Report on our activity in the framework of the grant ESA PECS *C 98056* during *2010*

Contributors to this report

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Editor

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This grant project began in September 2007. It consists of 4 areas of simulations and preparation for the actual GOCE data (which were made available in mid 2010, after a delay), three submitted AO's, accepted and supported by ESA in 2007 in the frame of ESA GOCE; one remaining (the first item in the following list) has occurred as a result of consultations with Dr. Rune Floberghagen (at that time ESA ESTEC, Noordwijk), GOCE Project Manager and his colleagues. The following items are studied:

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

2. ***Novel geodetic computational methodologies***
   (responsible person: Josef Sebera)

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)

Following the suggestion made during our last year's PECS presentation, we also add the section on:

5. Financial plan for 2010 and its fulfilment

1. Orbit choice and tuning for GOCE measuring phases

(prepared by A. Bezděk, J. Klokočník, and J. Kostelecký)

The major international meeting related to GOCE in 2010 was ESA Living Planet Symposium in Bergen, Norway, where the first GOCE gravity models were officially released by ESA. These models were based on 71 days of GOCE data from November 2009 to January 2010 and were computed in the frame of the ESA project "High Level Processing Facility" by applying 3 independent and complementary processing strategies. We presented there our results on fine orbit tuning [1] of GOCE orbit for the mapping phases of the mission, we paid a particular attention to the proposed possible repeat orbits for the next measurement phase (Fig. 1).

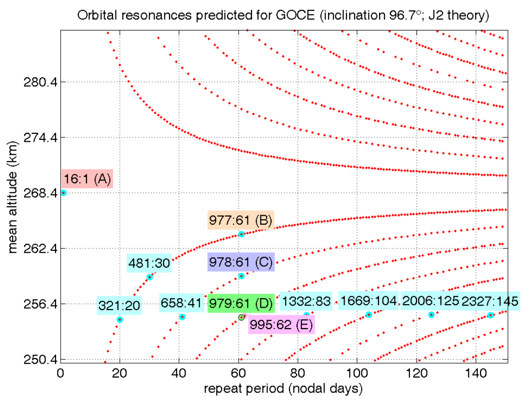

Fig. 1 Several resonant orbital configurations, studied as candidates for GOCE measurement operational phases [2].

In November 2010 ESA approved the extension of the GOCE mission from April 2011 until the end of 2012. This is a good news for the whole GOCE scientific community, and particularly for this item of our PECS project, as we were informally asked by GOCE mission managers to analyze possible orbits of GOCE for the next measurement phase from the point of view of orbit resonance and optimum Earth coverage. One also has to take into account the current ascending phase of the cycle of solar activity, which is connected with the increase in atmospheric drag and thus the performance of the unique GOCE onboard ion thrusters.

In December 2010 GOCE and other ESA Earth observing missions were highlighted at world's largest scientific conference, the annual American Geophysical Union (AGU) Fall Meeting, this year attracting around 18 000 scientists. We successfully presented there our fine orbit tuning analyses applied to CHAMP, GRACE and especially GOCE [2]. We also described the results of such analyses applied to space probes around our neighbouring celestial bodies [3]. In the case of Mars orbiters, the situation is similar to that of satellites revolving around the Earth, and our conclusions may actually help Mars orbit designers to chose better orbits from gravity modelling point of view "at almost no cost" just by shifting the mean altitude by a few hundred metres to avoid low order resonances. For Moon, Mercury and Venus no similar problems in gravity sampling arise, as their rotation rate is too slow for an orbiter to repeat the ground tracks in a reasonably short time.

