SUMMARY AND RECOMMENDATIONS FROM THE FIFTH INTERNATIONAL USER WORKSHOP

Jérôme Benveniste(1), **Rune Floberghagen**(1), **and Session Co-Chairs**(2)

(1) *ESA, via Galileo Galilei, Frascati, 00044 (RM), Italy, Email: Jerome.Benveniste@esa.int*
(2) *See acknowledgements*

Introduction

This paper summarises the main results, discussions, conclusions and recommendations of the GOCE Fifth International User Workshop. It also provides guidance for future research activities and sustainable gravimetry data exploitation.

Nearly 210 scientists, engineers and managers gathered in Paris in November 2014 from 38 countries worldwide, submitting 114 papers with 285 co-authors: 59 posters, 55 oral presentations and 5 keynotes (Fig. 1). The closing plenary session was the opportunity to have a community discussion focused on the future of gravimetry and the future observational and research requirements. Seed questions were drawn-up prior to the workshop and discussed by the participants.

Figure 1: GOCE Fifth International User Workshop, *held at Unesco Headquarters, Paris 25-28 November 2014.*

Opening Session

The workshop was opened by a welcome address by Ms Watson-Wright, Assistant Director-General and Executive Secretary, Intergovernmental Oceanographic Commission (IOC)/UNESCO. Nicolaus Hanowski, Head of Earth Observation Ground Segment & Mission Operations Department, gave ESA's welcome address on behalf of the Director of Earth Observation Programmes recalling ESA's EO Programmes, in particular the Earth Explorers Programme and the GOCE Mission. Dr. Pascale Ultré-Guérard, Head of Earth Observation at CNES also welcomed the participants to France on behalf of the French delegation to ESA.

After the welcome addresses, the objectives of the workshop were recalled by Jérôme Benveniste and seed questions prepared by the session co-chairs were exposed for thoughts during the many discussion times scheduled throughout the workshop and nourishing the open forum and discussion time scheduled on the last day. These seed questions are reported by topic in the following thematic sections.

Figure 2: The GOCE 2014 Workshop.

Session 1: Mission Accomplished – Exploitation Continues

The session was chaired by R. Floberghagen and J. Benveniste.

GOCE: 1700 days of flight operations - and science for a lifetime

This session focused on the main achievements of the GOCE mission, highlighting the essential feats of the flight operations of this mission at extremely low altitude – made possible only by the excellent functioning of the drag-free control system. Enabled by the extremely good gravimetric data (gradients, field models, gravity anomaly maps and geoid maps), keynote speakers then addressed the fundamental results and improvements that GOCE has brought about in all its application areas, predominantly oceanography, solid earth, geodesy, seismology and aeronomy). These presentations also sketched possible avenues for the 'next phase' in GOCE data-based research and application areas, which are reflected in the recommendations from the various sessions described in the following. The link was also made to the excellent demonstration of instrument and satellite technology that GOCE has provided, in view of future missions targeting gravimetry and mass variations in the Earth system. The opening session was also broadcasted live

Proc. '5th International GOCE User Workshop', Paris, France 25–28 November 2014 (ESA SP-728, March 2015)

on Internet and is available on the ESA website: http://www.esa.int/Our_Activities/Observing_the_Earth/GOCE/Watch_live_Latest_results_from_GOCE.

Session 2: The New GOCE Science Products, Gravity Field Models and Gravity Gradients

The session was chaired by H. Sünkel and P. Visser.

Summary of session highlights

Concerning global models, the mission objectives in terms of geoid/gravity anomaly precision (2 cm/1 mgal@100 km) and gravity anomaly have been achieved. The mission as such can therefore be considered very successfully completed. Further improvements are possible taking into account peculiarities of gravity gradients (e.g. the calibration of the YY component near the geomagnetic poles needs improvement due to the strong influence of common-mode accelerations) and, for GOCE only models, the peculiarities of precise science orbits (e.g., the performance along geomagnetic equator and at magnetic poles).

Concerning gravity gradients, there is a clear interest for Level 2 gravity gradients and derived grids at satellite altitude and near the surface for direct use in geophysical applications. More information is needed about quality of the grids (calibrated variances/co-variances). The gravity gradients contain additional information over spherical harmonic expansions (e.g. time variable gravity) and therefore should be exploited further.

