherent carriers. Code info is modulated on the carrier.

The travelling time of signals (and its changes in time) between the GPS satellite and the receiver are the basic measurements.

➔ With the speed of light *c* the distances ρ (and their time evolution) between satellite and receiver may be reconstructed.

Global Navigation Satellite Systems 2010

The so-called pseudo-range is composed of

$$c\,(t_r - t^s) = \rho + c\,(\Delta t_r - \Delta t^s) + \Delta\rho_I(\lambda) + \Delta\rho_t$$

- **ρ is used to determine the position of the reciever, but also the orbit of the satellite.**
- **$c\,(\Delta t_r - \Delta t^s)$ is used for clock-synchronisation.**
- **$\Delta\rho_I(\lambda)$, the delay of the signals due to the ionosphere, may be used for ionosphere modelling.**
- **$\Delta\rho_t$, the signal delay in the neutral atmosphere, may be used in meteorology (in particular to determine the rapidly varying water vapor content).**

Global Navigation Satellite Systems 2010

The scientific use of GNSS is coordinated by the IGS.

Created in 1989 with I.I. Mueller, G. Mader, B. Melbourne, and Ruth Neilan as protagonists.

The IGS became an official IAG service in 1994.

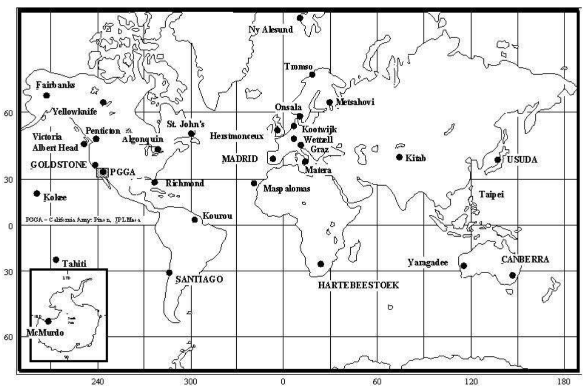
The IGS first was a pure GPS Service, it was renamed as the International GNSS Service in 2004.

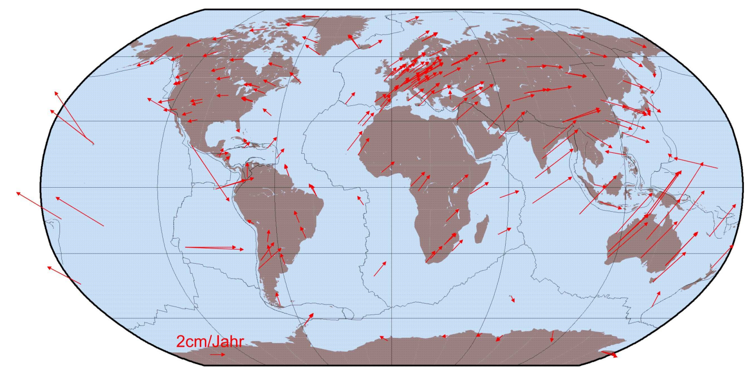
Today the IGS is an interdisciplinary service in support of Earth Sciences and Society, making optimum use of the data from all GNSS.

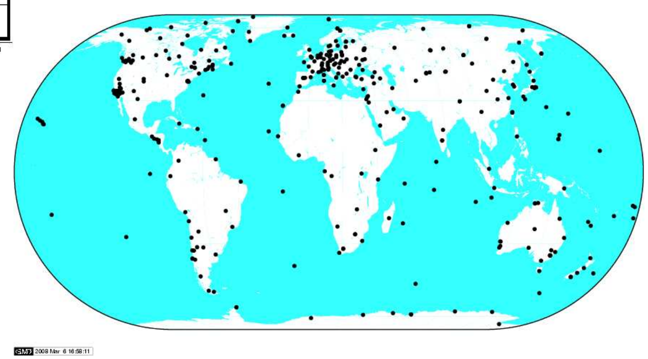
Since its creation the IGS Central Bureau is located at JPL, Pasadena, with Ruth Neilan as director.

Global Navigation Satellite Systems 2010

Station Locations for the IGS Pilot Campaign, 1992







IGS Network in March 2010

Monitor station motion in „real time“

In 1992 the IGS was based on about 20 geodetic receivers, 400+ receivers are active and their data openly available today

Global Navigation Satellite Systems 2010

In 1992 the IGS started off as an orbit determination service (few dm accuracy) for about 20 GPS satellites.

Today, **the IGS provides ephemerides (?accuracy/consitency? of 2-4 cm) for about 30 GPS satellites and for all GLONASS satellites, i.e., for all currently active GNSS satellites.**

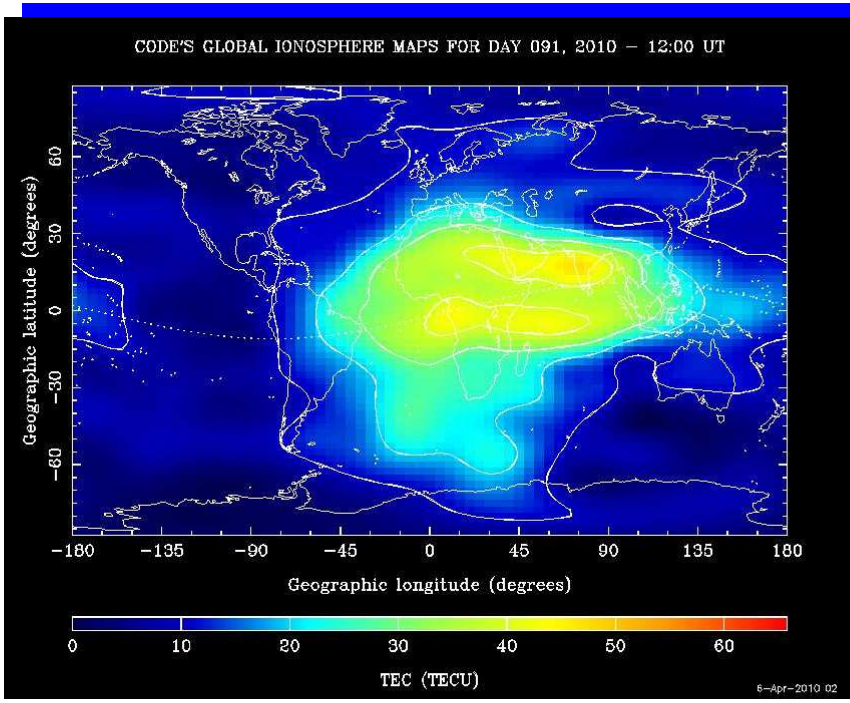
In addition the IGS provides

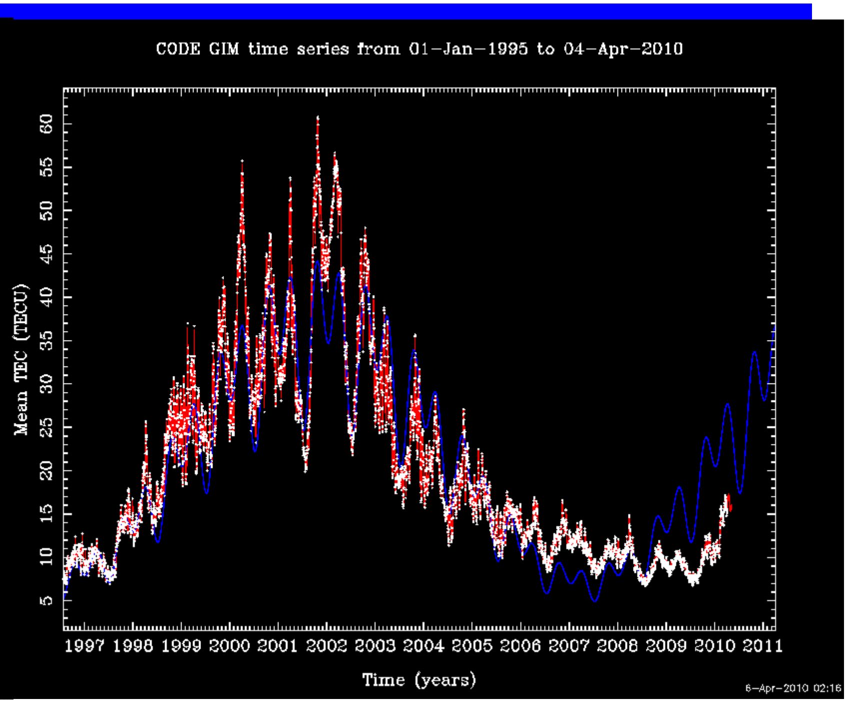
- **archive of all globally relevant GNSS data since 1991**
- **satellite and receiver clock corrections (sub-ns accuracy)**
- **polar motion (PM) and length of day (lod) (mm-cm [/day] accuracy)**
- **coordinates & velocities for 200+ sites (mm-cm / mm/y accuracy)**
- **atmosphere information (ionosphere and troposphere)**

The IGS products are

- **accurate, reliable and robust,**
- **available in a timely manner.**

Global Navigation Satellite Systems 2010



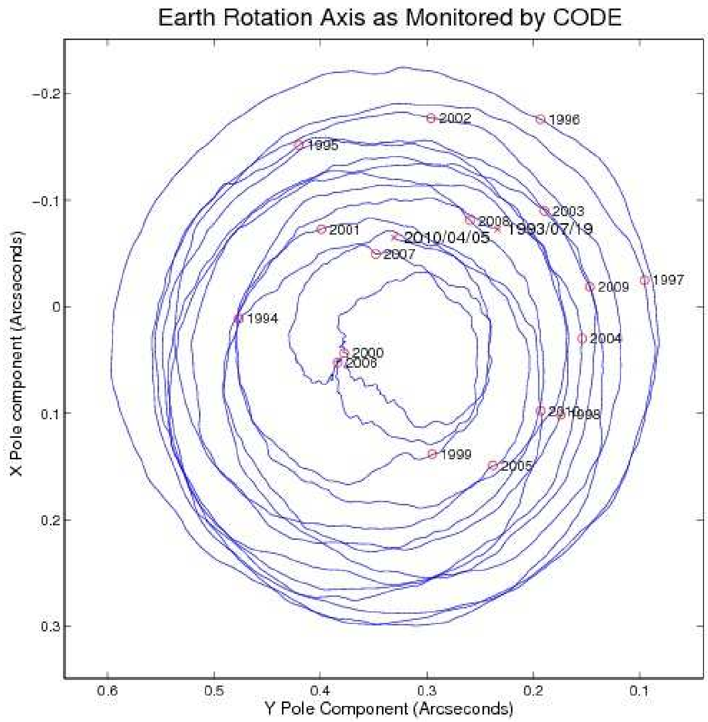


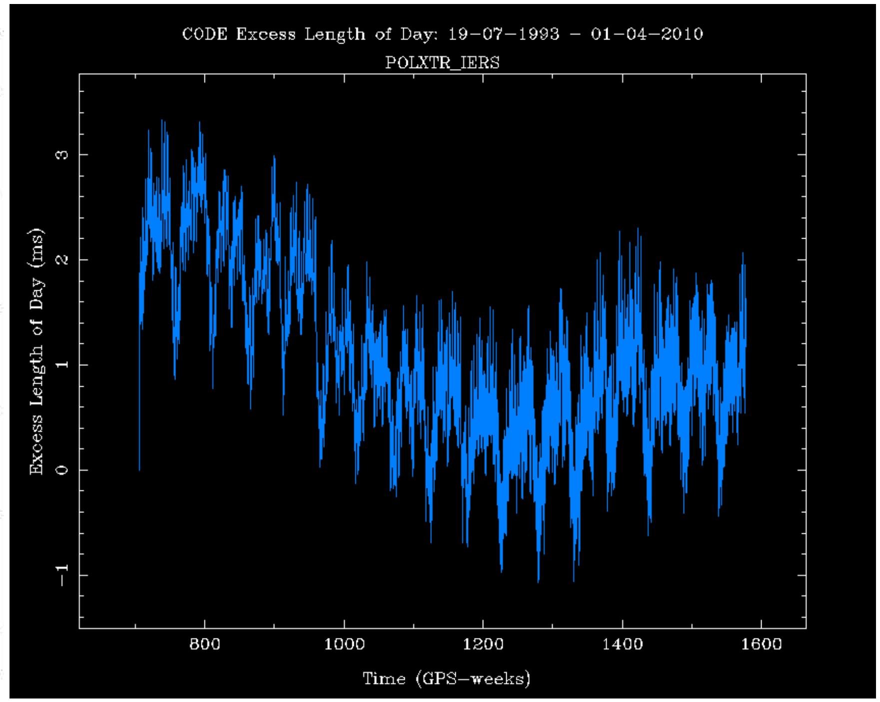
Left: Ionosphere map (2^{h} time resolution) routinely derived by IGS Analysis Centers

