PECS Project No. 98056

GOCE – specific tasks on fine gravity field structure of the Earth

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Presented by Aleš Bezděk

Project team

- Jaroslav Klokočník (PI), Astronomical Institute of the ASCR

- Aleš Bezděk, Astronomical Institute of the ASCR

- Josef Sebera, Astronomical Institute of the ASCR

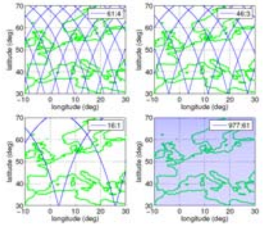
- Jan Kostelecký, Faculty of Civil Engineering, CTU Prague

- Ivan Pešek, Faculty of Civil Engineering, CTU Prague

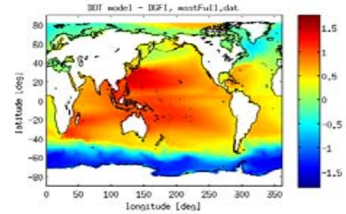
- Pavel Novák, Department of Mathematics, University of West Bohemia

Project activities during 2009

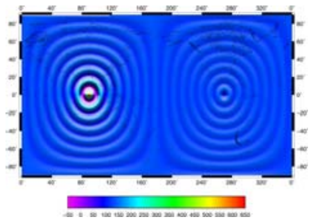
1. **Orbit choice and tuning for GOCE measuring phases**
   (responsible person: Aleš Bezděk)



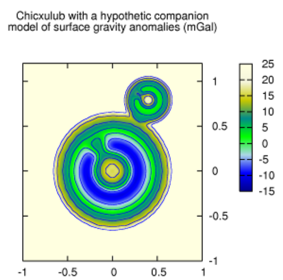
2. **Novel geodetic computational methodologies**
   (responsible person: Christian Gruber replaced by Josef Sebera during 2009)



3. **Comparison of detailed satellite and terrestrial data**
   (responsible person: Pavel Novák)



4. **Detection of hidden impact (meteoritic) structures on the Earth surface**
   (responsible person: Jaroslav Klokočník)



Publications in 2009

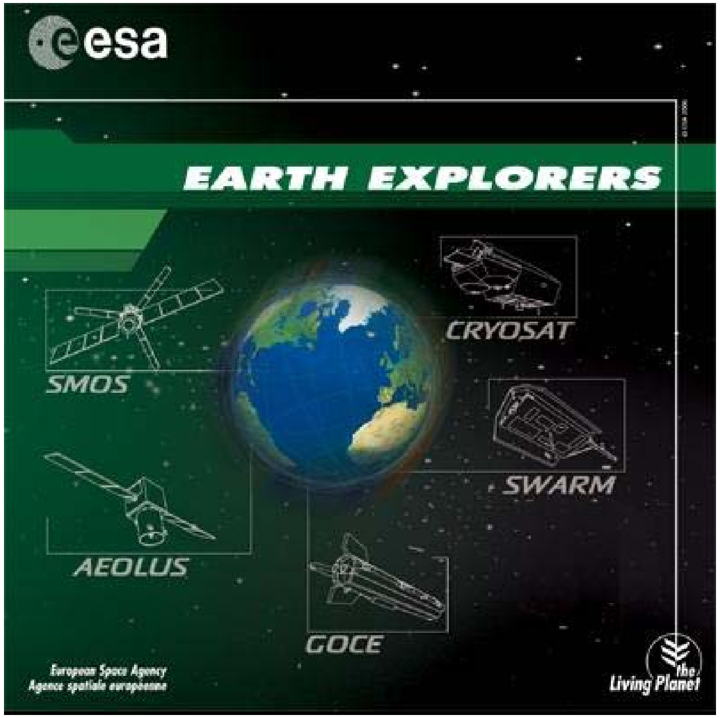
- Published papers: 10
- Submitted manuscripts: 4
- Presentations and posters: 14

Duration of PECS project: 1 Sep 2007 – 1 Sep 2011

GOCE – first Earth Explorer Core mission

Living Planet Programme

- Directorate of Earth Observation Programmes (D/EOP)
- Two types of missions:
  - Earth Explorers: science and research element
  - Earth Watch: service-driven (e.g. EUMETSAT, Sentinel)



Earth Explorers

- Defined, developed and operated in close cooperation with the science community
- Two categories of missions:
  - **Core**: specific areas of great scientific interest
  - **Opportunity**: faster, lower cost missions

To date, selected for implementation:

- Core missions: **GOCE** (03/2009), **ADM-Aeolus** (2011), **EarthCARE** (2013)
- Opportunity missions: **SMOS** (11/2009), **CryoSat-2** (02/2010), **Swarm** (2011)

GOCE – ESA's first gravity field mission

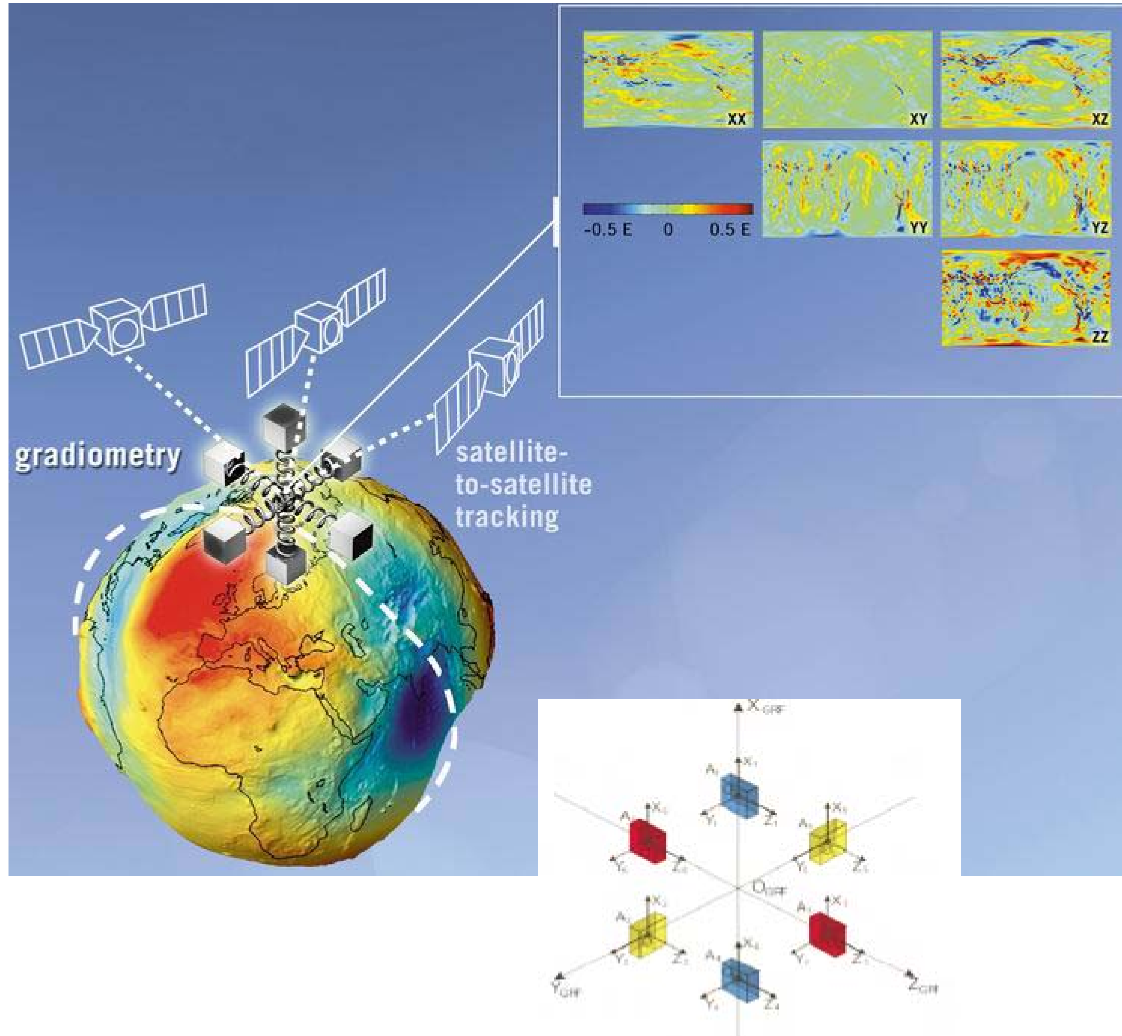
Gravity field and steady-state Ocean Circulation Explorer

- First-ever mission to fly a **space gradiometer**
- A unique drag free system using an **electric propulsion system**
- Extremely low-Earth orbit at altitude ~250 km
- Aerodynamic shape 5.3 m long, 1.1 m^2 cross section, 1050 kg
- Aim: measuring the Earth's gravity field with unprecedented accuracy and spatial resolution