Concerning the precise science orbits, the mission objective of cm-level precision orbits (1D) has been achieved. Some systematic error patterns are visible along the geomagnetic equator at magnetic poles due to L2 losses of GPS receiver, which were due to ionospheric scintillations during periods of strong geomagnetic activity.

Recommendations

Concerning global gravity field models, there is a recommendation to develop and implement methods for improved treatment/weighting of gravity gradient (time and geographically dependent quality).

The GOCE gravity field models and grids are – or can be – associated with quality information such as (calibrated) covariance matrices. It is recommended that the data provider (ESA) conduct a survey to assess the actual usage and needs for this quality information. In addition, it is recommended that this survey include an assessment for the need of providing gravity gradient grids for selected geographical areas at user defined spatial resolution and time periods.

For precise science orbits it is recommended to investigate methods for mitigating systematic error patterns (geomagnetic equator & poles) and their contribution to GOCE-only gravity field models.

Session 3: Oceanography

The session was chaired by M.-H. Rio, P. Knudsen and P. Woodworth.

Summary of session highlights

In the Oceanography session, the strong impact of using the GOCE geoid models for the estimation of the ocean Mean Dynamic Topography (MDT) and the related mean geostrophic currents was demonstrated. Both the enormous breakthrough made – as compared to pre-GOCE geoid models (e.g., GRACE based geoid models) - and the significant continuous improvements allowed throughout the GOCE mission life as more and more GOCE data were included in the geoid models (from release 1, including only 2 months of data, to release 5 including all the mission data), were highlighted. The lowering of the GOCE orbit during the last year of the mission was shown to have brought significant further improvement, mainly for deriving the zonal component of the currents. As revealed by the different studies presented in this session, most work in the past years has focused on the optimal extraction of the oceanographic information (MDT and ocean currents) from the combination of altimeter Mean Sea Surface and GOCE geoid models. This includes the development of sophisticated filtering techniques and the careful analysis of the accuracy of the obtained solutions, through the comparison to oceanographic measurements. This comparison to independent in-situ data also demonstrated clearly the significant amount of physical signal in ocean mean currents at scales shorter than the targeted 100km resolution of the GOCE mission, and the interest of exploiting the synergy of GOCE data with other in-situ measurements to resolve shorter scales of the ocean mean circulation. The difficulty of retrieving accurate currents in the Arctic Ocean and the Mediterranean Sea was also highlighted, due to the seasonal ice coverage, and the limited accuracy of altimeter data in the first case, and due to the short scales of the ocean circulation in semi-enclosed basin in the second case.

Summary of the discussion

During the discussion, the need for additional work to optimize the exploitation of GOCE data in regional Seas (Mediterranean Sea, Arctic Ocean…) and in coastal areas was therefore highly recommended. In particular in coastal areas, accurate MDT information would make possible a worldwide height system unification. The strong added value of using tide gauge data for that purpose was emphasized. Also, in coastal areas, the combination of GOCE data with high-resolution in-situ gravity data (both terrestrial and marine) could be further exploited.

The need for further investigating the Mean Dynamic Topography and errors in the mean currents was also discussed, a requirement valid both for coastal areas and the open ocean. This information is indeed essential for the assimilation of GOCE derived MDT into operational ocean forecasting systems.

Recommendations

The necessity of focusing future research on demonstrating the usefulness of GOCE data for investigating oceanographic science topics was emphasized. It was recommended that a number of priority studies should be short-listed, among the following broad topics: Impact of GOCE-derived ocean currents for the calculation of heat and freshwater transports, eddy/mean flow interactions, assimilation of GOCE data into ocean numerical models (for providing both improved short term forecasts and better boundary conditions for long range climate models), impact of GOCE data for climate change studies (which formed the basis of the Granada report), understanding important signals in MDT near to the coast (for height system unification as well as oceanography). These could be done at a global scale, but the focus on selected test areas was also recommended, where the mean circulation is well known, thanks to good spatial and temporal in-situ data coverage (both oceanographic and geodetic), and high resolution ocean models. The North Atlantic Ocean could be a good candidate (tide gauges, HF-radar, SVP buoys, Argo floats, airborne gravity data, several existing ocean model).