Right: Development of mean daily TEC since mid 1996

(figures from CODE/IGS Analysis Center)

Global Navigation Satellite Systems 2010

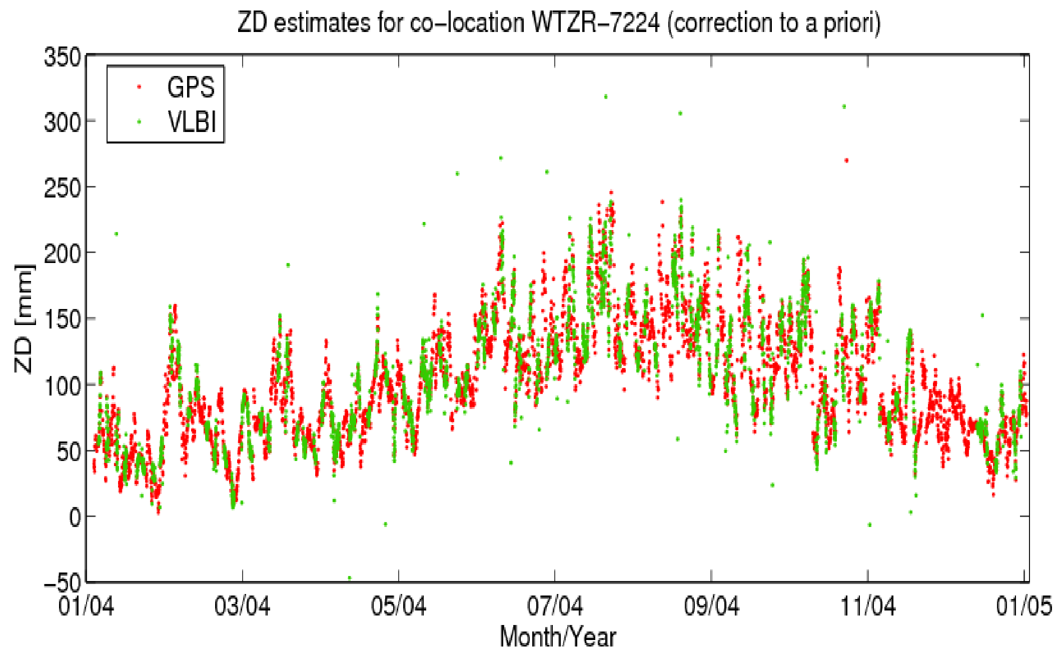




Left: Polar motion (~motion of rotation axis on Earth's surface) since 1993 (diameter of figure about 14m)

Right: Excess Length of day since 1993 (milliseconds) (from CODE Analysis Center)

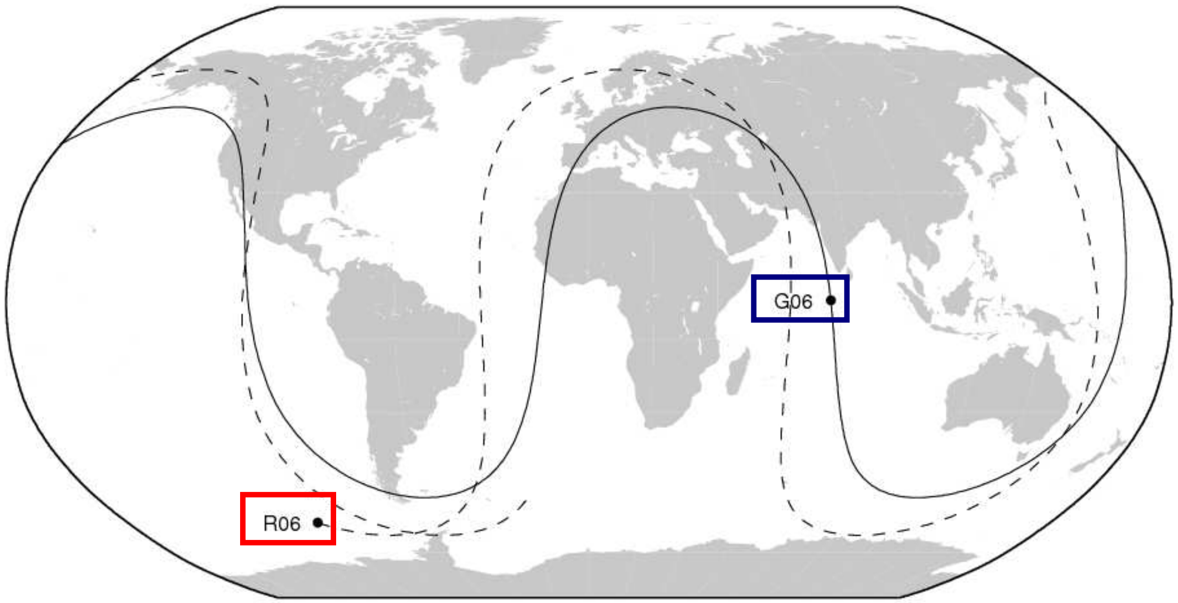
Global Navigation Satellite Systems 2010



Tropospheric zenith delays for 2004 as estimated by GPS and VLBI for the collocated GPS and VLBI sites in Wettzell. The variations are mainly due to the atmospheric water vapor content.

From: D. Thaller, M. Rothacher, and M. Krügel (2009). Combining one year of homogeneously processed GPS, VLBI and SLR data. In H. Drewes (editor), Proceedings of the IAG Symposium on Geodetic Reference Frames GRF2006, number 134 in IAG Symposia. Springer-Verlag.

Impact of Different GNSS Constellations



July 7, 2006: sub-satellite tracks of:

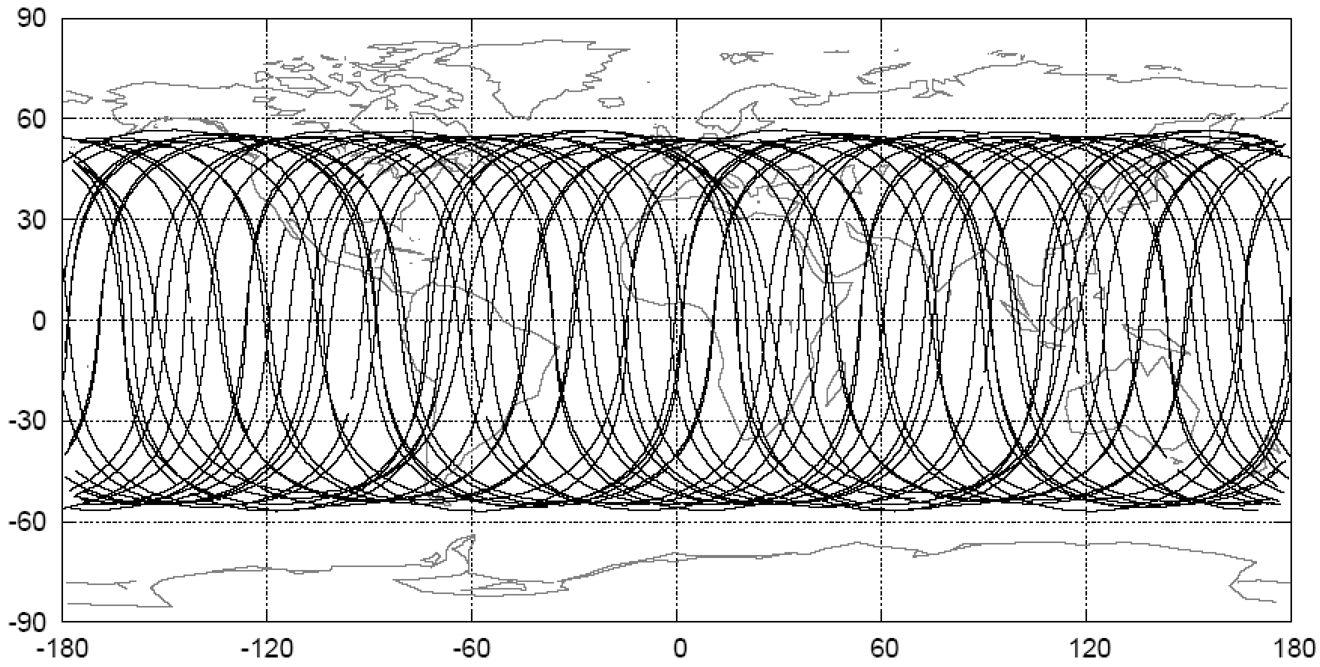
GPS PRN 06, with daily repeat orbit and

GLONASS R06, orbit repeating after 8 days.

The GNSS constellations differ considerably (inclinations, daily vs. 8-day repeat orbits for GPS and GLONASS, respectively)

Different constellations improve the geometry, help to understand systematic errors

Impact of Different GNSS Constellations



Mean observation geometry of a particular satellite, as viewed from a site at a particular latitude ϕ, is longitude-dependent.

Impact of Different GNSS Constellations

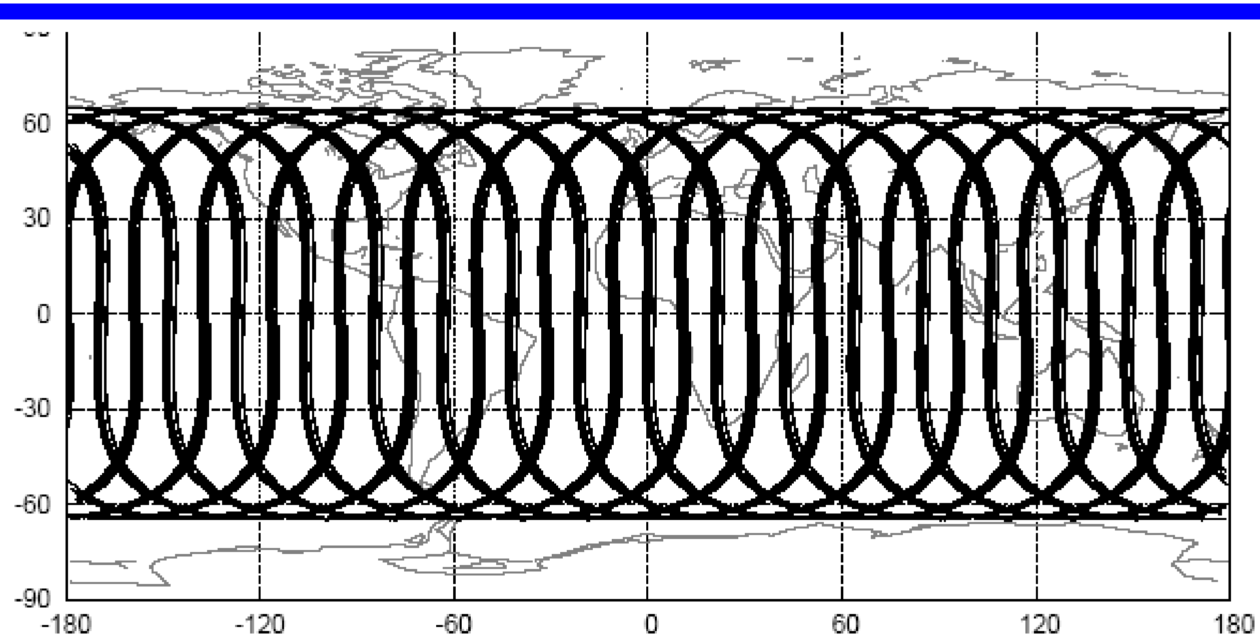
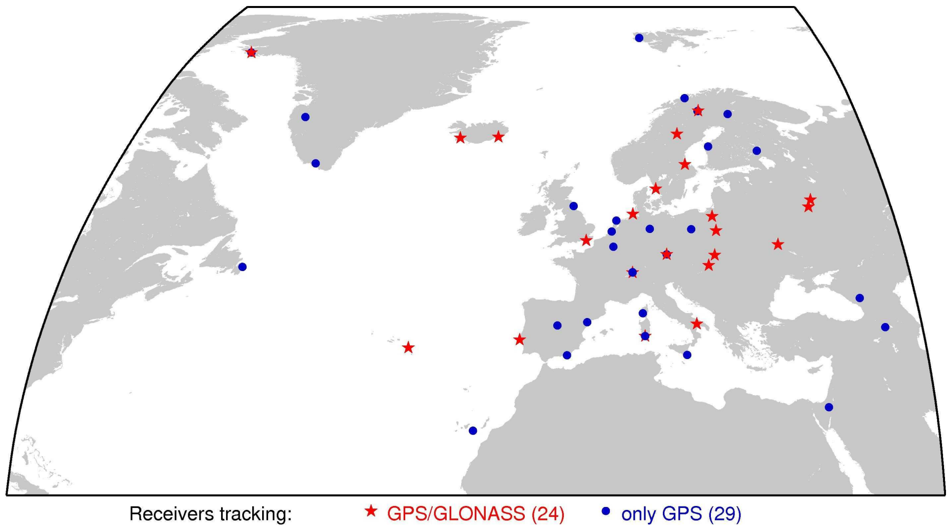