Gradiometer – main payload of GOCE

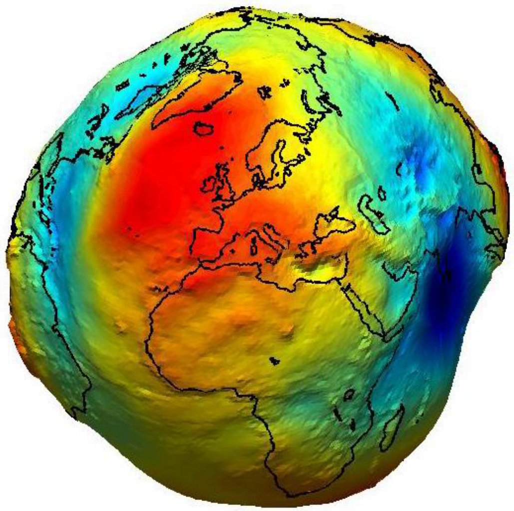
- Six state-of-the-art accelerometers
  - mounted in pairs along three perpendicular axes
  - 0.5 m arm length

- Measured quantity:
  differences in gravity acceleration
  → tensor of gravity gradients
  (unit: Eötvös 1E = 10^{-9} s^{-2})
- Symmetric 3×3 *Marussi tensor*, the trace of which is zero in empty space



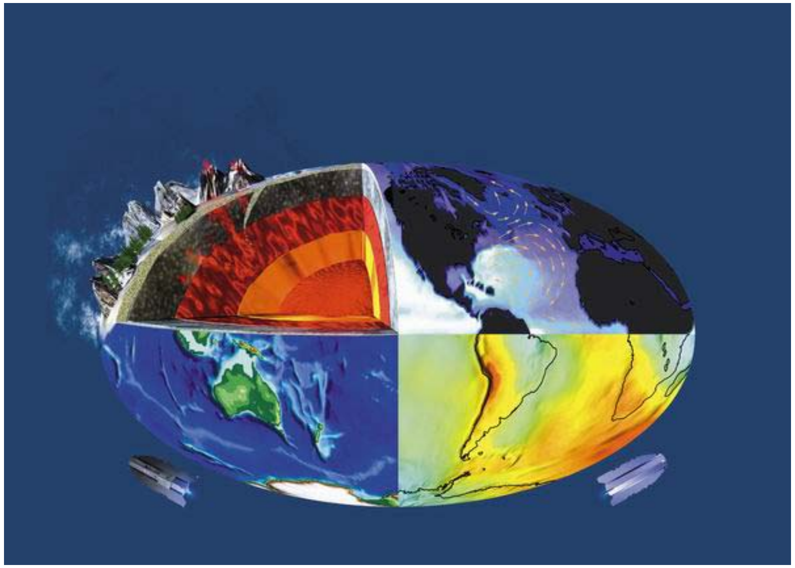
GOCE – scientific objectives

- determine Earth's **gravity field** with an accuracy of 1 mGal ≡ 10^{-5} m.s^{-2}
  (i.e. 1 millionth of the Earth gravity)
- determine the **geoid**
  (i.e. the equipotential surface for a hypothetical ocean at rest)
  with a radial accuracy of 1–2 cm
- achieve this **globally** at length scales down to 100 km



Better Earth gravity field model is useful for all geosciences, especially for:

- geodesy
- oceanography
- geophysics

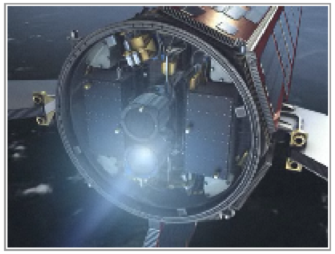


GOCE in 2009 – launch and commissioning

GOCE liftoff

ESA launches Earth Explorer mission GOCE

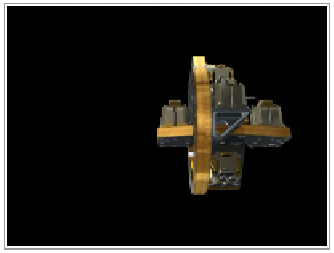
17 March 2009
ESA PR 06-2009. This afternoon, the Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite developed by the European Space Agency (ESA) was lofted into a near-Sun-synchronous, low Earth orbit by a Rockot launcher lifting off from the Plesetsk cosmodrome in



GOCE counteracting drag

GOCE's electric ion propulsion engine switched on

6 April 2009
GOCE's sophisticated electric ion propulsion system has been switched on and confirmed to be operating normally, marking another crucial milestone in the satellite's post-launch commissioning phase.



GOCE gradiometer

GOCE's 'heart' starts beating

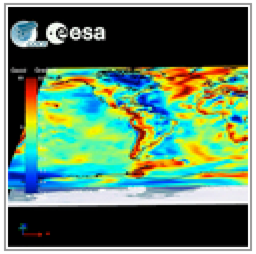
8 April 2009
GOCE's highly sensitive gradiometer instrument has been switched on and is producing data. Forming the heart of GOCE, the gradiometer is specifically designed to measure Earth's gravity field with unprecedented accuracy.

GOCE in orbit

GOCE achieves drag-free perfection

26 May 2009
ESA's gravity mission GOCE has achieved a first in the history of satellite technology. The sophisticated electric propulsion system has shown that it is able to keep the satellite completely free from drag as it cuts through the remnants of Earth's atmosphere – paving the way for the best gravity data ever.

GOCE in 2009 – gradiometer measurements successfully started



GOCE delivering data for best gravity map ever

30 September 2009 Following the launch and in-orbit testing of the most sophisticated gravity mission ever built, ESA's GOCE satellite is now in 'measurement mode', mapping tiny variations in Earth's gravity in unprecedented detail.

'Keys' to GOCE satellite handed over

25 November 2009 ESA's GOCE gravity mission has achieved another major milestone as control of the satellite is transferred to the operations teams, marking the end of its commissioning and calibration phase.

GOCE completes first mapping of the Earth's gravity field

07 January 2010

On 26 December 2009, the GOCE satellite completed its first 61-days repeat cycle.
The 979 revolutions mapping cycle has delivered a set of gravity gradients measurements and satellite-to-satellite tracking data that has a longitudinal spacing (at the equator) of less than 0.4 degrees.

GOCE first results presented

21 January 2010

GOCE first results presented at the 2009 American Geophysical Union Fall Meeting are now also available online for users to consult:

- GOCE - Mission Overview and Early Results [pdf]
- Status and Performance of the GOCE Satellite [pdf]
- The GOCE gradiometer - instrument status, data processing and product performance [pdf]

Item 2. Novel geodetic computational methodologies

Novel geodetic computational methodologies

- **Aim**: process the GOCE data in full complexity
  - ➢ Determine geopotential parameters + covariance matrix

- Covariance matrix
  - ➢ Enables error estimation on the ground, external validation by terrestrial data

- Simulations: using the EGM 96 model
  - ➢ Degree and order 70, covariance matrix ≈ 5000×5000
  - ➢ Good agreement with the official results
  - ➢ Figure: differences in accuracy over ocean and land

- Further development is needed
  - ➢ The GOCE gravity field products: degree and order 250
  - ➢ Covariance matrix ≈ 60,000×60,000

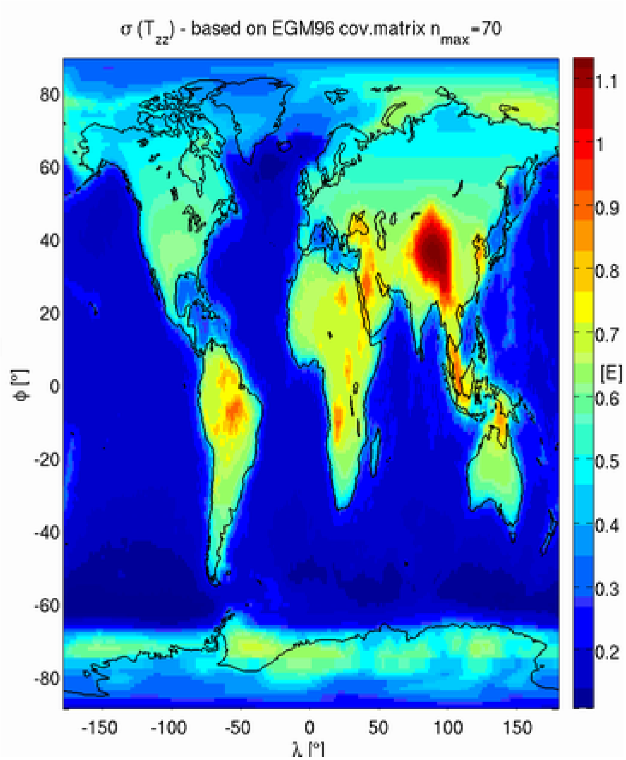


Figure: Standard deviation of the second radial derivative of the disturbing potential T_{rr}