It was recommended that ESA organises a 6th GOCE User workshop in a couple of years in order to discuss and highlight the results of these studies. Finally, an important discussion took place on the need for higher resolution gravity field for oceanographic applications. A key question was raised: what is the required geoid resolution for oceanographic applications? Using the classical approach based on the calculation of intermediate reference surfaces (Mean Sea Surface and Mean Dynamic Topography), the needed resolution is given by the expected resolution of the ocean Mean Dynamic Topography. Although this depends on the averaging time period (dictated by the altimeter observation time period), the response is partly given by the value of the first Baroclinic Rossby Radius of Deformation. This value ranges between 10 km at high latitudes to 200km at the Equator (Chelton et al, 1998) and indicates the scales at which geostrophy is a valid approximation to derive ocean currents from the sea level. This does not however preclude the fact that the Mean Dynamic Topography might still contain shorter spatial scales (that would not result in geostrophic currents). It was therefore concluded that the resolution needed for oceanographic applications is about 10 km. In order to achieve such a resolution, two solutions were discussed (one not excluding the other). Firstly, as synergy with in-situ data has been shown to be highly valuable, it was recommended that in-situ data should be considered not only as validation datasets, but as complementary information that enhances the value of ESA space missions. The sustainability of such datasets shall therefore be ensured, with an adequate, global spatial and temporal coverage. Secondly, a clear recommendation emerged for a new, dedicated space gravity mission. The recommendation for such a mission for ocean Mean Dynamic Topography and ocean currents retrieval is 10 km (if feasible) to a maximum of a few tens of kilometres globally. As discussed in a parallel session on science requirements for a future satellite gravity constellation, such a mission should also allow for the retrieval of the temporal variations of the Earth's Gravity Field, as this information is essential for monitoring the ocean mass changes, and to better understand the Earth's climate system.

Session 4: Solid Earth

The session was chaired by M. van der Meijde and J. Ebbing.

Summary of session highlights

The session showed that some of the key questions from the 2012 GOCE Solid Earth workshop have been addressed in the meantime, and that there is a vast range of possible studies that can be carried out based on the GOCE data set to study both the static and dynamic behaviour of the Solid Earth.

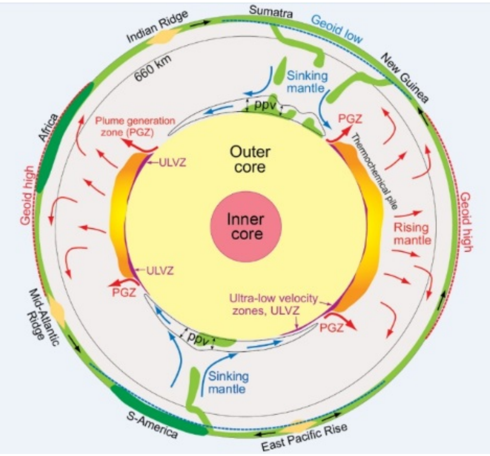


Figure 4: Deep Earth (Centre for Earth Evolution and Dynamics, Oslo).

There is added benefit in using gravity and gradient data from the GOCE satellite mission as it fills an important link between terrestrial data and satellite mission like GRACE.

The use of gradients at satellite altitude has advantages as one can exploit the sensitivity of the tensor components without the need of additional filtering, but this depends very much of the target of interest, e.g. crustal thickness, upper mantle or mineral resources.

Clearly, the contributions showed that GOCE data are useful to link to seismic or seismological derived models, which provides a mean to assess the contribution of mantle dynamics to surface topography. However, the uncertainties in the crustal models are often not given or defined and residuals interpreted as upper mantle signal may be biased by incorrect estimates of crustal sources.

Recommendations

GOCE data and the techniques that have been developed to process and interpret the gradients from the GOCE mission open a series of new applications, e.g. integration with airborne gravity surveys, as background models for geological exploration.

Most important will be the validation of regional models that are based on the integration of seismological, petrological and satellite data. Here, integration of data from the Swarm magnetic satellite mission opens the possibility to study the Earth from surface to the core (Figure 4).