Figure 3.5: Ground-tracks of 12 GLONASS satellites over 17 orbital revolutions, for October 28 - November 4, 2006

Only two (of three) orbital planes filled with satellites in 2006.

Mean observation geometry of a particular satellite (in the average over 8 (or more) days), as viewed from a site at a particular latitude ϕ, is (almost) longitude-independent.

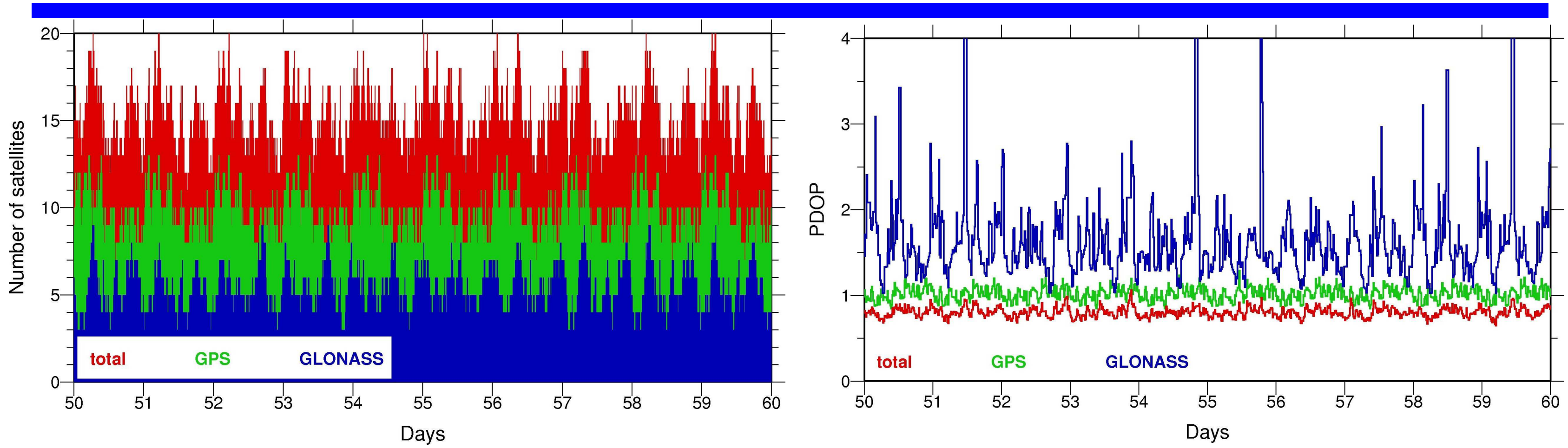
Impact of Different GNSS Constellations



A regional network consisting of GPS and combined GPS/ GLONASS receivers was analyzed in (short) batches of 0.5, 1, 2, 3, etc min. Otherwise: network analysis with settings of CODE Analysis Center of the IGS. Details see

Dach, R., E. Brockmann, S. Schaer, G. Beutler, M. Meindl, L. Prange, H. Bock, A. Jäggi, L. Ostini; (2009) *GNSS processing at CODE: Status report.* JoG, Vol. 83(3-4), pp. 353-366.

Impact of Different GNSS Constellations



Left: Number of satellites (left) and Right: PDOP (right) for Zimmerwald.

These indicators are promising. The mentioned paper revealed, however, that the improvement of station coordinates and Earth rotation parameters is moderate to not existing.

Clear improvements were observed when generating solutions GPS and combined solutions using only short data spans (of up to 30 minutes). Improvements of > 10% resulted.

→ The heaviest impact of multi-GNSS will occur in kinematic positioning.

Expectations concerning GALILEO

The scientific community will not switch from one GNSS to another, but combine the measurements from all systems (the IGS is already doing that with GPS and GLONASS).

It is assumed that at least the same information as in the case of GPS (code and phase on at least two carriers) will be *openly* available for all GNSS.

The obvious advantages of combining GNSS are:

- When using *n* different GNSS with the same number of satellites the common parameters should at least improve by a factor of $n^{1/2}$ ... (not yet realized in practice)
- Inconsistencies in the reference frames „cannot" occur.
- System-specific systematic errors may be detected more easily (and hopefully removed).
- Better coverage for (spaceborne) kinematic positioning and atmosphere sounding

Expectations concerning GALILEO

Kinematic applications of GNSS are delicate because of

- **the huge number of parameters (four unknowns, namely position *x* and receiver clock correction τ per observation epoch in addition to general parameters like ambiguities, troposphere, etc.).**

Spaceborne kinematic applications are particularly delicate because of

- **the rapid changes of the GNSS observation scenario: A particular GNSS satellite is above horizon for 4-5 hours for Earth-fixed receivers, for 10-20 minutes for spaceborne receivers.**

Expectations concerning GALILEO

GALILEO has the potential to revolutionize the scientific and other high accuracy applications of GNSS because of its passive hydrogen space masers.

The well-known exlicit or implicit double-differencing of observations may be left in favor of models for the GALILEO space clocks as functions of time. The consequences are

- Substantially reduced number of parameters → increased degree of freedom.
- better separation of clock errors and model errors attributed, e.g., to orbits.
- Need to better model the orbits, time-dependent cable delays, ...
- Correlation of observations in time → use of weight matrices covering the entire observation time span.

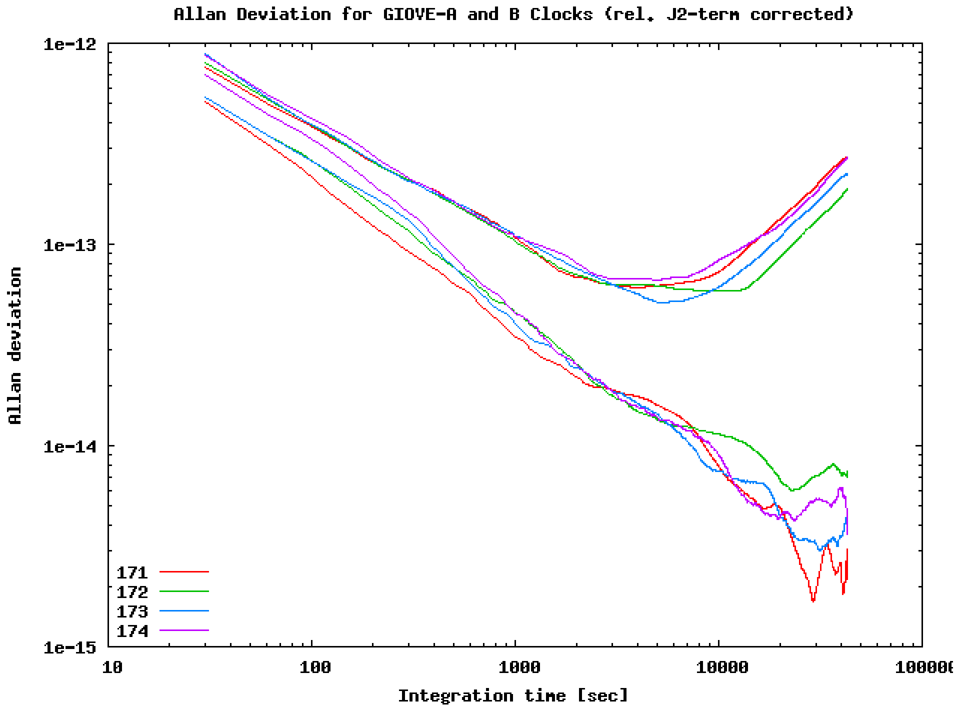
Expectations concerning GALILEO

In 1984 G. Beutler et al. wrote:

„*In the authors' opinion, the best way of modelling the clocks is the following: define a statistical model of clock performances using available information on clock offset, drift, jitter. This leads to a simple stochastic differential equation ... For the clock synchronization error as a function of time ...*"

From: G. Beutler, D.A. Davidson, R.B. Langley, R. Santerre, P. Vanicek, D.E. Wells (1984) „*Some theoretical and practical aspects of geodetic positioning using carrier phase difference observations of GPS satellites*", Technical Report, Dept. Of Durveying Engineering, University of New Brunswick

Expectations concerning GALILEO



Potential impact:

Clock prediction for real-time applications: Orbit errors might become the limiting factor for prediction.

Double-difference approach may have to be left.

But: The algorithms have to be kept managable for the user! → Challenge

From Hugentobler et al. (2010) „Evaluation of GIOVE Satellite Clocks using the CONGO Network ". Allan deviations derived from an orbit & clock analysis using the data of the CONGO network of GNSS reveivers (deployed by DLR and BKG, Germany → Paper in Session 3, GNSS Timing I).

The Galileo Science Advisory Committee

The Galileo Science Advisory Committy (GSAC) was set up to:

- **Recommend improvements to Galileo and EGNOS for scientific applications.**
- **Maintain the Galileo Science Opportunity Document (GSOD), highlighting scientific priorities.**
- **Support the preparation of announcements of opportunity (AO) for scientific studies – first announcement imminent!**
- **Advise on the use of Galileo and EGNOS data for scientific applications.**
- **Consider and review ESA-furnished documents related to the scientific use of GNSS signals.**

The Galileo Science Advisory Committee

The members of the GSAC were nominated by the ESA member countries.

The GSAC was created towards the end of 2008 and so far met four times.

The fourth meeting took place 24 March 2010 in ESA-HQ, where the first version of the GSOD was (almost) finalized.

The purpose of the GSOD is to provide an overview of scientific endeavours benefiting from the Galileo system and to establish a common background for the scientific exploitation of the Galileo system and possible future versions.

The GSOD is maintained by the GSAC to advise the ESA directorate and to stimulate research related to Galileo in the wider scientific community.