Further, last year we started to work up the method of gravity field inversion based solely on the precise orbital data. Such methods started to be broadly used by the space geodesists with the CHAMP onboard GPS receiver data, which had sufficiently dense and continual sampling of the satellite orbit. For GOCE, the lower part of global gravity field spectrum obtained from the mission data should be based on this orbital information. Contrary to many teams, which use only the along-track part of the orbital information, our method uses the vector equation, allowing one to use the three components in a more homogeneous fashion. We already presented the first results using the real-world orbital data of GRACE and GOCE at the AGU FM [2]. These studies are useful for studying the resolvability of gravity field inversion, what is maximum degree and order of the modelled geopotential spherical expansion, given a particular repeat orbit. We will also use these lower degree models in combination with the high-frequency part of the gravity spectrum obtained from the GOCE gradiometer (studied in Item 3 of this PECS project, see below). We plan to present our results at the fourth international GOCE user workshop in March 2011 in Munich and publish them subsequently.

Results of the fine orbit tuning were also presented by J. Klokočník at the WEGENER meeting in Istanbul 2010 [4]. The application of the same approach to bistatic altimetry (GNSS-Reflectometry) has been studied at ESA Workshop in Barcelona [5].

Published or presented contributions:

[1] Bezděk A, Klokočník J, Kostelecký J, Floberghagen R, Sebera J, 2010. Some aspects of the orbit selection for the measurement phases of GOCE. Proceedings of the ESA Living Planet Symposium, Bergen, Norway, 28 June–2 July, ESA SP-686.

[2] Bezděk A, Klokočník J, Kostelecký J, Floberghagen R, Sebera J, 2010. Fine orbit tuning to increase the accuracy of the gravity-field modelling. Presented at 2010 AGU Fall Meeting, 13–17 December, Moscone Convention Center, San Francisco, California, USA.

[3] Klokočník J, Bezděk A, Kostelecký J, Sebera J, 2010. Orbit tuning of planetary orbiters for accuracy gain in gravity-field mapping. Journal of guidance, control, and dynamics 33(3), 853–861. http://dx.doi.org/10.2514/1.46223

[4] Klokočník J., Bezděk A., Kostelecký J., Orbit tuning for GOCE measuring phases and for planetary orbiters to maximize accuracy gain in the gravity field mapping, pres. at session 4 „Earth Obs. Systems…“, WEGENER 2010, 15th Gen. Assembly Wegener, Sept. 14-17, 20010, Istanbul, Turkey.

[5] Klokočník J, Bezděk A, Kostelecký J. GNSS-R concept extended by a fine orbit tuning, ESA Workshop on GNSS-R 2010, Barcelona (poster, now paper in review)

2. ***Novel geodetic computational methodologies.***

(prepared by Josef Sebera)

a) Satellite altimetry and satellite gradiometry

We have continued validation-combination efforts of the satellite altimetry and satellite gradiometry that resulted in an internal Deutsches Geodätisches Forschungsinstitut report (DGFI) which will be placed on the DGFI website soon (http://www.dgfi.badw.de/). The final conclusions we made are: before both techniques are compared (case of validation) or joined into one data set for the gravity field modelling (case of combination), the data themselves must relate to the same equipotential surface, that is, to the geoid. Secondly it was found that satellite altimetry data must be corrected for the effect of Dynamic Ocean Topography (DOT, see our ESA PECS report 2009) before use in GOCE combination/validation to incorporate the difference between “reality” (ocean surface) and the equipotential surface of geoid. The problem is that DOT models can be based on different approaches causing a difference at the same level of magnitude as the gravity correction itself. However, this problem only affects areas of the main ocean currents (e.g. Gulf stream, Kuroshio current) and thus we recommend the use of satellite altimetry data for GOCE validation-combination over the oceans except over these currents as the uncertainty in DOT modelling is too significant there. See [1].

b) Straightforward parametrization of the Eötvös tensor (Direct approach)