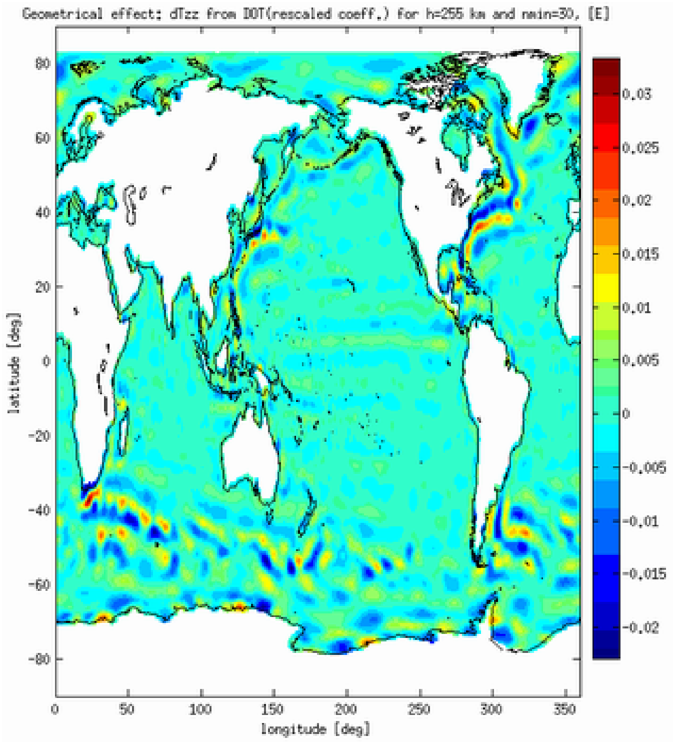
DOT effect on the Cal/Val of GOCE by satellite altimetry

- Combination of gradiometry with satellite altimetry
  - Currently studied in cooperation with DGFI Munich

- DOT (Dynamic Ocean Topography)
  - Thin shell of water, which oscillates around the geoid, mainly caused by ocean currents
  - It cannot affect the GOCE measurements by its gravitational action
  - It can adversely affect the quantities derived from the geoid provided by satellite altimetry

- Figure
  - Effect of DOT on the second radial derivative T_{rr}
  - Magnitudes (tens of mE) exceed the expected accuracy of the GOCE gradiometer (few mE)
  - Largest magnitudes correspond to the main ocean currents (e.g. Gulf Stream, Kuroshio)

- Publication
  Bouman J, Bosch W, Sebera J. Assessment of systematic errors in the computation of gravity gradients from satellite altimeter data. Submitted to *Marine Geodesy* in December 2009.



Item 3. Comparison of detailed satellite and terrestrial data

Data combination

- Earth's gravitational field described by the potential *V*
- spaceborne data of type GOCE represent in-situ *grad* $\otimes$ *grad V*
- ground (airborne, marine) data correspond to *grad V*
- all data used for derivation of the potential *V*
- for the general data type *f(V)* the inversion can be done through

$$f(V) = \frac{1}{S} \iint_S V(S)\, f(K)\, dS$$

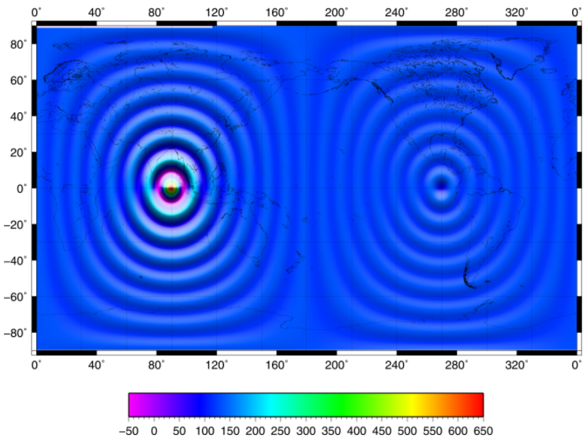
with the functional of the Abel-Poisson kernel function *f(V)*

Combination through integral inversion

- for GOCE $f = grad \otimes grad$, for ground gravity $f = e \cdot grad$

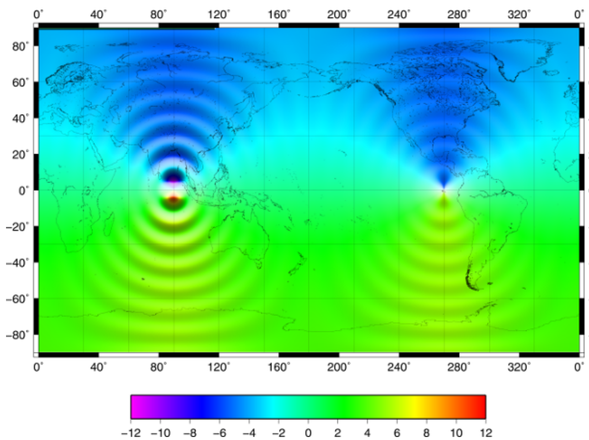
  (for a unit vector e along a local plumbline - local vertical)

- tensor-values integration kernel for GOCE : $grad \otimes grad\ K$

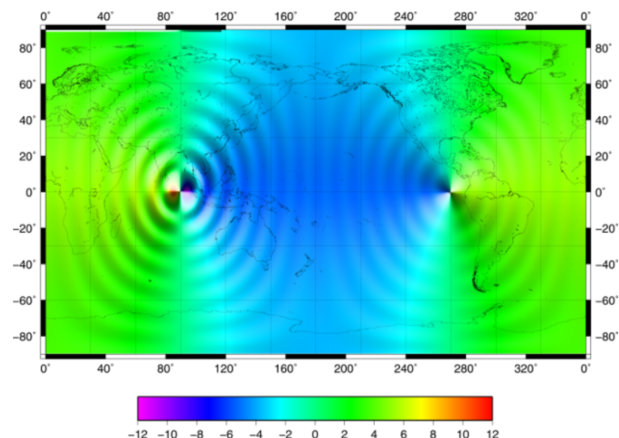


$h^2_r\, D^2_r$

$h_r\ h_\varphi D^2_{r\varphi}$



$h_r\ h_\lambda D^2_{r\lambda}$



Item 3 – publications

- Novák P, Kostelecký J, Klokočník J (2009) On accuracy of current geopotential models estimated through a comparison of quasi-geoid models and GPS/levelling data. Studia Geophysica et Geodaetica 53(1): 39-60.

- Novák P, Klokočník J, Kostelecký J, Zeman A (2009) Testing EGM08 using Czech GPS/leveling data. Newton's Bulletin 4: 126-132, ISSN 1810-8555.

- Novák P (2010) High resolution constituents of the Earth gravitational field. Surveys in Geophysics 31(1): 1-21, doi: 10.1007/s10712-009-9077-z.

Oral or poster presentations

- Novák P (2009) On combination of heterogeneous gravitational observables for cm-level accurate geoid models. 7th Hotine-Marussi Symposium, Rome, July 2009.

- Novák P (2009) Selected constituents of the high-resolution Earth gravitational model. IAG Scientific Assembly "Geodesy for Planet Earth", Buenos Aires, September 2009.

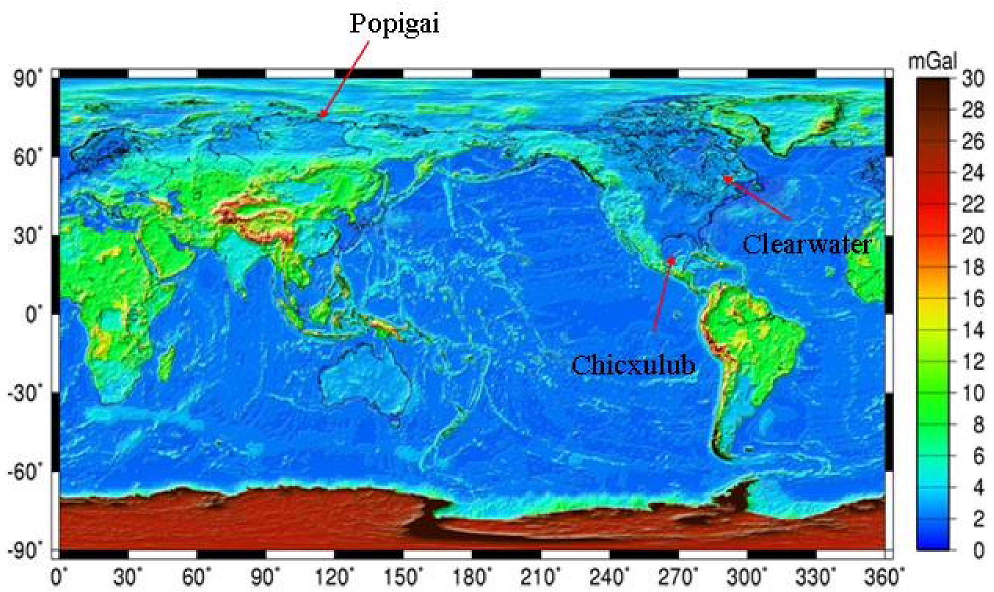
- Novák P, Huang J (2009) Local geoid modeling in the era of EGM08. IAG Scientific Assembly "Geodesy for Planet Earth", Buenos Aires, September 2009.