The parameters of the magnetic or electric Earth have, however, no direct physical relation to velocity and density and require therefore definitions of the thermal state and composition.

This clearly requires an integrated modelling approach and both forward and inverse set-ups, should be explored and exploited in the coming years.

Another key aspect will be to continue the efforts to outreach to the Solid Earth science community, e.g. seismologist, geologist and dynamic modellers. One possibility is through the TopoEurope workshop to be held in Antibes, France in October 4-7, 2015, where “Earth and Space” will be a key theme of the workshop.

Session 5: Geodesy

The session was chaired by G. Balmino, T. Gruber and F. Sansò.

Seed Questions

1. What have we learnt on the gradiometer/accelerometers from the low orbit phase?
2. Can we quantify the advantage of directly using the measured gravity gradients?
3. Where in the world GOCE models have already been used to evaluate/unify height systems?
4. In view of GOCE results and considering actual needs, where are the priorities for future airborne gravity campaigns?

Summary of session highlights

The session addressed various aspects of making use of GOCE data and gravity field models for geodetic applications. This included in particular the processing and direct application of GOCE gravity gradients, the validation and combination with airborne and terrestrial gravity data and the application of GOCE models for the analysis of height systems.

The presentations clearly have shown that the excellent quality of the GOCE gravity gradients and models offer completely new possibilities for geodetic applications. In particular with GOCE it became possible to check at large scales the consistency and homogeneity of surface and airborne data sets like gravity observations and physical heights. Vice versa high quality terrestrial data sets were used in order to validate the GOCE models and to quantify their performance. The knowledge about spectral performances of GOCE gradients and models and terrestrial/airborne data enables new approaches for optimal combination of both data sources in order to determine high-resolution regional geoid solutions.

Recommendations

New adaptive filters developed to extract the gravity signal within the measurement bandwidth of the gradiometer seem to be very promising. Applying this filter in level 2 gravity field processing of the low orbit phase data exhibits a 10% gain in accuracy. It should be further investigated what is the impact of such an improved filter on GOCE gravity field models specifically applying data from this phase and ESA is encouraged to support such activities. Further room of improvement at gravity gradient level might be possible in the gradiometer calibration approach. Therefore, ESA and science community is encouraged to continue studies on the gradiometer calibration and to investigate possibilities to calibrate individual accelerometers.

The direct use of measured gravity gradients is encouraged for local to regional studies in geodesy, geophysics and oceanography because they contain more information than what is represented by global spherical harmonic models. It may also be possible to enhance the determination of the time variable gravity field over some areas by combining them with GRACE data over the lifetime of GOCE.

GOCE models and data should be systematically used for evaluating and unifying height systems. In the same way GOCE results should be used to diagnose large errors in gravity surveys and calibrate them for the benefit of all users.

Airborne gravity data collection is expanding at an amazing pace. National agencies are encouraged to provide support to organise aerogravity campaigns over areas in need, and it is recommended that such data sets be made widely available to all users within a short time.

Session 6: Aeronomy and Novel Applications

The session was chaired by S. Bruinsma and M. Kern.

Seed Questions

- What can GOCE contribute to (semi-) empirical thermospheric density and wind models, and what are the limitations?
- What can GOCE contribute to space weather investigations?
- What is the added value of GOCE to ionospheric modelling due to its low altitude?
- What additional GOCE information/products are needed by the scientific community (vertical winds, thruster data, detailed satellite model, etc)?

Summary of session highlights

The main theme of this session was aeronomy, though there were also presentations on GOCE EGG data for spacecraft positioning, a presentation on GOCE and GRACE data combination towards improved temporal gravity solutions and a presentation of thermospheric density variations due to space weather.