The second intention of this year was to develop the mathematical model for the GOCE data processing. This involves describing the relationship between the observables (GOCE measurements = Eötvös tensor = gravity gradients) and the unknowns represented by the spherical harmonic parameters (parameters of the Earth's gravitational field). In cooperation with Carl A. Wagner from USA we developed an approach based on Hotine's formulation of gravitational potential and its derivatives, a concept that has not been used often in last 15 years although it is very convenient for setting the general observation equation. The problem is that the GOCE gradiometer measures gravity gradients in an arbitrary rotated reference frame dependent upon the satellite orientation which must be determined in order to utilize the data. If the orientation parameters are known, there are two ways to proceed. The first is the rotation of the tensor into a conventional reference frame in which the observation equation can easily be set. However, such a rotation can introduce an unpleasant error from the rotation because the new rotated tensor element is a function of all the original tensor components that significantly differ in accuracy (Vxx, Vyy, Vzz, Vxz are very precise, Vxy, Vyz are less precise). Thus the rotation of measurements can contaminate the most precise components through incorporation of less accurate ones. On the other hand we can avoid this using the rotated observation equations, where data rotation is substituted by the rotation of the base functions. This prevents error contamination from the less accurate components. To do this we used an elegant Hotine's formulation that offers a favourable algebraic and numeric properties. The structure of the rotated equation is almost the same as the un-rotated equation. This formulation does not need the derivatives of the associated Legendre functions of the first kind and thus, when computing, it is faster than other formulations and in principle less affected by rounding errors. See [2].

c) Ellipsoidal harmonics

Working with terrestrial data (like in section a) brought us logically to the ellipsoidal modelling of the Earth's gravitational field as the Earth is closer to an ellipsoid than a sphere. The gravity signal on the Earth is better approximated by ellipsoidal functions than by spherical functions. Our first step was to develop the algorithms used for the computation of the associated Legendre functions of the second kind up to the highest degrees/orders which correspond with the most current Earth's gravitational field model, the EGM2008 to d/o=2190. These functions are crucial base functions for the development of the Earth's outer gravitational field into a harmonic series. We successfully derived the formulas up to the second derivative required to compute all the potential functionals and optimized them with respect to rounding errors that can be gauged by the Legendre differential equation as it is a generating equation as well as the required condition. For more details see [3,4].

Published or submitted contributions:

[1] Sebera J., Bouman J., Bosch W., Dynamic ocean topography and vertical gravity gradient computation, DGFI Report 87, November 2010.

[2] Sebera J., Wagner C.A., Bouman J., Bezděk A., Klokočník J., Kostelecký J., Novák P., Gravitational tensor in the GOCE reference frame by direct harmonic synthesis. Pres. at EGU GA Vienna 2010, Geophys. Res. Abstracts 12, EGU2010-7103-3, 2010.

[3] Sebera J., Bosch W., Bouman J., Kostelecký J., Klokočník J., Bezděk A. Upward continuation of satellite altimeter data for GOCE validation. Pres. at the ESA Living Planet Symposium, Bergen, Norway, 28 June – 2 July 2010.

[4] Sebera J., Bouman J., Bosch W., On computing ellipsoidal harmonics using Jekeli's renormalization, Journal of Geodesy (submitted).

3. Comparison of detailed satellite and terrestrial data

(prepared by P. Novák)

Formulations and numerical experiments in the field of forward modeling of selected gravitational effects were summarized in an article published in *Surveys in Geophysics*. Related numerical aspects were later analyzed in another contribution published in *Acta Geodynamica at Geomaterialia*. The methodology is based on spectral representation of Newtonian potential integrals with numerical coefficients of a global height function. Results were presented namely at the *7th General Assembly of the European Geosciences Union* (EGU) in Vienna, May 2010, and at the *Fall Meeting of the American Geophysical Union* in San Francisco, December 2010.

Methods based on harmonic representations of parameters used for description of the Earth's gravitational field require stable and efficient algorithms for harmonic analysis and synthesis. The key role in these computational steps play algorithms for computing Legendre functions of the first/second kind. A new algorithm for their evaluation was developed, tested and presented at the *7th General Assembly of the European Geosciences Union* (EGU) in Vienna, May 2010. The algorithm was described in an article submitted to *Studia Geophysica et Geodaetica* (after the first review, small modifications suggested).