Item 4. Detection of impact (meteoritic) structures on the Earth surface

Study of candidates for multiple impact craters

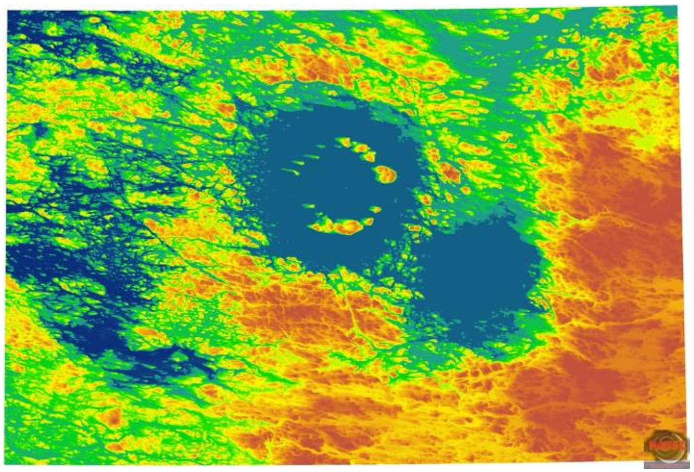
- First, we modelled the known double craters to learn how to do the modelling (Clearwater Lakes)
- Some of the impact craters show evidence of double or multiple character
  - Final decision is always on geologists
  - but – the relevant (geological) data in the areas of hypothetical craters Chicxulub II or Popigai II are not yet available

- We tried to model these putative objects by a point masses model
  - Accessible geological data used as constraints
  - We compared the theoretical gravity anomalies with those derived from EGM08
  - In both cases, the hypothetic companion looks like a “twin” of the primary crater



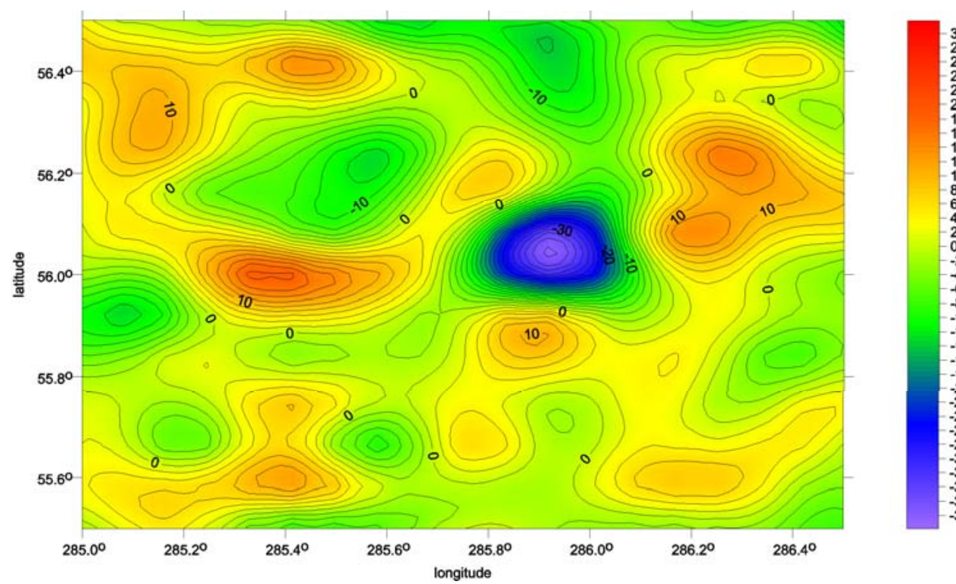
Clearwater Lakes, Quebec, Canada – test area

- Double crater supposed to have been created simultaneously by two impactors of a comparable size



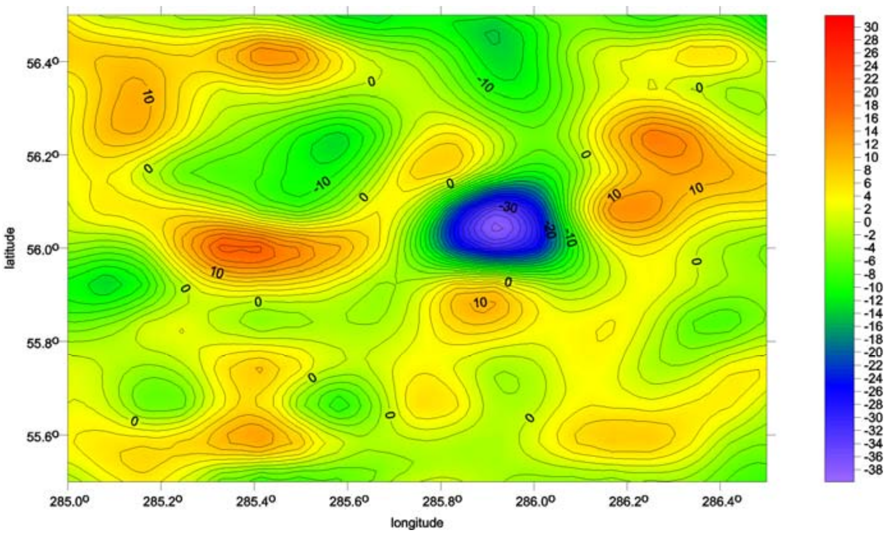
- Two craters as seen from a Space Shuttle
- Craters of 26 km and 36 km in diameter
- Age 290 million years

- Second derivatives T_{rr} of the geopotential, full 2160×2160 model EGM08 (scale in mE)

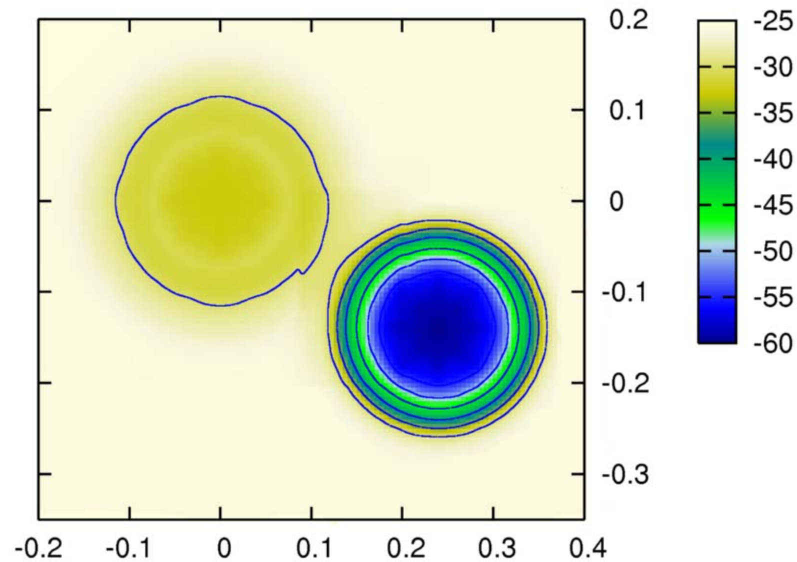


Clearwater Lake, Quebec, Canada – test area

- Left figure: Double impact crater as represented by EGM08 (second derivatives T_{rr})
- Right figure: Modelled by point masses with geological constraints
- Conclusion: We are able to produce a realistic mass model of the actual double crater