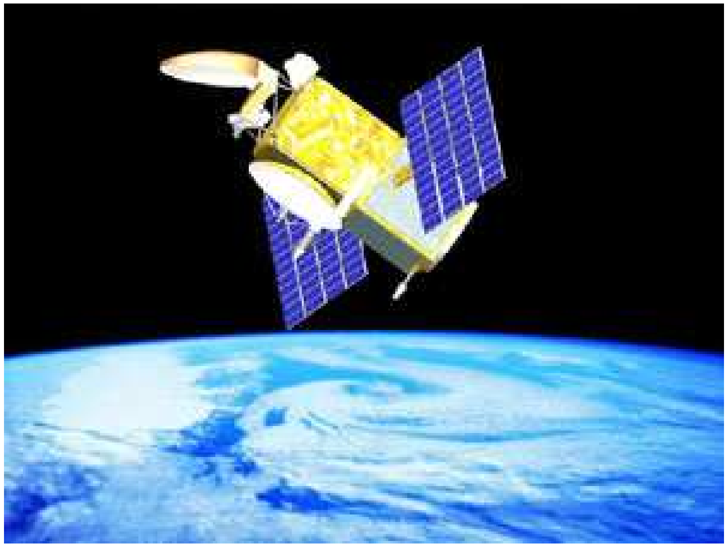
The Galileo Science Advisory Committee

The second International Colloquium on *Scientific and Fundamental Aspects of the Galileo Program* gave detailed insight into the science aspects considered by the GSAC.

More information see: http://www.congrex.nl/09c10/

A third symposium is expected for 2011.

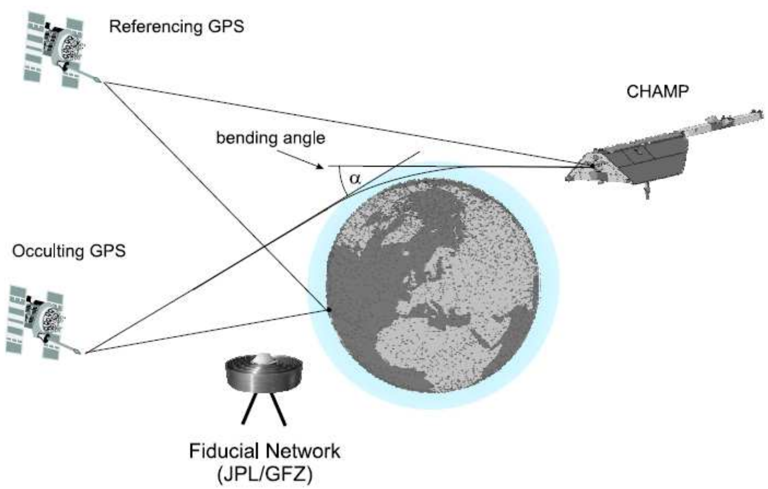
Spaceborne Applications of GNSS

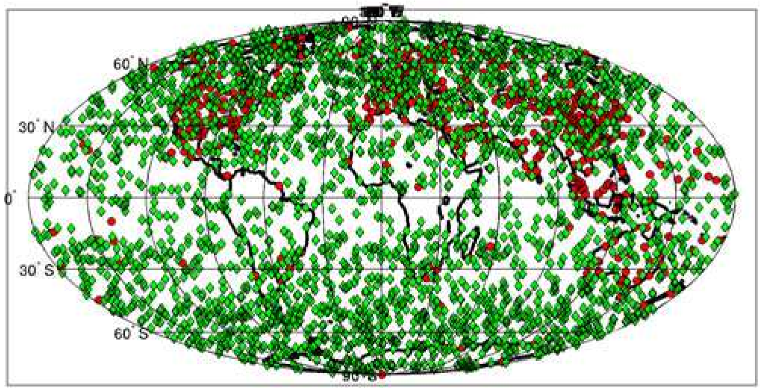


Jason-2, **TerraSAR-X**

- **Most Low Earth Orbiters (below 2000km) are today equipped with GPS receivers. Most receivers are dedicated to Precise Orbit Determination (POD).**
- **Examples for LEOs equipped with GPS: Altimeter satellites Topex-Poseidon, Jason-I, Jason-2, gravity field satellites CHAMP, GRACE-A, GRACE-B, GOCE, SAR mission (TerraSAR-X)**

Spaceborne Applications of GNSS



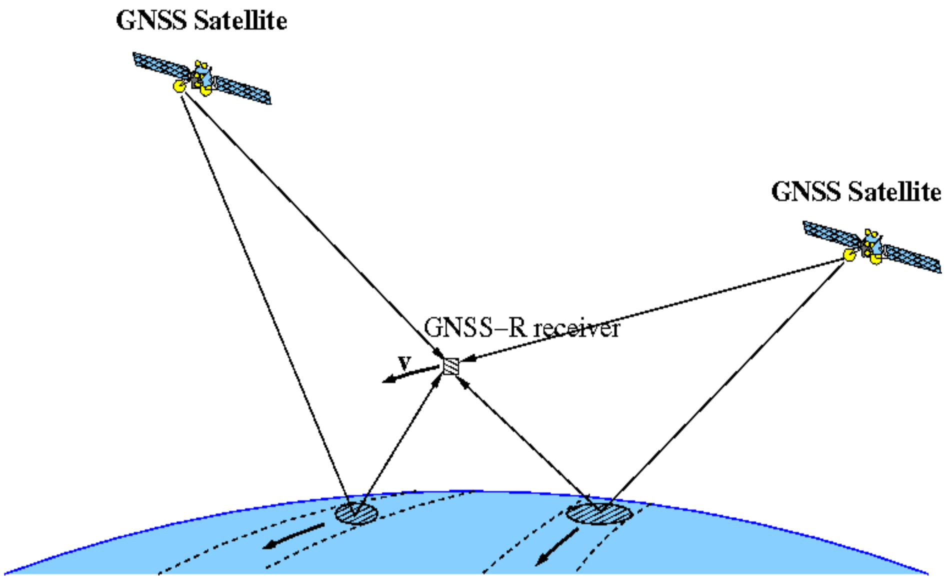


Atmosphere sounding using the GPS occultation technique exploiting the rising/setting of individual GPS satellite (proof oc oncept GPS/MET, CHAMP, GRACE-A, Formosat-3/COSMIC mission with a constellation of six micro-satellites carrying GPS radio occultation (RO) receivers gaining in total about 2500 profiles/day,

Left: from G. Beyerle, J. Wickert, R. Galas, K. Hocke , R. König, C. Marquardt, A. G. Pavelyev , Ch. Reigber and T. Schmidt (2001) „GPS Occultation Measurements with GPS/MET and CHAMP“,

Right: from http://www.ucar.edu/news/releases/2006/).

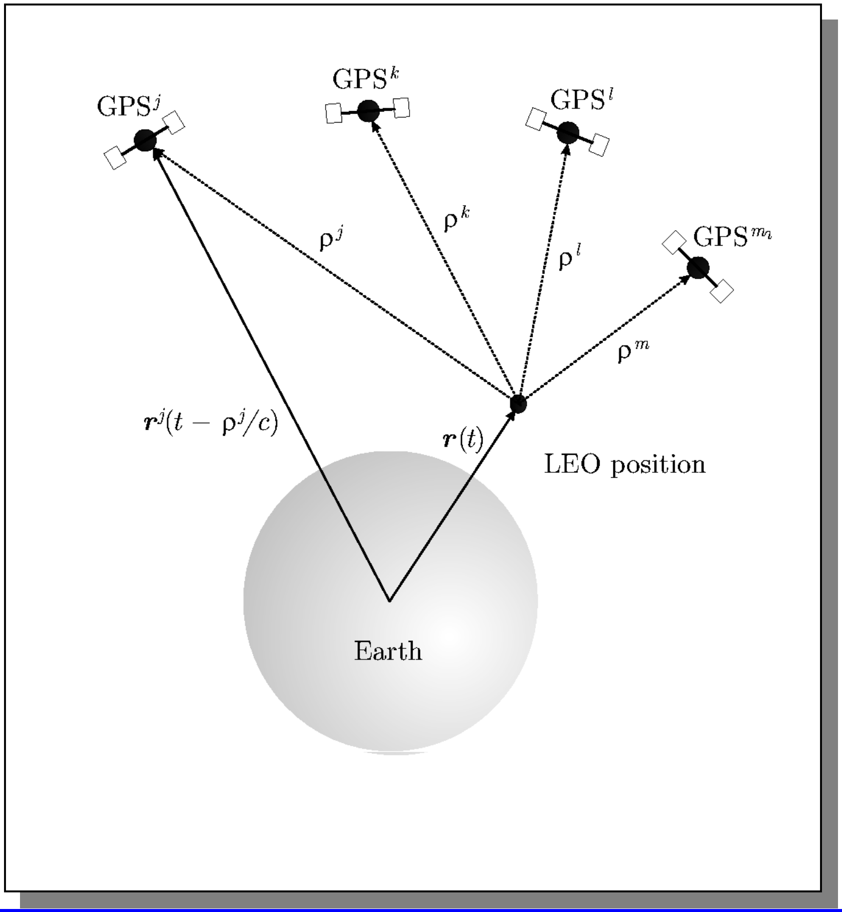
Spaceborne Applications of GNSS



From „Galileo Science Opportunity document“ prepared by the Galileo Science Advisory Committee (GSAC)

GNSS reflectometry: A vehicle flying over the Earth‘s surface observes the GNSS signals emitted by the GNSS constellations, both direct and reflected, using a GNSS-R receiver. The correlation function of the reflected and direct signals (or suitable replicas) provides altimetric and scatterometric information. Several mission concepts are considered, no mission is flying.

GNSS for Orbit Determination



GNSS Observation equations:

$$P^k = \rho^k + c\,(\Delta t - \Delta t^k) + \Delta\rho^{Ik}$$
$$L^k = \rho^k + c\,(\Delta t - \Delta t^k) - \Delta\rho^{Ik} + \lambda\,B^k$$

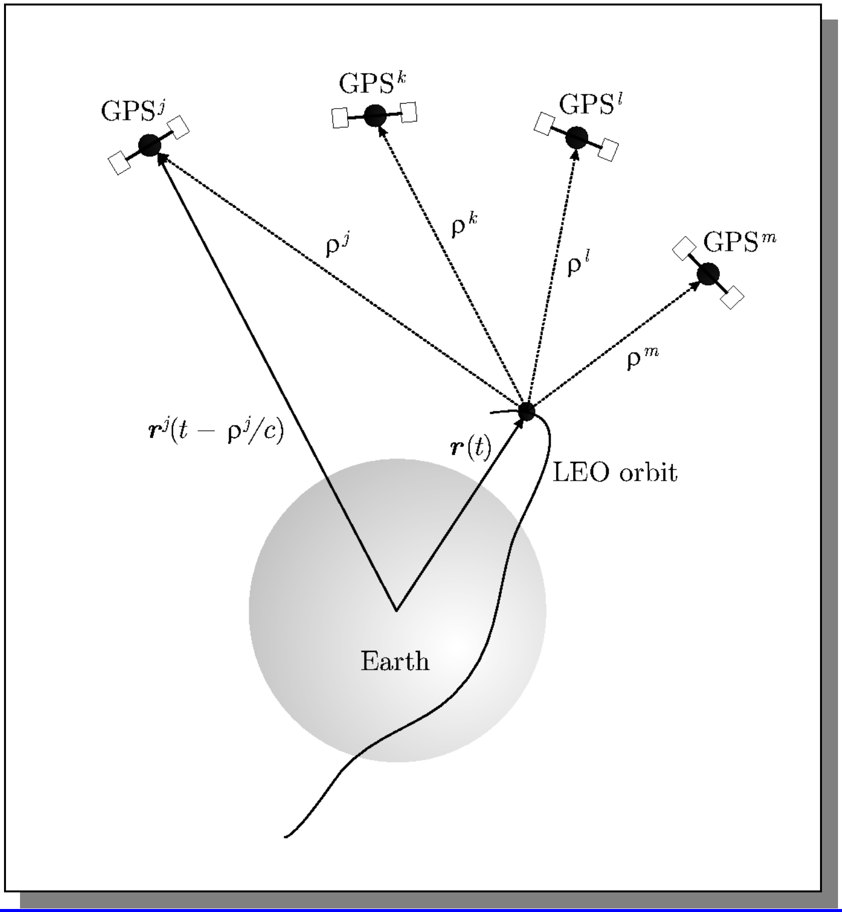
Code- und Phase-Measurements, respectively (on two carriers), contain information about the distances between GNSS satellites and LEO .

$$\rho^k = |r(t) - r^k(t - \rho^k/c)|$$

r(t) : LEO position (unknown)
$r^k(t)$: GNSS position (known)

Different options to parametrize the orbit *r(t)*.