The GOCE density and cross-track wind data including their error estimates, which are the results of an ESA Support To Science Element study, are publicly available on ESA's Earth Online web portal. The value of the dataset was demonstrated in several presentations. For modeling purposes, thus far with the semi-empirical model DTM2013 and the NCAR first principles model TIEGCM, it constitutes the only highly accurate low altitude dataset with a good data distribution. The dataset allowed also evaluating model accuracy at low altitude, and a surprising finding was the bias as a function of solar activity for the COSPAR reference model for drag JB2008. Assimilation of the density data leads to a model with a 1-σ error of 10% when compared with the observations that are given about every 80 km along the orbit. Wave coupling, or tidal studies in general, require a minimum precision at the 1-2% level because of the small amplitudes in question. GOCE data qualify for these kind of studies, as was shown by a wave coupling study relating tide constituents inferred from TIMED data at about 100 km with GOCE. Joule heating estimations of the GUMICS-4 model were used in a computation of the GOCE orbit decay, and significantly better results were obtained than when the ap index was used. The altitude of GOCE was in the F layer of the ionosphere but well below F2. That makes GOCE interesting to use in combination with higher-orbiting satellites in order to deduce vertical profiles. Gravity field solutions from GOCE GPS kinematic orbits were tested in combination with GRACE monthly models, but the resulting solutions were only marginally different.

Summary of the discussion

The density and wind datasets are unique mainly because of their accuracy, 10-second cadence along the orbit, and low altitude, but also because the error information is given. The datasets are still relatively new and their scientific exploitation has only just begun. The semi-empirical thermosphere model DTM2013 was developed in the framework of an FP7 project. Presently, it is the only model that used high-resolution CHAMP, GRACE, and GOCE accelerometer-inferred densities. Thanks to the assimilation of those datasets, and the use of a new solar proxy, it is a significant improvement over the CIRA models JB2008 and NRLMSISE-00. The GUMICS-4 model, through assimilation of solar wind data essentially, is capable of modeling and nowcasting the Joule heating, for which the geomagnetic index ap is a proxy. GOCE orbit decay computations were more accurate with the Joule heating than with ap, which is promising for future thermosphere density nowcast and forecast models. The vertical coupling between the lower and upper thermosphere has been studied already using CHAMP and GRACE densities. GOCE, however, is at a lower altitude, for which the model top of the first principle models has not been reached under low solar activity. Secondly, the data is more precise than the CHAMP and GRACE densities (and winds). First results were presented, but the entire dataset has not been processed yet. The contribution of GOCE to GRACE temporal gravity field products is negligible.

Recommendations

Several recommendations were made during the session and in the general discussion. The GOCE data have been computed in the most accurate way possible (i.e. with the most accurate satellite surface model, the most realistic model for aerodynamic interactions). This led to a large scale offset with existing datasets because they are computed in a less rigorous way. Thermosphere models attempt to correct for data bias by estimating scale factors, but there is of course a limit to its success. The only way forward is to reprocess as a minimum the accelerometer-inferred density datasets (CHAMP and GRACE) in a similarly rigorous fashion; then, thermosphere models can be updated using these unbiased density datasets.

The vertical winds have not been produced, but in principle the precision of the accelerometers makes it possible. This type of measurement is at present inexistent globally, and only GOCE can provide it. It would be very valuable for gravity wave studies in particular.

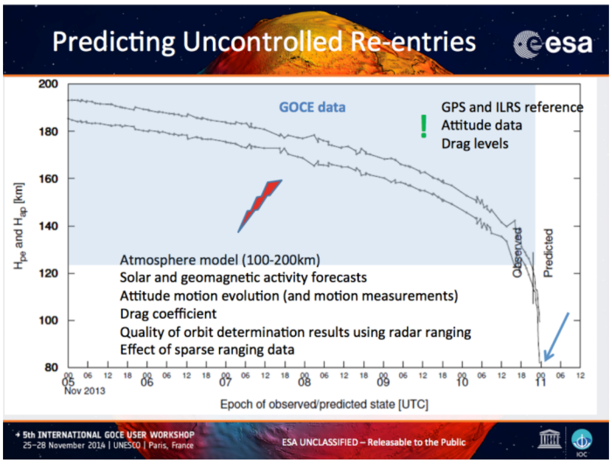
Finally, it was recommended to study the use of rotational dynamics data to analyse potential improvements for satellite aerodynamic modelling.

Session 7: Science and Engineering Lessons from the De-orbiting and Re-entry Phase

The session was chaired by C. Pardini and H. Krag.