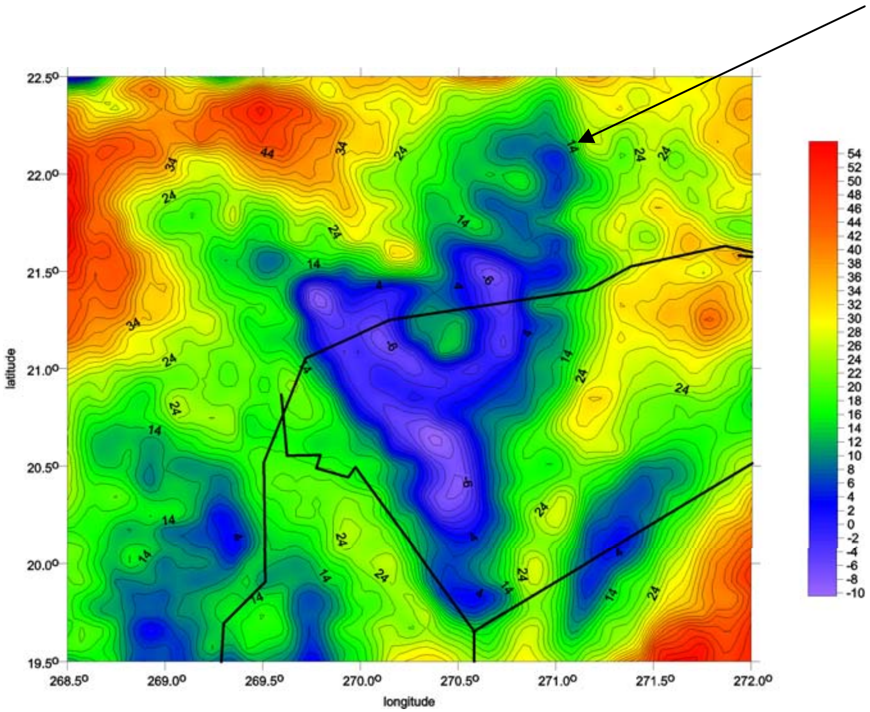
Clearwater double crater
model of surface gravity anomalies based on the EGM 08 (mGal)

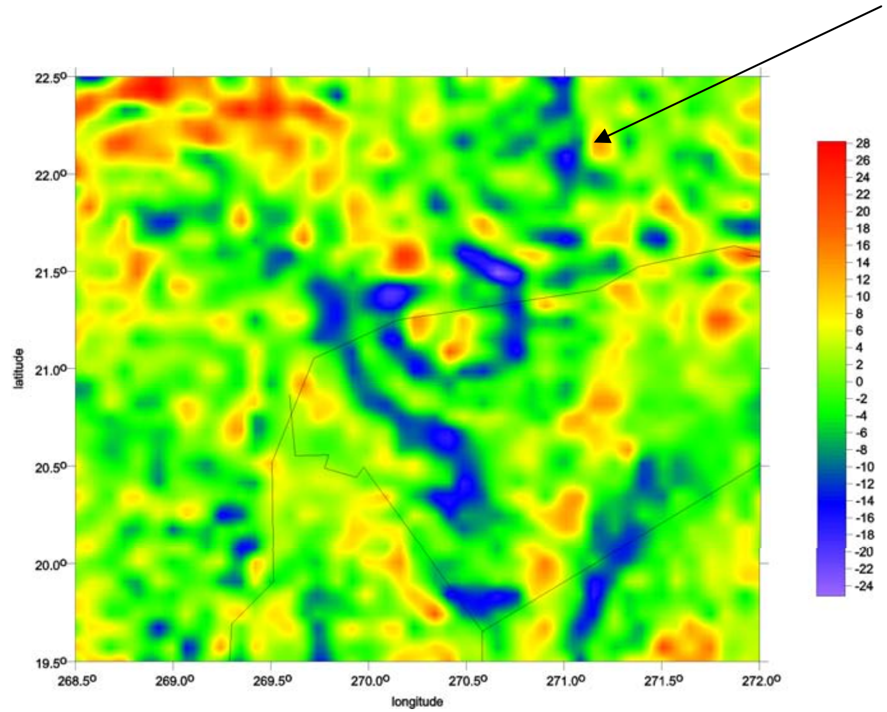


Candidate double crater Chicxulub, Mexico

- A multi-ringed impact crater buried partly partly under a shallow sea
- Two rings with the diameters of about 80 and 170 km
- Age 65 MY, the impact possibly caused the extinction of the dinosaurs

- Left figure: Gravity anomalies Δg [mGal]: the arrow indicate a possible second crater **Chicxulub II**
- Right figure: Second radial derivatives T_{rr} [mE]



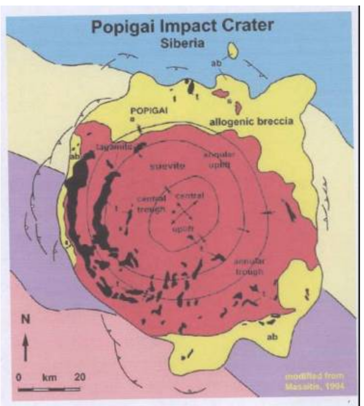


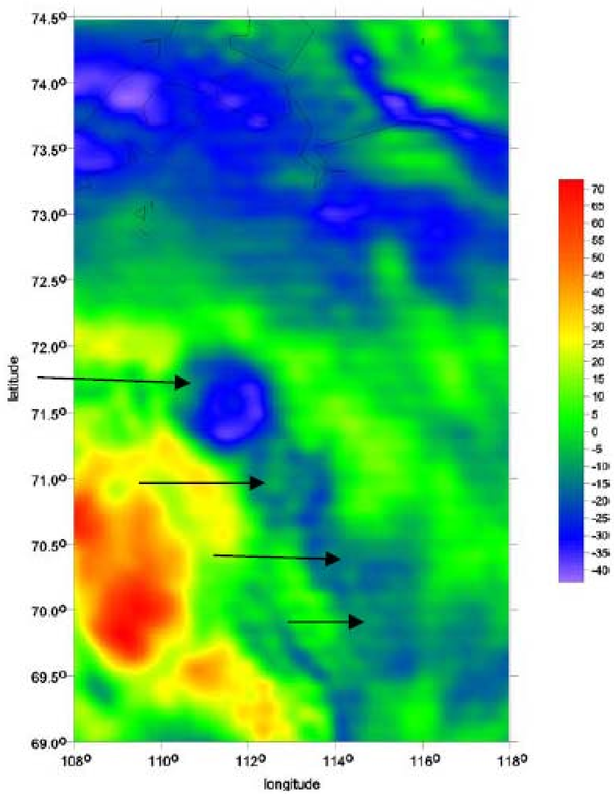
Candidate multiple crater – Popigai, Siberia, Russia

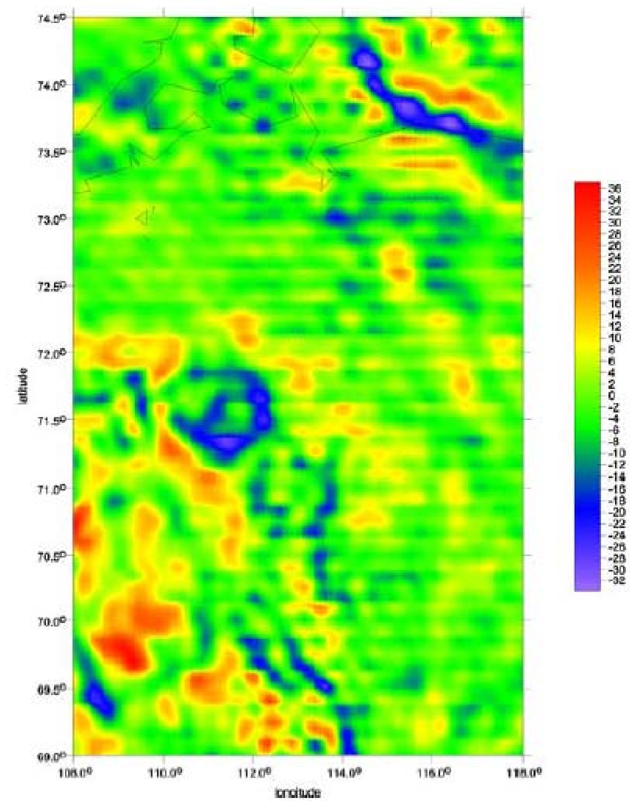
- Large impact structure (ø 100 km, age 36 My), the main crater is partly visible on the surface
- Shock pressures from the impact transformed graphite into diamonds near the central zone of the crater

Figures

- Geological map, satellite map, gravity anomalies Δg and second radial derivatives T_{rr} from EGM08
- The arrows point to Popigai I and hypothetical Popigai II, III and IV