GNSS for Orbit Determination



Kinematic orbit ***r(t$_k$)***:

LEO Positions are estimated for each epoch without making use of the equations of motion.

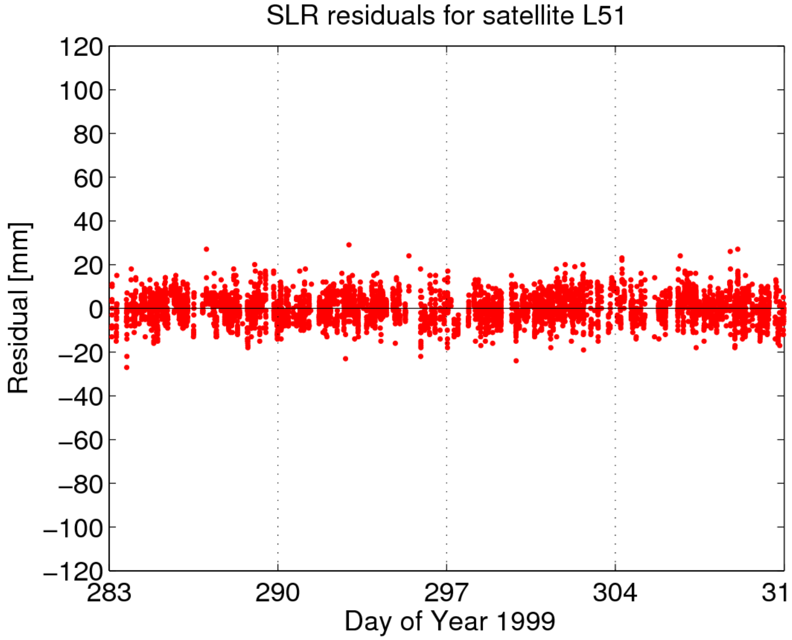
Dynamic Orbit ***r(t)*** :

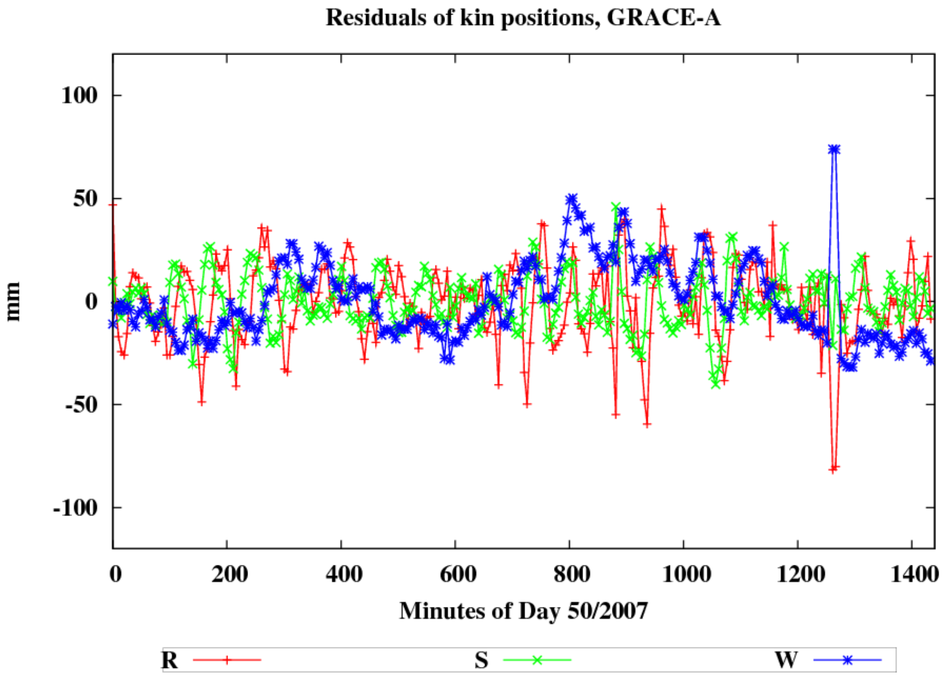
Equations of motion (with known force model) determine orbit.

(Pseudo-)stochastic Orbit ***r(t)*** :

Piecewise constant accelerarions or velocity changes at known epochs give the orbit stochastic properties (generalized short arc).

GNSS for Orbit Determination

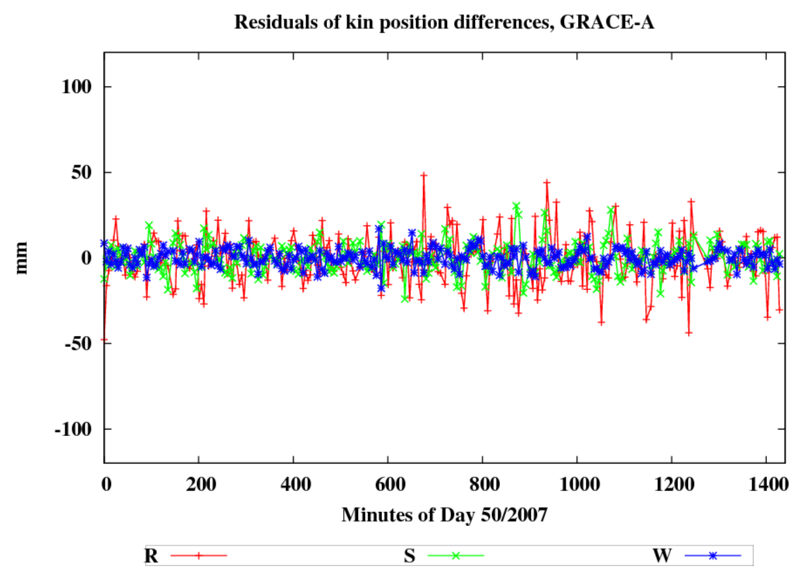


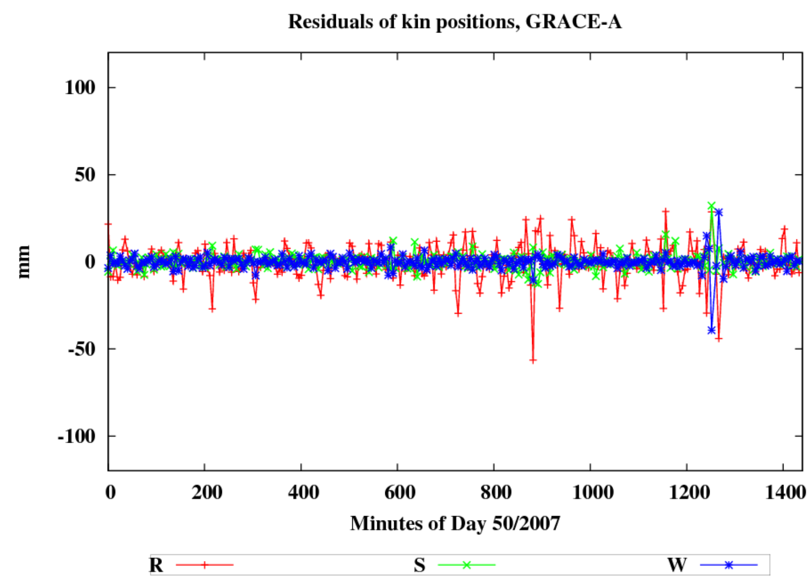


Left: SLR residuals of four contiguous 7-day LAGEOS-orbits (from ILRS Bench-mark test, < 20 parameters/arc, CODE)

Right: Residuals of fitting 30s kinematic positions with contiguous arcs of 90 min → shorter arcs or use position differences between subsequent positions (GRACE gravity field up to n=m=150).

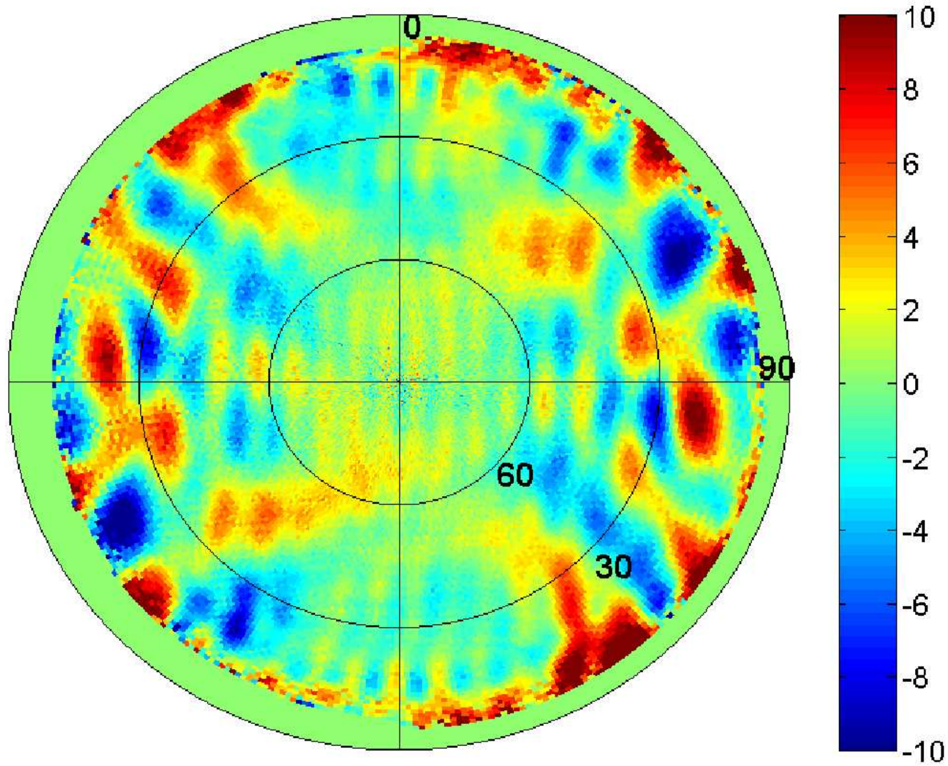
GNSS for Orbit Determination





Left: Residuals of position differences using 90 min contiguous arcs
Right: Residuals of positions using 15 min contiguous short-arcs
Accuracy of kinematic positions (validated with SLR): 1-3 cm rms.