Background and session highlights

Currently, approximately 70% of the re-entries of intact orbital objects are uncontrolled, corresponding to about 50% of the returning mass, i.e. ~100 metric tons per year. On average, there is one spacecraft or rocket body uncontrolled re-entry every week, with an average mass around 2000 kg. Also in the case of objects not specifically designed to survive the re-entry mechanical and thermal loads, a mass fraction between 20% and 40% of sufficiently massive structures is typically able to reach the Earth surface. Re-entry predictions are affected by various sources of inevitable uncertainty (as listed in Fig. 5) and, in spite of decades of efforts, mean relative errors of 20% often occur. This means that even predictions issued 3 hours before re-entry may be affected by an along-track uncertainty of 40,000 km, corresponding to one orbital path. In consequence of the expanding use of space, concurrently with the increase of the world population, the ground casualty risk due to uncontrolled reentries, even if still small compared to other commonly accepted risks linked to the lifestyle or the workplace and household safety, will presumably show a tendency to grow in the coming years. For this reason, specific guidelines to minimize the risk to human life and property on the ground have been defined and are continually revised and upgraded, and future missions will have to comply with such regulations.


Predicting Uncontrolled Re-entries

GOCE data

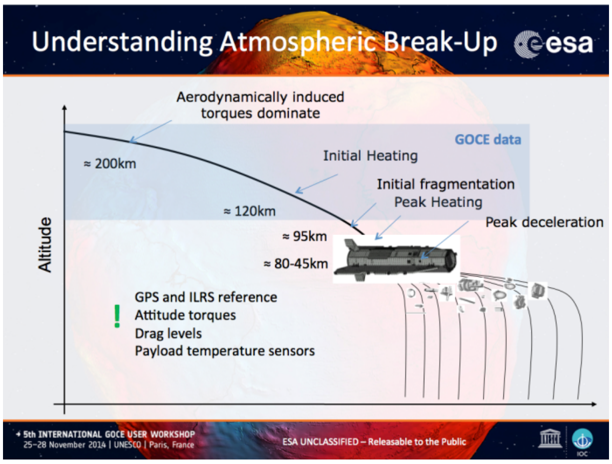
GPS and ILRS reference
Attitude data
Drag levels

Atmosphere model (100-200km)
Solar and geomagnetic activity forecasts
Attitude motion evolution (and motion measurements)
Drag coefficient
Quality of orbit determination results using radar ranging
Effect of sparse ranging data

Figure 5: Predicting uncontrolled re-entries.

After depletion of the xenon fuel for the drag compensating ion propulsion system, on 21 October 2013 GOCE began its orbital decay phase from a height just above 220 km. It was the first uncontrolled reentry of an ESA satellite in more than 25 years, and its orbital evolution, up to the final decay phase, was monitored in the framework of the GOCE international campaign promoted by the Inter-Agency Space Debris Coordination Committee (IADC). Thanks to an ESA pre-launch destructive analysis using the SCARAB software tool, the beginning of the satellite fragmentation was predicted around an altitude of 95 km and the end around 35 km, even if most of the debris generation was expected in between 80 and 45 km (see Fig. 6). Overall, 43 macroscopic pieces, totaling approximately 270 kg (i.e. nearly 27% of the satellite dry mass), should have survived reentry, hitting the ground along a 900 km footprint during a 17 minutes time interval. The most massive fragment would have had a mass just below 95 kg.

Once the fuel ran out, GOCE entered in fine-pointing mode (FPM), a phase of the orbital decay during which the satellite maintained a stable attitude minimizing the drag force. The on-board attitude control system was expected to compensate the gravity gradient and the aerodynamic torques until an average drag force along the orbit of 20 mN was reached. But exceeding all expectations, the attitude control system kept working until reentry, even when the drag levels encountered exceeded 2000 mN, i.e. far beyond (more than 100 times) the project specifications.


Understanding Atmospheric Break-Up

GPS and ILRS reference
Attitude torques
Drag levels
Payload temperature sensors

Figure 6: Understanding atmospheric break-up.