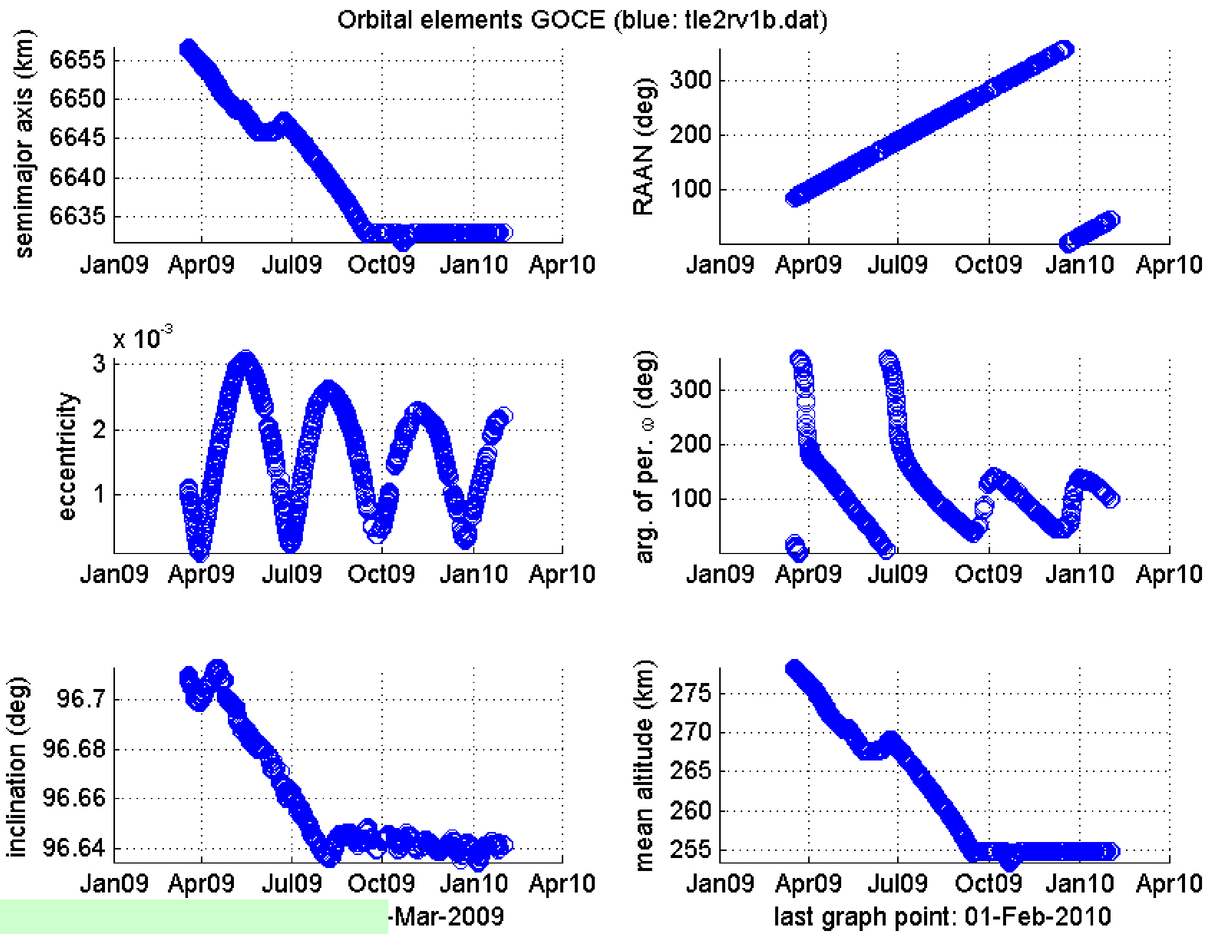






Item 1. Orbit choice and tuning for GOCE measuring phases

GOCE – first measurement operational phase (MOP1)



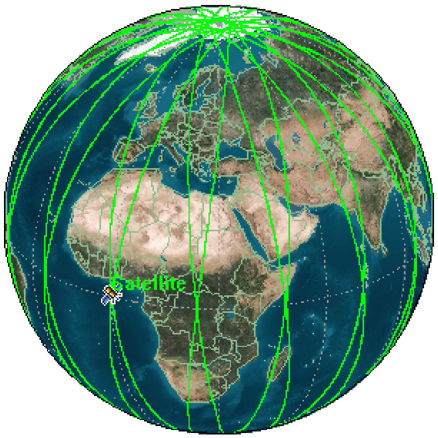
Planned phases:

- Comm. @ 273 km, Apr 2009 – Aug 2009 (5 months)
- MOP1 @ 263 km, Sep 2009 – Mar 2010 (7 months)
- HOP1 @ 273 km, Apr 2010 – Aug 2010 (5 months)
- MOP2 @ 263 km, Sep 2010 – Mar 2011 (7 months)
- (HOP2 + MOP3: optional)

Orbital resonances

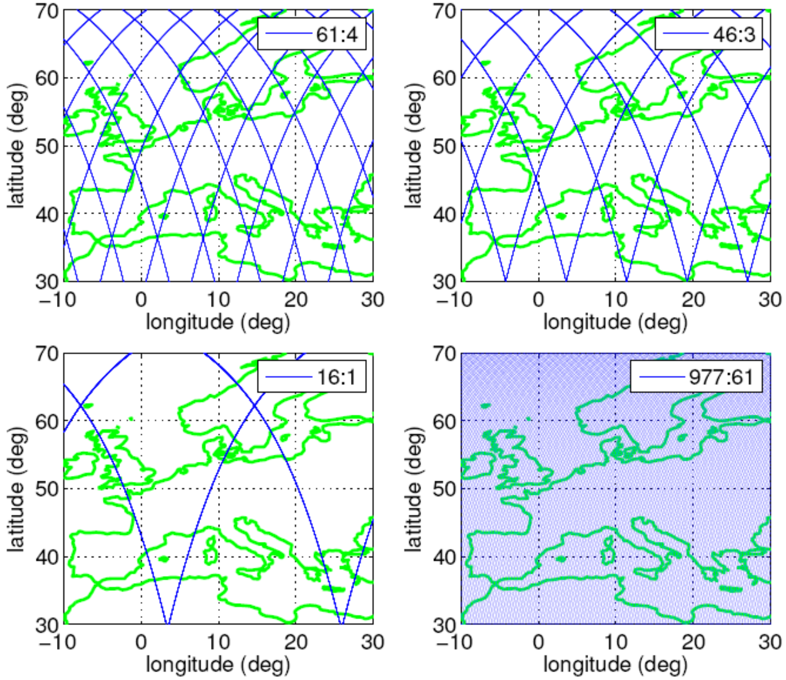
Orbital resonance R:D takes place, if:

- Satellite makes R revolutions w.r.t. ascending node, while the Earth rotates D-times w.r.t. ascending node
- Groundtracks are exactly the same after R nodal revolutions and D nodal days



Examples of using the resonance orbits

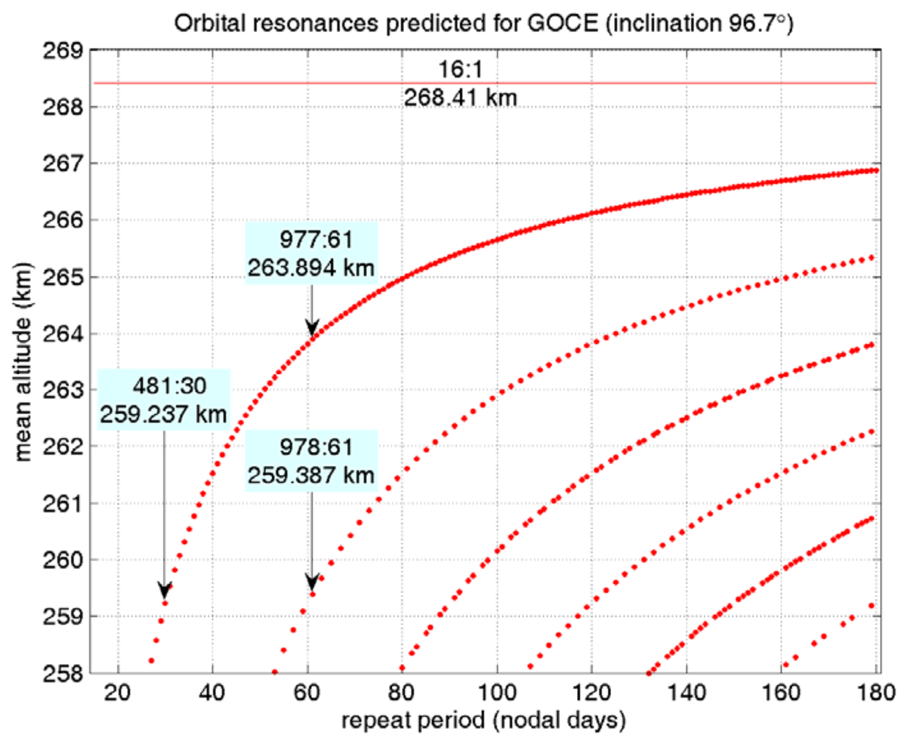
- Remote sensing of Earth – a need of sampling the same position in regular periods
- Modelling of gravity field