GNSS for Orbit Determination



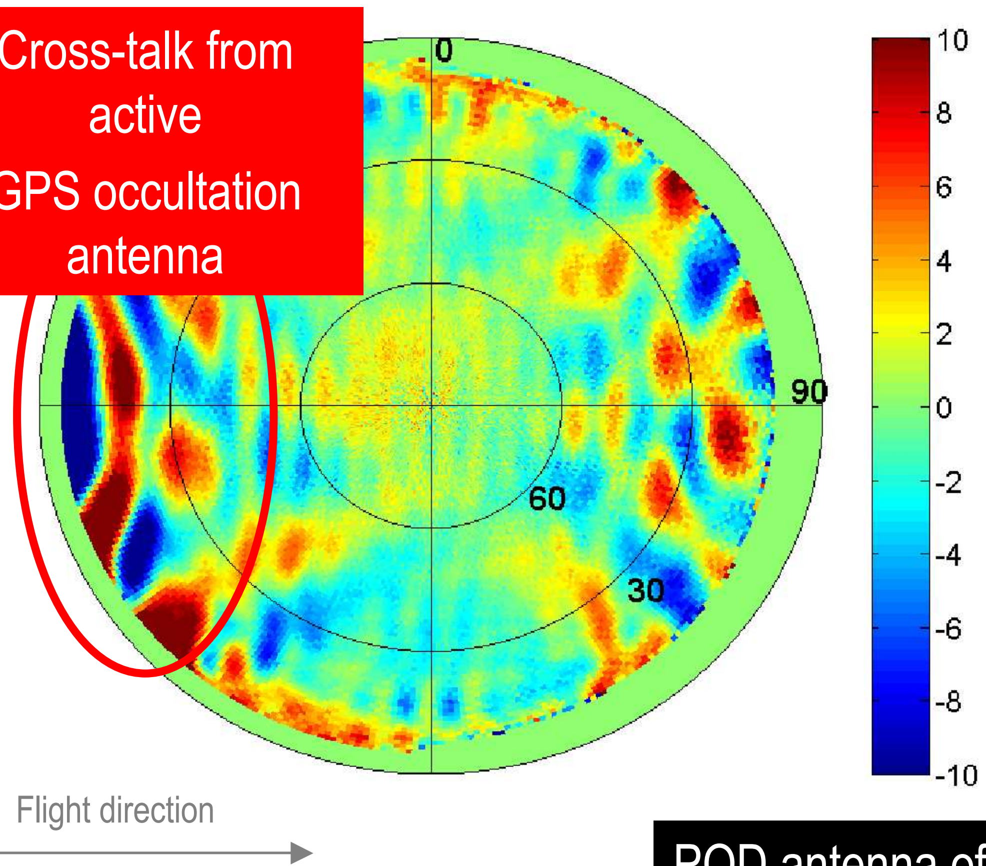
Empirical antenna PCVs

(mm)

Flight direction

POD antenna of GRACE B

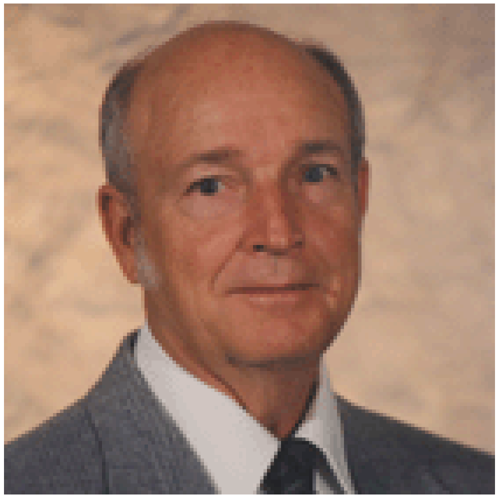
GNSS for Orbit Determination



Empirical antenna PCVs (mm)

POD antenna of GRACE A

Gravity Field Missions 2000-2010

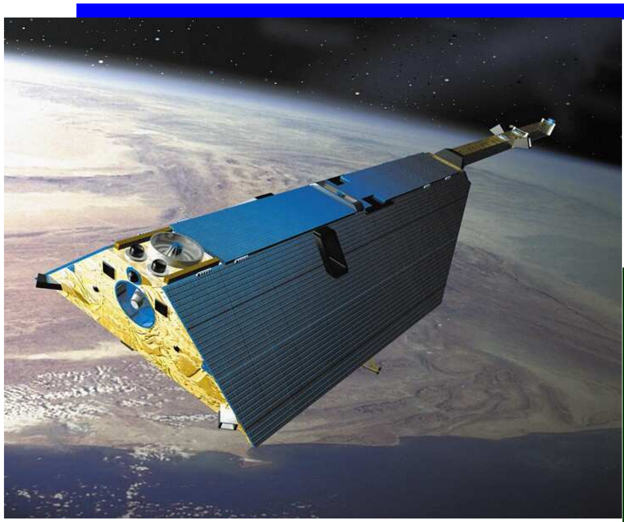
  

From the beginning of space age to the end of the 20th century the information about the Earth's gravity field emerged from the SLR (+astrometry and altimetry).

Lacking temporal and spacial coverage: → Need for dedicated LEO missions.

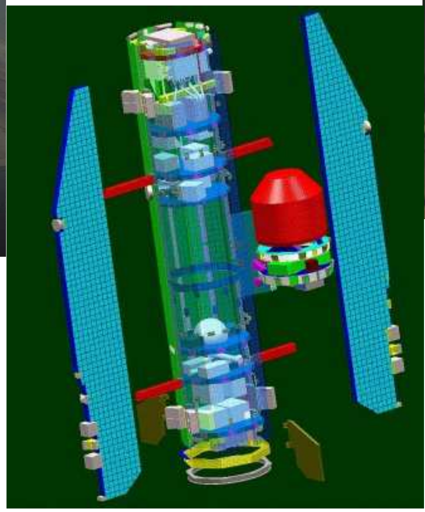
The protagonists of the missions CHAMP: Christoph Reigber, GRACE: Byron Tapley & Ch. Reigber, GOCE: Reinhard Rummel (left to right).

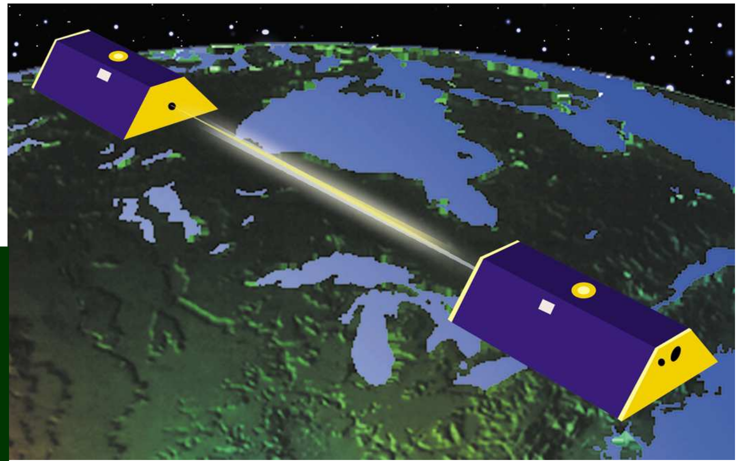
Gravity Field Missions 2000-2010



CHAMP

GOCE





GRACE A and B

The golden age of Gravity field determination was initiated with the start of CHAMP in July 2000. GRACE was launched in 2002 in particular to study the time varying gravity field. ESA's GOCE mission was launched on March 17, 2009 with a European GPS receiver and a three-dimensional gradiometer (three pairs of 3-d accelerometers).

Gravity Field Missions 2000-2010

$$V(r,\lambda,\phi) = \frac{GM}{r} \sum_{i=0}^{\infty} \left(\frac{a}{r}\right)^i \sum_{k=0}^{i} P_i^k(\sin\phi)\{ C_{ik} \cos k\lambda + S_{ik} \sin k\lambda \}$$

$$N(\phi,\lambda) = a \sum_{i=2}^{\infty} \sum_{k=0}^{i} P_i^k(\sin\phi)\{ C_{ik} \cos k\lambda + S_{ik} \sin k\lambda \}$$

The Earth's gravity field is usually expressed in spherical harmonics (top) with *r*=Absolute value of geoc. Radius vector, ϕ=latitude, λ=longitude.

For *r*=*a*=Earth's equatorial radius) the geoid height *N* (bottom) above the selected reference ellipsoid) may be easily established.

Gravity Field Missions 2000-2010

The strength of the signals of degree *i* are expressed by the so-called degree amplitudes σ_i , where:

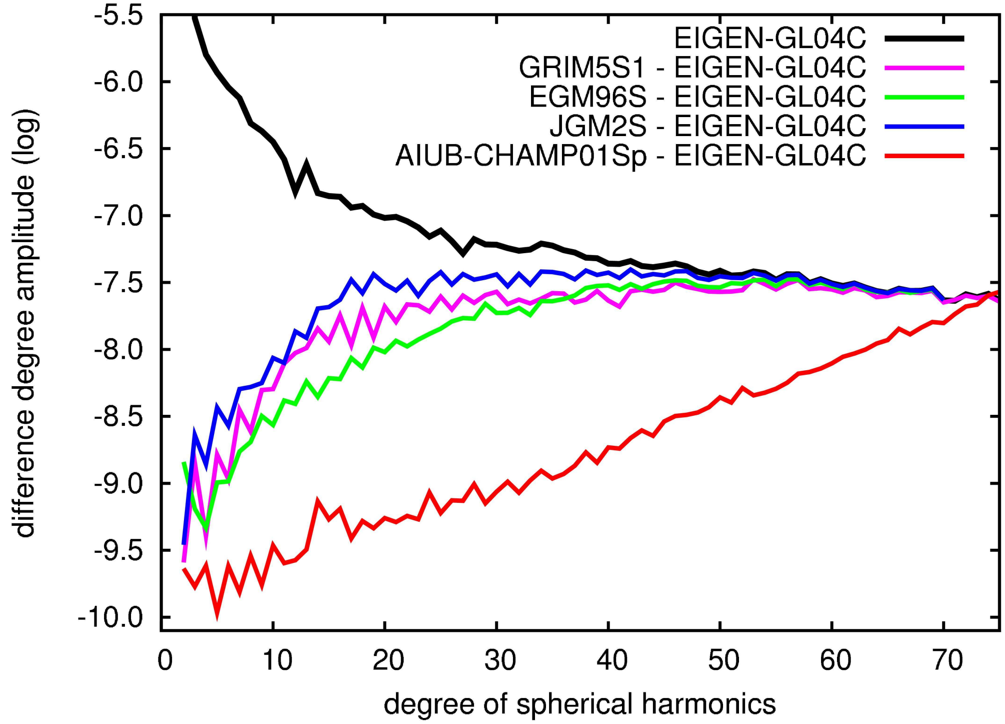
$$\sigma_i^2 = \sum_{k=0}^{i} \left\{ C_{ik}^2 + S_{ik}^2 \right\}$$

The degree-specific differences between two gravity fields is conveniently expressed by the difference degree amplitudes $\Delta\sigma_{ik}$:

$$\Delta\sigma_i^2 = \sum_{k=0}^{i} \left\{ \left(C_{ik,1} - C_{ik,2} \right)^2 + \left(S_{ik,1} - S_{ik,2} \right)^2 \right\} = \sum_{k=0}^{i} \left\{ \Delta C_{ik}^2 + \Delta S_{ik}^2 \right\}$$

Usually, the difference degree amplitudes are represented in a logarithmic scale. The $\Delta\sigma_{ik}$ may either be analyzed directly or transformed into geoid height differences.

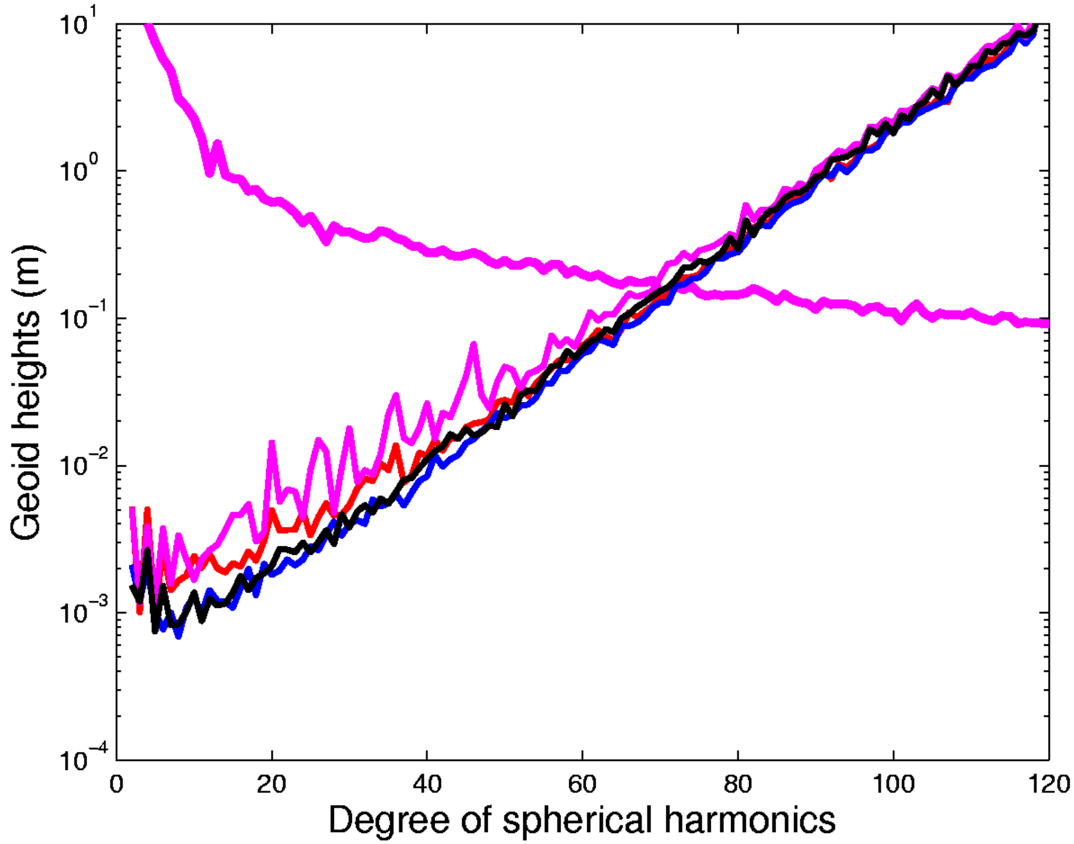
Gravity Field Missions 2000-2010



Difference degree amplitudes w.r.t. a GRACE multi-annual solution of three of the best 20th century gravity field solutions (mainly based on SLR and terrestrial measurements) and a CHAMP-only solution using „only“ one year of GPS-data: A quantum jump in gravity field determination is obvious!