The mathematical model for combined processing of local ground, airborne and global spaceborne data is based on the theory of potential and its boundary-value problems, namely the Dirichlet (first) boundary-value problem for the Laplace equation. The solution is based on Greens's surface integrals over the unknown potential function at some simple, closed and connected surface (geocentric reference ellipsoid). Observation equations in the form of surface integrals can be formulated for all types of currently available gravity field observables. Due to the observation noise, a linear system of inconsistent equations must be solved with the solution estimated through some criterion (such as minimizing the quadratic form of the vector of residuals). Details of this model presented at *7th Hotine-Marussi* symposium in Rome, July 2009, were described in the article submitted and accepted for publication in the proceedings from the *7th Hotine-Marussi symposium* (*IAG Series to be published soon by Springer*).

Besides solving for geographically-limited values of the gravity potential, methods based on global parametrization of the gravity potential were also tested. Namely a method of 2-D Fourier representation of the Earth's gravity potential at the surface of a geocentric sphere was tested because of the approximate spherical symmetry of the Earth's gravity field. Numerical coefficients in this series can be estimated directly from observed data, however, this approach requires some stable algorithms for the spherical harmonic analysis and synthesis. These methods were also investigated and results were presented at the *7th European Sciences Union* in Vienna, April 2010.

A possible application of GOCE data for definition and establishment of a global height system was tested within the Inter-Commission project "World Height System (WHS)" of the International Association of Geodesy (IAG). A preliminary study was presented at the *2nd*

Symposium of the International Gravity Field Service (IGFS) held in Fairbanks, September 2010. The project is also based on combination of heterogeneous gravity data: spaceborne data locally enhanced by ground or airborne gravity data.

Published or submitted contributions:

- 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.

- Novák P (2010). Direct modeling of the gravitational field using harmonic series. *Acta Geodynamica at Geomaterialia* 157(1): 35-47.

- Klokočník J, Kostelecký J, Novák P, Wagner CA (2010). Detection of Earth impact craters aided by the detailed global gravitational model EGM2008. *Acta Geodynamica at Geomaterialia* 157(1): 71-97.

- Vajda P, Ellmann A, Meurers B, Vaníček P, Novák P, Tenzer R (2010). Harmonic continuation and gravimetric inversion of gravity in areas of negative geodetic heights. In Mertikas SP (ed.) *Gravity, Geoid and Earth Observation*: 25-30, Springer-Verlag Berlin Heidelberg, ISBN: 978-3-642-10633-0.

- Vajda P, Vaníček P, Novák P, Tenzer R, Ellmann A, Meurers B (2010). On ambiguities in definitions and applications of Bouguer gravity anomaly. In Mertikas SP (ed.) *Gravity, Geoid and Earth Observation*: 19-24, Springer-Verlag Berlin Heidelberg, ISBN: 978-3-642-10633-0.

- Tenzer R, Novák P (2010). Effect of the long-wavelength topographical correction on the low-degree Earth's gravity field. In Mertikas SP (ed.) *Gravity, Geoid and Earth Observation*: 355-360, Springer-Verlag Berlin Heidelberg, ISBN: 978-3-642-10633-0.

- Douša J, Filler F, Šimek J, Kostelecký J, Kostelecký J (jr), Novák P (2011). New implementation of ETRS89 in the Czech Republic: Campaign EUREF-Czech-2009. *Geodetický a kartografický obzor* 55(99): 25-35.

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

(prepared by J. Klokočník)

We continued in a survey of the Earth's special structures with the 2160×2160 gravitational potential model EGM08 using both its computed gravity anomalies in spherical approximation and second radial derivatives.

Over most of the well known impact crater sites we find the second derivatives offer finer discrimination of the circular features than the anomalies themselves. We also find indications for double or multiple impact craters in close vicinity of the "original" well-known single craters verified by geologists. We published finally [1] and [2] about the impact craters. These findings were tested by geophysicists and geologists. Chicxulub was refused by geologists as a double impact crater [2], but Popigai still remains as a candidate for a multiple crater [2]. We developed special method how to model double/multiple impact craters with point mass models [1], [2], [3]. The application of EGM08 for searching the impact craters has also been presented at [4].