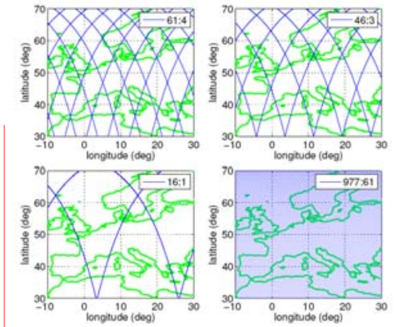


GOCE and orbital resonances

Scientific requirements of GOCE project: global and homogeneous sampling of Earth gravity field

- Resolution of geopotential 100 km → minimum repeat period of 2 months
- Satellite altitude as low as possible – limited by performance of ion thruster

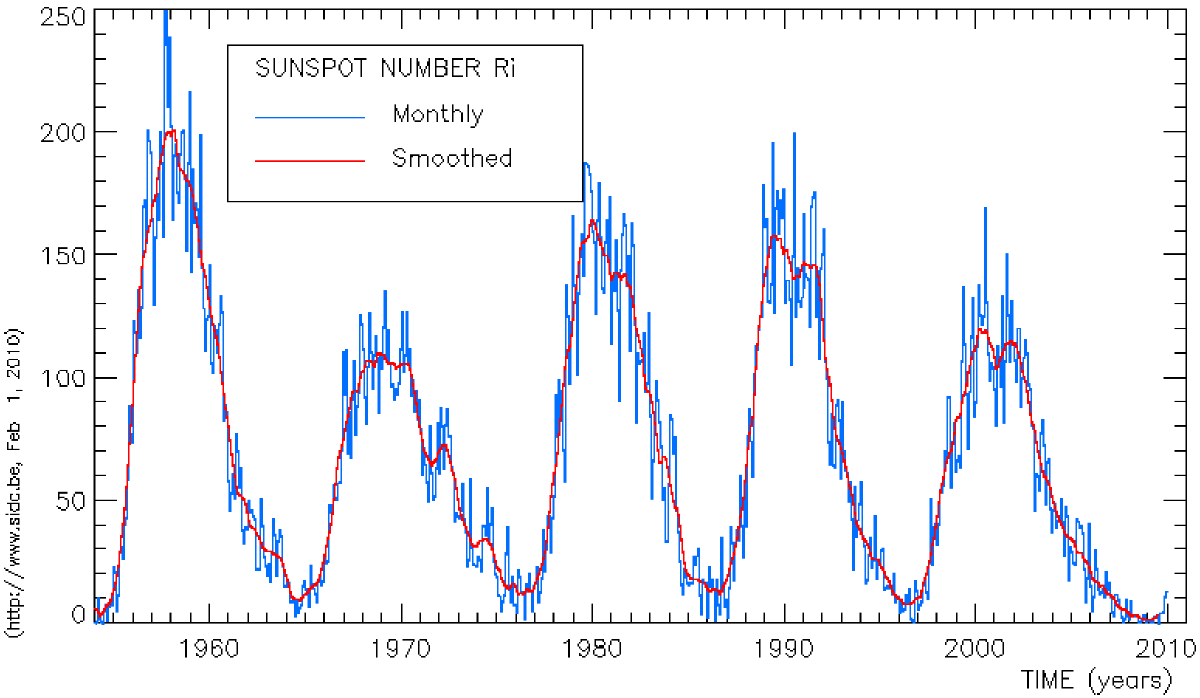


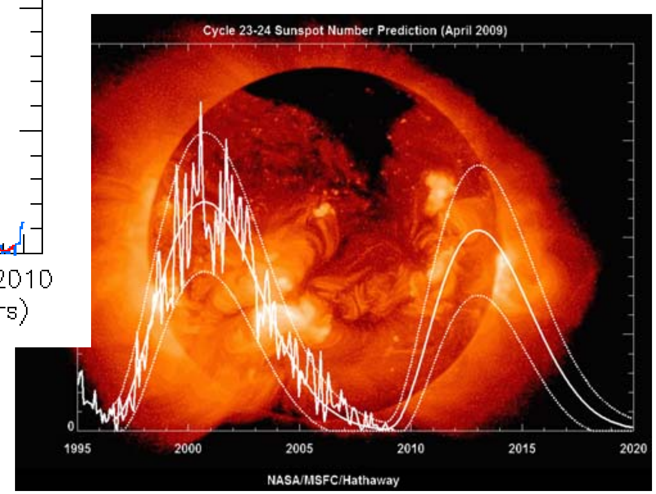


- Bezděk, A., Klokočník, J., Kostelecký, J., Floberghagen, R., Gruber, C. Simulation of free fall and resonances in the GOCE mission. *Journal of Geodynamics* 48(1), pp. 47-53, 2009

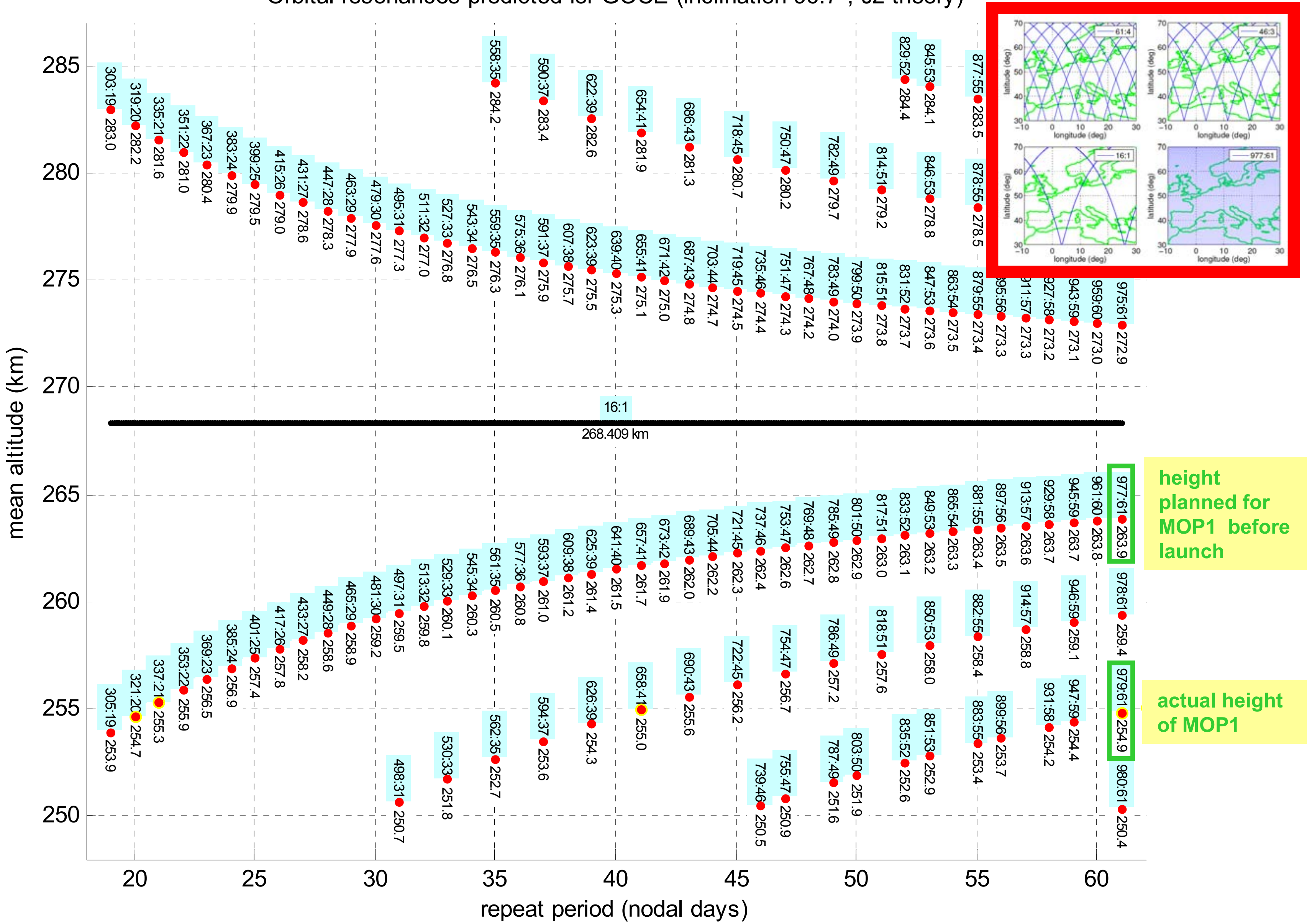
Deep solar minimum and GOCE

- Very low solar activity
  - Lower atmospheric drag to be counteracted by the onboard ion thrusters
  - MOP1 altitude of 254.9 km is 8 km below the one announced at launch
  - Important change as regards the neighbouring repeat orbits
  - We updated our computations and graphs for this new lower altitude