In session 7, the uncommon nature of the GOCE reentry campaign, sharing an uncontrolled orbital decay with a finely controlled attitude along the atmospheric drag, was highlighted. In particular, the impact on reentry predictions of different assumptions on the satellite performances, in terms of attitude modes, was investigated. Additionally, considering that GOCE remained functional and the contact was maintained down to extreme altitudes of little over 100 km, dedicated observations and measurements were possible up to the very end. These were also presented and discussed in Session 7, with special attention to the following outcomes:

- The calibration of the re-entry predictions and the exploitation of the GOCE telemetry data had just been initialised. The bulk of the results was still to come.

- Orbit measurements using radar facilities had been characterised with the use of the precise GOCE reference orbit.
- The governing environmentally induced torques on GOCE, as a function of the altitude regime, had been identified.
- A characterisation of the prediction accuracy had been achieved.
- Attempts to independently determine the satellite attitude using ground-based radars had been performed.

Seed questions and discussion

The discussion mainly focused on topics related to the re-entry prediction process, both in the IADC frame or for civil protection applications. It was intended to explore the accuracy and reliability of the methods and tools used to carry out re-entry predictions, with specific attention to models adopted to compute the atmospheric density. That was to reply to one of the formulated seed questions, i.e.: *To which degree will an upgraded atmospheric density model between 100 km and 200 km improve the prediction results*? This was in fact the range of altitudes crossed during the GOCE uncontrolled re-entry. It was pointed out that only a very limited subset of the most widely used atmospheric density models could be used to calculate the air density during the GOCE re-entry. For instance, among the CIRA 2012 standard reference models, only NRLMSISE-00 is defined up to the ground, while JB2008 is able to compute the air density above an altitude of 120 km.

Another critical point concerned the accuracy of the prediction results, i.e.: *What can we learn in terms of understanding how accurate our predictions are?* Also in the case of GOCE, typical unavoidable uncertainties were expected to affect the estimation of the re-entry time. However, due to the GOCE active control system and to the unpredictability of the instant and altitude at which the system would have failed, it was not possible to adopt standard criteria, i.e. for instance ±20% of the residual lifetime, to define the uncertainty reentry windows. Instead, reasonable conservative criteria, mainly based on the uncertainty affecting the duration of the FPM phase, were elaborated and applied.

As a consequence, the seed questions: *To which degree are the results obtained with GOCE transferable to other uncontrolled re-entries*? or: *There is a similarity to re-entering upper stages*? have negative answers if simply applied to the re-entry prediction process. On the other hand, the experience acquired during the GOCE re-entry phase, thanks to the monitoring of the drag levels, satellite orbital decay and payload properties, might be of interest for future uncontrolled re-entries. Therefore, the processing of the measurements and observations collected during the campaign could help to: *Get knowledge in the area of ground-based measurements of uncooperative low altitude targets*, as well as: *To learn what could be expected from recorded component temperatures*.

Eventually: *Which kind of future data might be of interest for a further refinement of re-entry predictions*? Further to improve atmospheric density models, the discussion converged on the need to have more accurate tracking data as well as more precise forecasts for the solar and geomagnetic indices. However, events like sudden geomagnetic storms in the last days preceding the re-entry might change significantly the estimation of the re-entry time and remain unpredictable up to their occurrence.

Recommendations

Although the last orbital elements were issued by ESA at just one hour before the actual re-entry, when the satellite was at an average altitude around 115 km and its attitude was still stable despite the extremely high drag force encountered, the last re-entry prediction was – according to all participating experts – affected by an obvious bias of roughly 20 min (in advance with respect to the actual re-entry time) which was not understood.

Therefore, the following actions were agreed:

- The attitude information from telemetry should be evaluated to investigate whether lift effects dominated during the last orbit.
- Improved atmosphere models should be tested to verify to which degree they improve the results.
- A full 6 degree-of-freedom simulation based on the last orbit/attitude state needs to be completed.
- Payload temperature readings need to be exploited and compared to the modelling of the initial heating above 115 km altitude.

It was eventually recommended to organize a future workshop to have a recap of the results in light of the observations and measurements collected during the GOCE re-entry campaign. It could be a dedicated GOCE workshop or/and a Session of the 7th European Space Debris Conference.

Session 8: Future Gravity Field Missions

The session was chaired by N. Sneeuw and R. Haagmans.