GNSS Contribution to the Gravity Fields

PCVs are very important for GPS-only solutions



Reference field:

ITG-GRACE03S

Differences:

GRCB (w/o PCV)

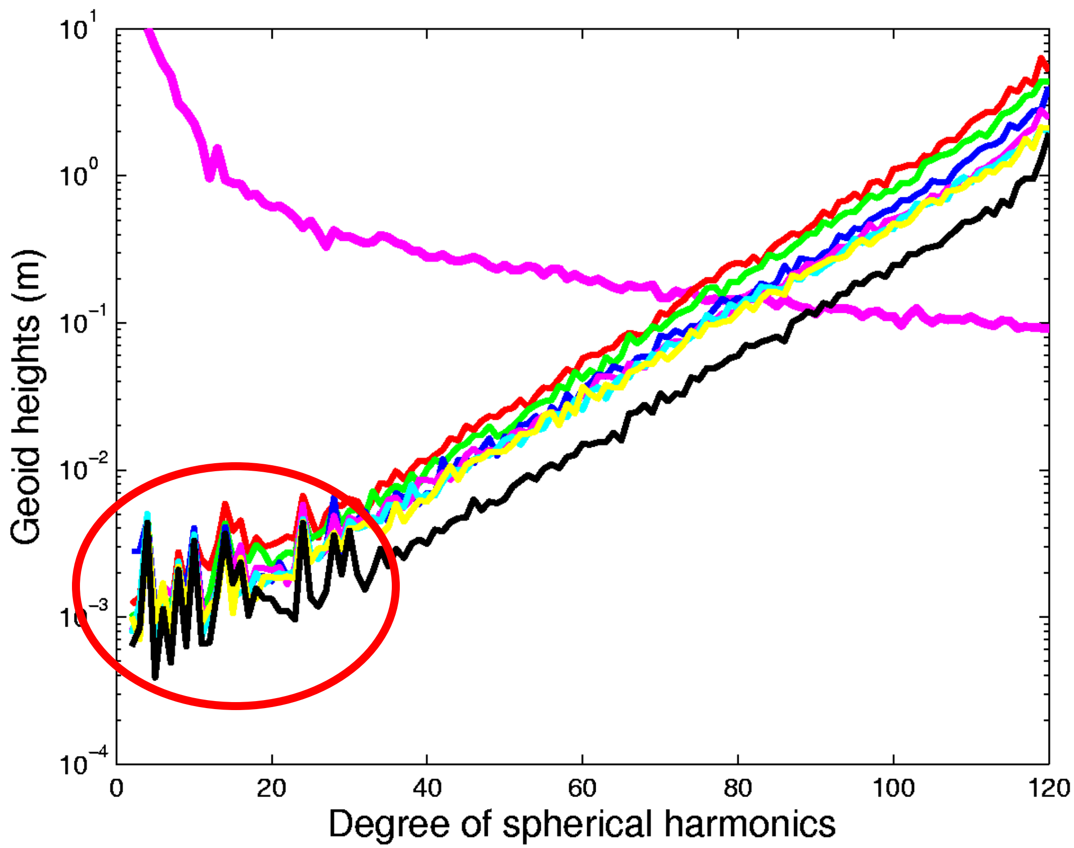
GRCB (with PCV)

GRCA (w/o PCV)

GRCA (with PCV)

GNSS Contribution to the Gravity Fields

CHAMP solutions with “normal” modeling



Reference field:

ITG-GRACE03S

Differences:

Year 2002

Year 2003

Year 2004

Year 2005

Year 2006

Year 2007

Combination:

6-year solution

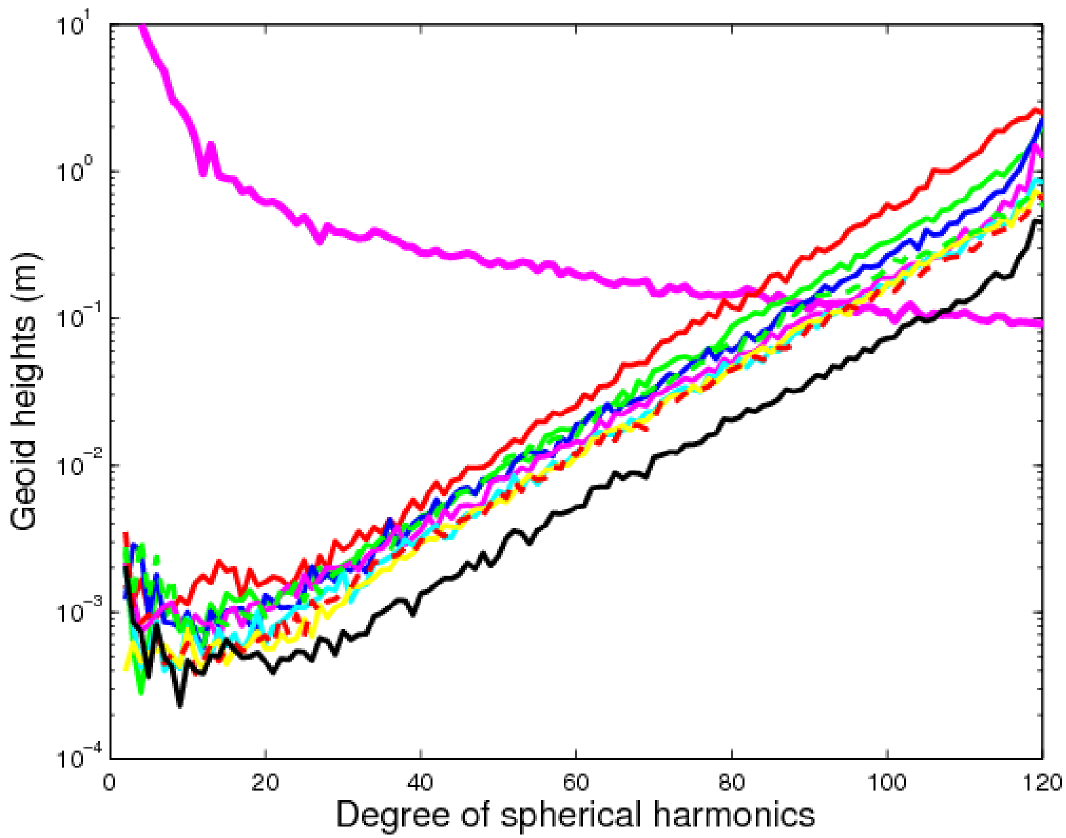
Astronomical Institute, Uni Bern

AIUB

Low degree coefficients disagree with the reference field

GNSS Contribution to the Gravity Fields

CHAMP solutions with "advanced" modeling



Reference field:

ITG-GRACE03S

Differences:

Year 2002

Year 2003

Year 2004

Year 2005

Year 2006

Year 2007

Year 2008

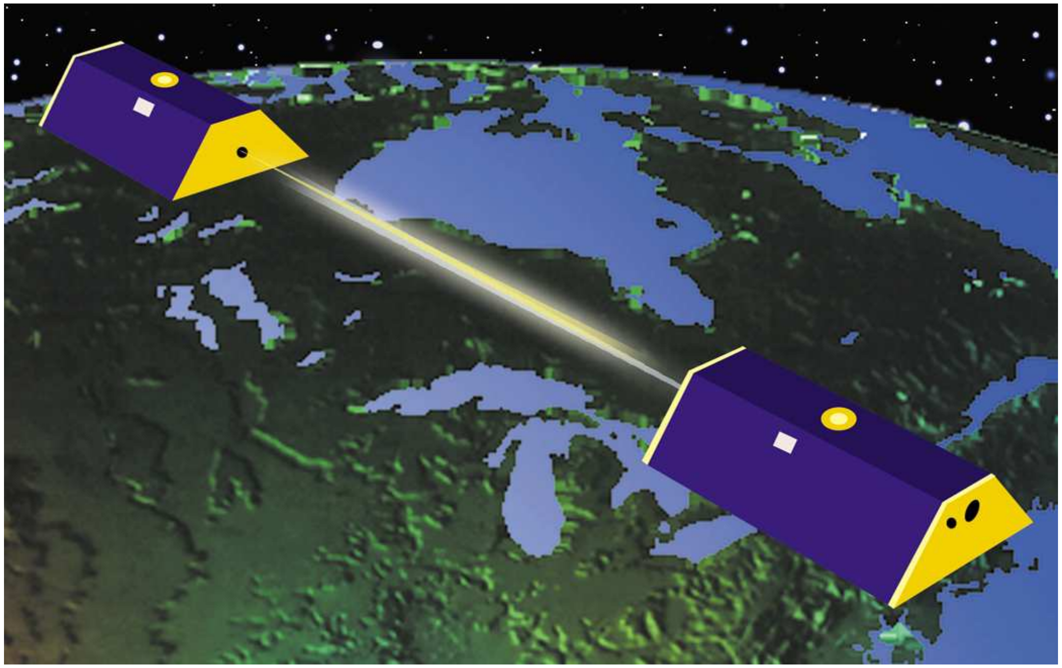
Year 2009

Combination:

8-year solution

Excellent solution (PCVs, COVs, 10s sampling, …)

Gravity Fields from GNSS and K-Band

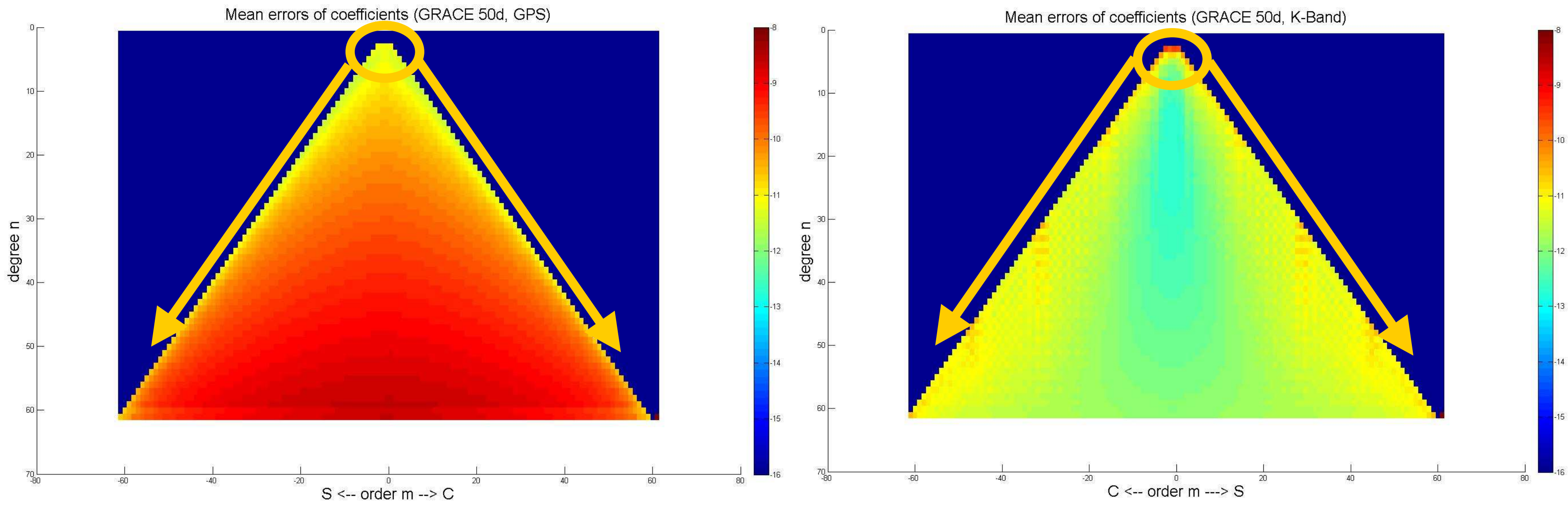


GRACE-A and –B are in close to circular and polar polar orbits about 450km above the Earth's surface.