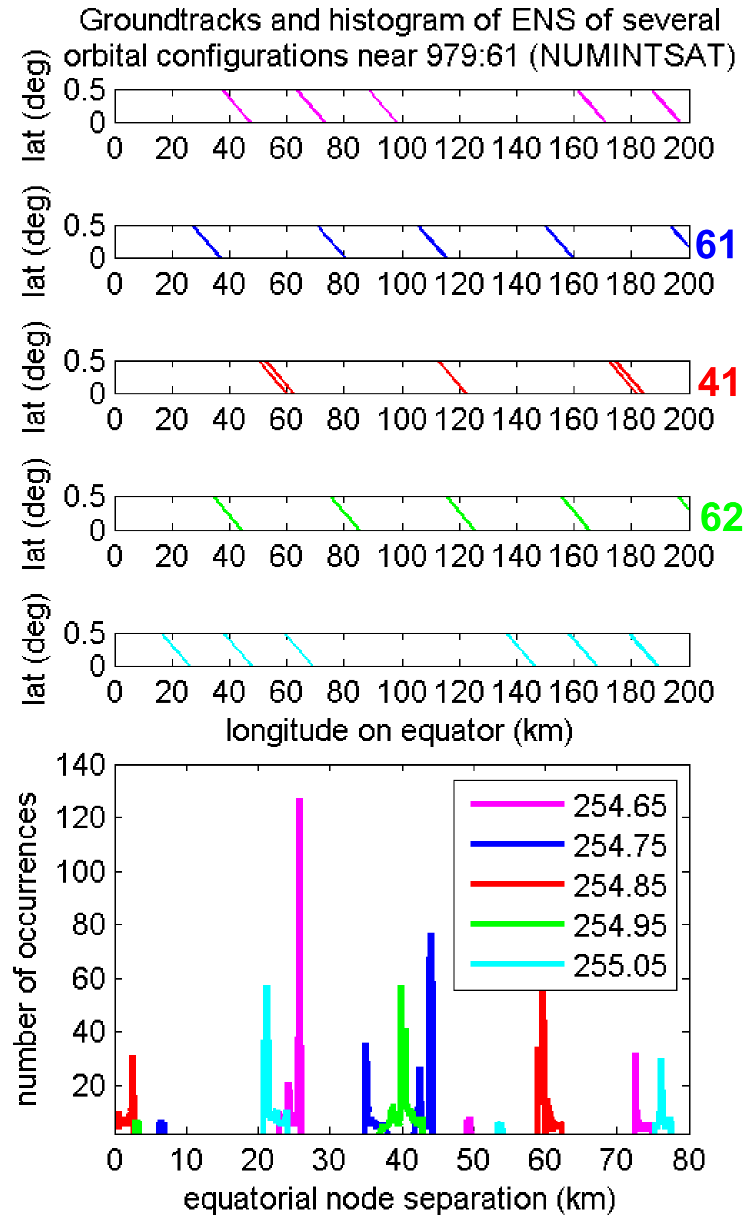


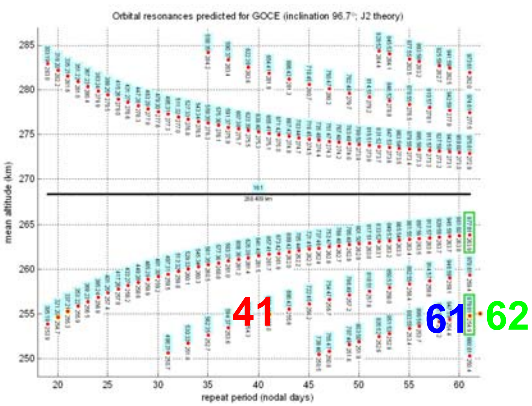
Orbital resonances predicted for GOCE (inclination 96.7°; J2 theory)



Orbits of GOCE near 979:61 resonance (254.9 km) for MOP1

- Shown is a part of equator with groundtracks after 65 days; panels differ in mean altitude
- Groundtrack grid of some orbits is regular (61-day, in green) of others is not (41-day, in red)
- Histograms show distance between the ascending nodes
- Orbit with **62-day** period compared with **actual 61-day** orbit
  - ➢ has more regular groundtrack grid
  - ➢ is only by 200 m higher
  - ➢ will be considered for MOP2 orbit choice



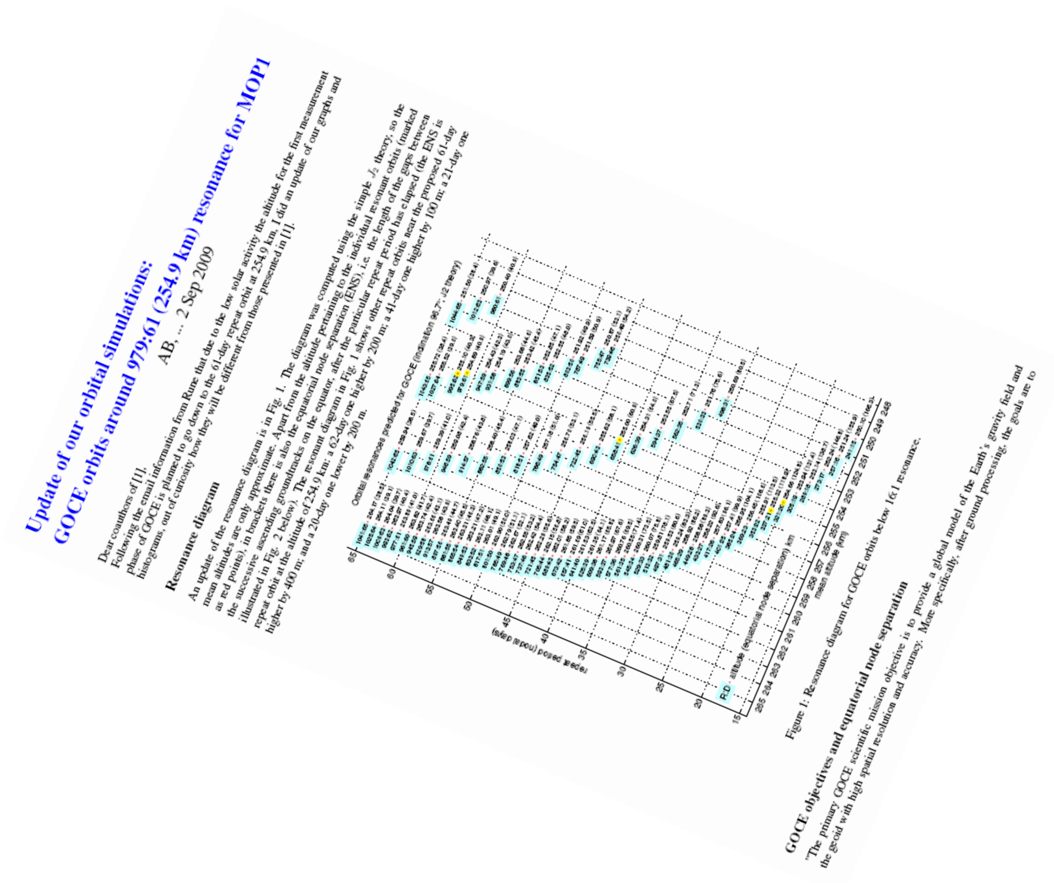


Update of our orbital simulations for 254.9 km repeat orbit

ESA Living Planet Symposium in June 2010 in Bergen

Some aspects of the orbit selection for the measurement phases of GOCE

- Bezděk, Klokočník, Kostelecký, Floberghagen, Sebera



Update of our orbital simulations:
GOCE orbits around 979:61 (254.9 km) resonance for MOP1

AB, ... 2 Sep 2009

Dear coauthors of [1],
Following the email information from Rune that due to the low solar activity the altitude for the first measurement phase of GOCE is planned to go down to the 61-day repeat orbit at 254.9 km, I did an update of our graphs and histograms, out of curiosity how they will be different from those presented in [1].

Resonance diagram

An update of the resonance diagram is in Fig. 1. The diagram was computed using the simple J_2 theory, so the mean altitudes are only approximate. Apart from the altitude pertaining to the individual resonant orbits (marked as red points), in brackets there is also the equatorial node separation (ENS), i.e. the length of the gaps between the successive ascending groundtracks on the equator, after the particular repeat period has elapsed (the ENS is illustrated in Fig. 2 below). The resonant diagram in Fig. 1 shows other repeat orbits near the proposed 61-day repeat orbit at the altitude of 254.9 km: a 62-day one higher by 200 m; a 41-day one higher by 100 m; a 21-day one higher by 400 m; and a 20-day one lower by 200 m.

Figure 1: Resonance diagram for GOCE orbits below 16:1 resonance.

GOCE objectives and equatorial node separation

"The primary GOCE scientific mission objective is to provide a global model of the Earth's gravity field and the geoid with high spatial resolution and accuracy. More specifically, after ground processing, the goals are to

Thank you for your attention