There is another, unexpected application of EGM 08 (and all new gravity models forthcoming now with the GOCE data included), namely the study of geomorphology of recently active zones like Himalaya and the second radial derivatives. First study is in [5].

Published or presented contributions:
(if not listed in preceding items)

[1] Klokočník J., Novák P., Kostelecký J., Wagner C.A., Detecting impact craters using the EGM 08, Acta Geodyn. Geomater. 2010, 7, #1 (157), 71-97.

[2] Klokočník J., Kostelecký J., Pešek I., Novák P., Wagner C.A., Sebera J., Candidates for multiple impact craters?: Popigai and Chicxulub as seen by the global high resolution gravitational field model EGM08, Solid Earth EGU 2010, 1, 71-83, DOI: 10.5194/se-1-71-2010.
See also: Is Chicxulub a double impact crater? Pres. at 6th EGU A. von Humboldt Interntl. Conf. on Climate Change, Natural Hazards, and Societies, Mérida, México, section: The Cretaceous/Tertiary Boundary

[3] Pešek I., Wagner C.A., Klokočník J., Kostelecký J., Sebera J., EGM 08 searches for hidden impact craters, with support from point mass modelling, Pres. at EGU GA Vienna 2010, Geophys. Res. Abstracts 12, EGU2010-2121, 2010.

[4] Kostelecký J., Klokočník J., Pešek I., Kalvoda J.: Possible applications of detailed Earth´s gravity field model. Presented on the „11th Czech-Polish workshop „On recent geodynamics of the Sudeten and adjacent areas“, Castle Třešť, 4 – 6 November 2010.

[5] Kalvoda J., Klokočník J, Kostelecký J. (in print): Regional correlation of the Earth Gravitational Model 2008 with morphogenetic patterns of the Nepal Himalaya. – Acta Universitatis Carolinae, Geographica, XLV, 2, 53 – 78, Prague. (2010) (SCOPUS)

[6] Kostelecký J., Klokočník J., Pešek I., Kalvoda J.: Některé možné aplikace modelů gravitačního pole Země. Předneseno na semináři s mezinárodní účastí „Družicové technologie a súčasná geodézia“, Stavebná fakulta STU Bratislava, 8.12.2010.

[7] Kalvoda J., Klokočník J., Kostelecký J. (in print): Comparison of morphogenetic features of the Nepal Himalaya with the Earth Gravitational Model 2008. Sborník konferenčních příspěvků XXII. Sjezdu České geografické společnosti, Ostrava 2010, 9 p., 8 figs. (ISI / Proceedings – Conference Proceedings Citation Index, Thomson / Reuthers).

5. Financial plan and its fulfilment

In table 1 there follows the overview of the fulfilment of the Financial Plan for year 2010. The planned amounts come from the PECS Experiment Arrangement No 98056, Appendix 2, p. 5. There were several small changes in the Financial Plan. We would like to comment the total sum paid for services (11.1 k€), which in fact falls under Item Salaries in Table 1, as it corresponds to the salary of Prof. J. Kostelecký formally paid through invoices. The second major difference with respect to the planned costs concerns somewhat higher travel expenses due to a busy year in the GOCE related international meetings. On the whole, the total sum planned to be spent in 2010 and the sum total factually paid are the same.

Table 1. Financial Plan for 2010 and its fulfilment

ITEM		AMOUNT (€)	
		planned	realized
Salaries incl. all insurances		46 400	28 800
Travel (incl. tickets, per diem, accommodation, fees, etc.)		9 000	18 500
Small equipment - smaller then 5000 Euro per piece		2 000	1 200
Large equipment		0	0
Miscellaneous	data GOCE, system eng. consultations	1 000	0
	publications of colour pages	500	0
	consumables	300	300
	services	500	11 100
Overheads		500	300
Total		60 200	60 200