The gravity field may be established from GPS alone, K-Band alone (?) and from a combination of the two.

The temporal evolution of the inter-satellite distance is measured with an accuracy of better than 10^{-6}m/s using a microwave link (in the K-Band) between the two satellites *in addition to* the absolute positions established by GPS → „Accuracy-wise" K-Band dominates GPS but K-Band alone cannot determine the orbits.

Gravity Fields from GNSS and K-Band

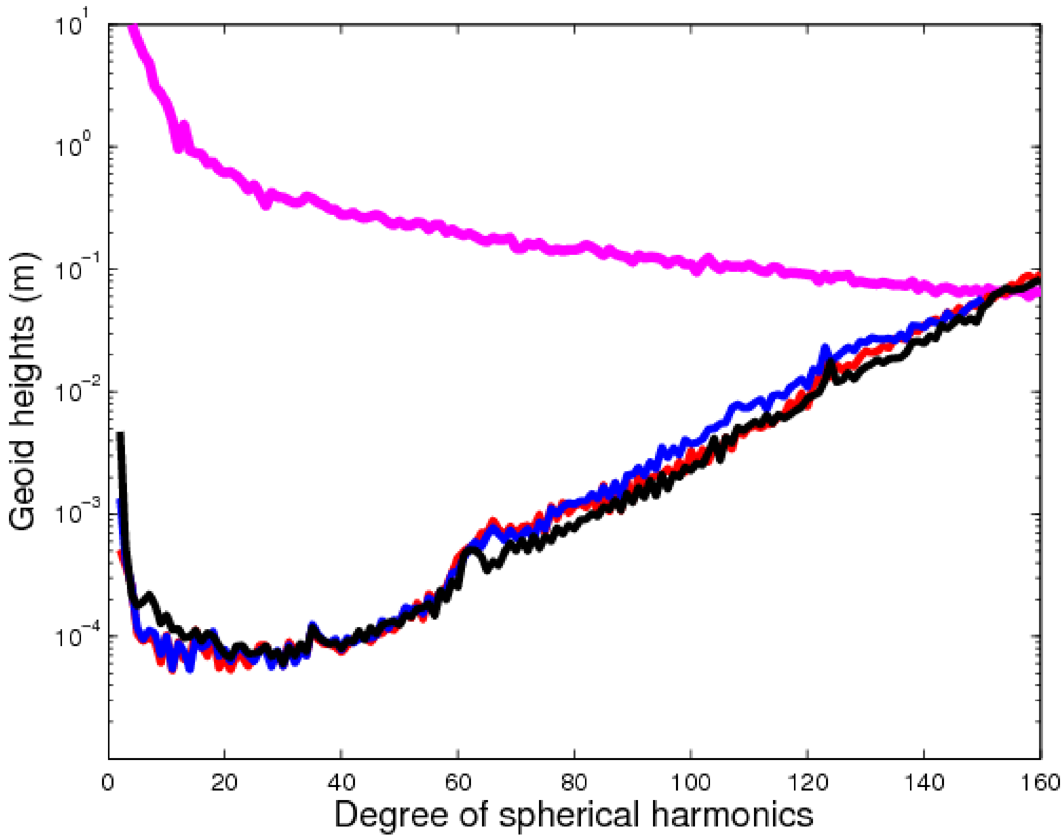


K-Band superior for all terms, except for low degree terms and sectorials!

→ Errors in GPS analysis are „well hidden“ in combined GRACE solutions

Gravity Fields from GNSS and K-Band

Consistency of multi-annual GRACE solutions (GPS+K-Band)



Reference field:

ITG-GRACE03S

Differences:

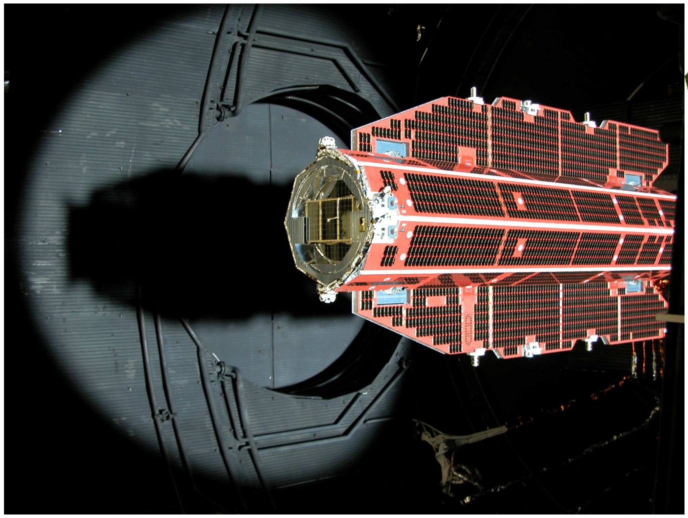
GGM03S (CSR)

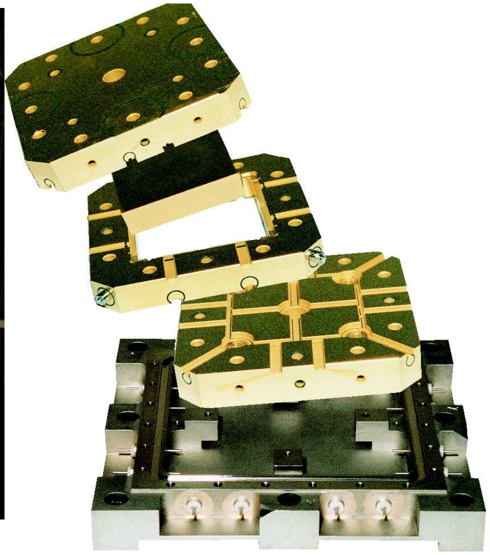
EIGEN5S (GFZ)

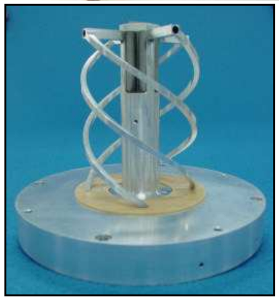
Differences:

AIUB-03Sp

Gravity Fields from GOCE

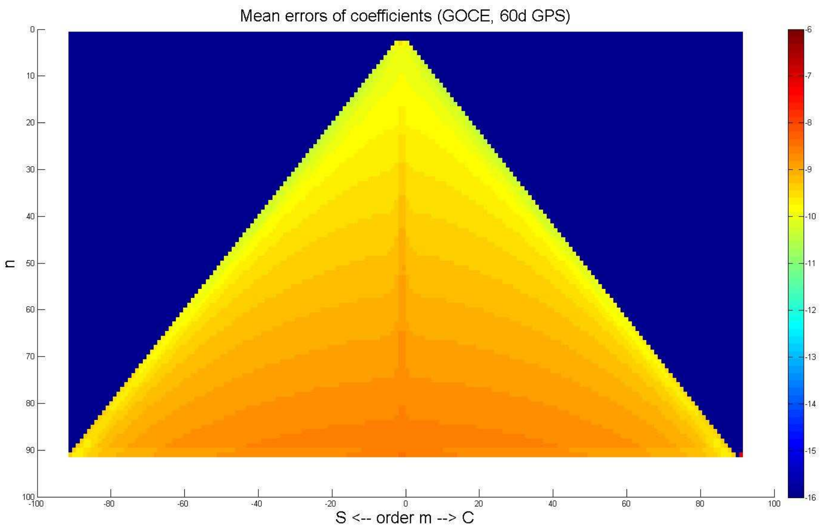


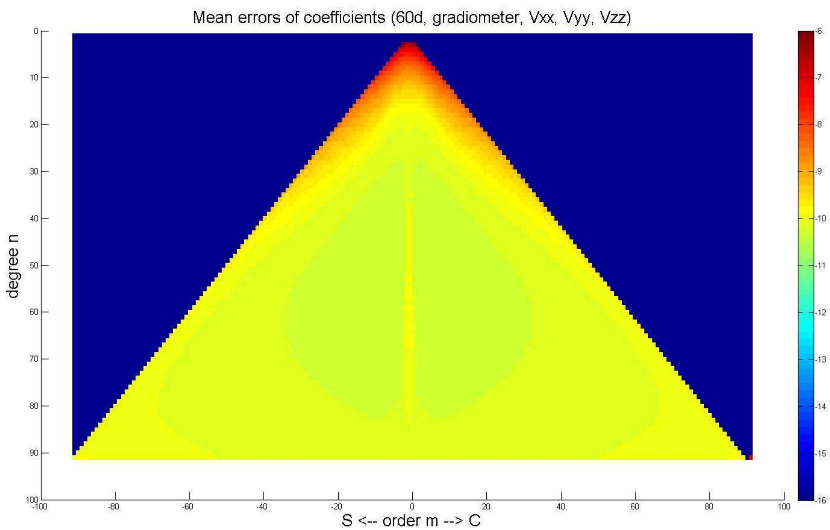




The GOCE satellite (left) carries an advanced European GPS receiver (right, bottom), a gradiometer consisting of three pairs of three-dimensional accelerometers (center). In addition it continuously corrects for atmospheric drag using ion thrusters (right, top).

Gravity Fields from GOCE





Approximate error behavior (from simulation of a 60^d measurement period) GPS-only (left) and gradiometer-only (right).

GPS will influence combined solution up to higher degrees. Gradiometer dominates from n=20-30 onwards.

Combination of GPS and gradiometer will be a challenge.

Summary I

GNSS has since 20 years a heavy impact on the determination of:

- the terrestrial reference frame
- polar motion and length of day
- ionosphere mapping
- local/regional troposphere motitoring

Spaceborne GNSS has a heavy impact on science since 10 years

- Orbit determination of LEOs and LEO constellations
- Atmosphere sounding using the GNSS occultation technique
- gravity field determination

Summary II

Spaceborne GNSS has revolutionized gravity field determination.

- **GPS plays an important role in all currently active missions (CHAMP, GRACE, GOCE)**
- **The GNSS contribution, together with the SLR contribution, is critical to determine the low degree terms of the gravity field.**
- **Multi-GNSS (GPS+GLONASS+GALILEO) will significantly advance orbit and gravity field determination with GNSS.**
- **GNSS might be even more successful if constellations of LEOS with significanly different inclinations would be used.**

Summary III

Spaceborne GNSS has not yet exploited its full potential: GNSS reflectometry should, e.g., be added to the list of spaceborne applications.

Galileo, with its rich ensemble of frequencies and and high-quality signals,

- **will significantly contribute to all aspects of science enabled by terrestrial and spaceborne GNSS,**
- **has the potential to invoke a revolution of GNSS methodology and will, if fully exploiting the options offered by its space clocks, trigger important new modeling activities (e.g., for orbits).**

The GSAC will do its best to stimulate the necessary developments.