Seed Questions

- What do users want?
  - Which users?
  - Consolidated requirements: space/time resolution, accuracy, …
  - What are limitations of recent missions?
  - keywords: aliasing, sensitivity, …
  - How to deal with them?
  - keywords: orbit design, constellation, sensor

technology, …

- Which technology in 10/20/30 years from now?
  - keywords: gradiometry vs. lo-lo SST, laser metrology, atom interferometry, …
  - Do we need to change our processing strategies?
  - keywords: multi-scale parametrization, post-processing, …
  - How to obtain the next mission, post GRACE-FO?

From GOCE to the Next Generation Gravity Mission

The global user community prepares a document for the IUGG with science and user needs for a future sustained satellite infrastructure to observe mass variations in the Earth system focusing on the following scientific aspects: the global water cycle and the closure of the global water balance, sea level rise, global ocean circulation; mass and heat transport in the oceans, melting of ice sheets, e.g., Greenland, Antarctica, inland glaciers, dynamical processes of solid Earth, interaction between land and atmosphere and separation of natural and human-made effects on global change. Furthermore, it aims to support several practical applications and services applications with societal benefit such as water management, forecasting of floods and droughts, climate impacts on water cycle and ice sheets, regional sea level changes and coastal vulnerability, risk assessment of natural hazards, globally unique definition of heights with impact on land management issues.

As a consequence of the developments over the past years in deriving thermospheric density and winds from all gravity missions, any future concept with measurements of non-gravitational forces will also allow the continuation of these products from low-Earth orbit for e.g. improving density and wind models, space debris, mission analysis.

Various studies have shown the benefit of a double pair in-line constellation over a single pair, as it allows better treatment and thus less disturbance of short term small scale variations whilst offering a finer spatial resolution at shorter time intervals which wideness clearly the application potential. Fine-tuning of the multiple pair constellation parameters is ongoing.

Besides direct heritage from GOCE, GRACE and GRACE follow-on, there are technology developments that can be used for the next generation gravity mission based upon laser ranging between two satellites:

- Laser ranging system
- Optical link acquisition devices and techniques
- Multi-function spacecraft control techniques
- Long-lifetime electric propulsion supporting all control functions
- Satellite COM position fine determination and adjustment techniques and devices

Alternative concepts using atom interferometric techniques for gradiometers are also under study and development as a potential measurement technique on medium term.

A joint gravity science working group is established for ESA and NASA consisting of community representatives, who are tasked to provide their opinion how to convert the ideas brought forward by the user community and keeping in mind the state of technology to arrive at a future sustained satellite observing system.

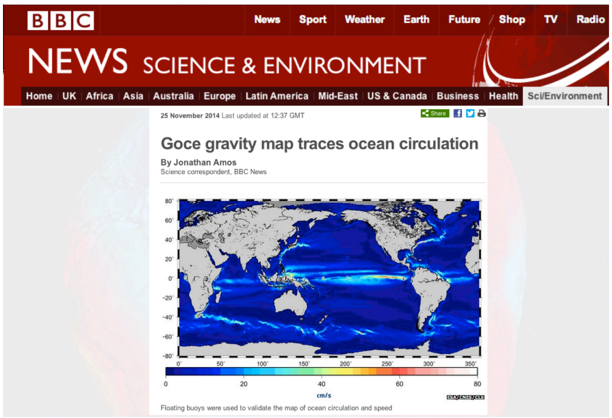
Summary

- Enormous potential for studying Earth with on-going gravity missions (and soon GRACE-FO)
- Past and current missions demonstrate on one hand technology concepts and on the other potential for science and applications.
- Current science and technology activities are a consequence, e.g., of laser demonstrator developments for GRACE-FO and past high quality proposals to ESA (Licody, e-motion).
- Lot of potential for future concepts that provide essential, sustained and unique high-resolution information on system Earth and for applications requested by the user communities.
- User community is in the driver seat: provide a convincing user case, convince politicians who decide on space agencies programmes and their funding.

Outreach

An article was published on BBC News on-line during the workshop (Fig. 7). It can be found at:

http://www.bbc.com/news/science-environment-30191584



25 November 2014 Last updated at 12:37 GMT

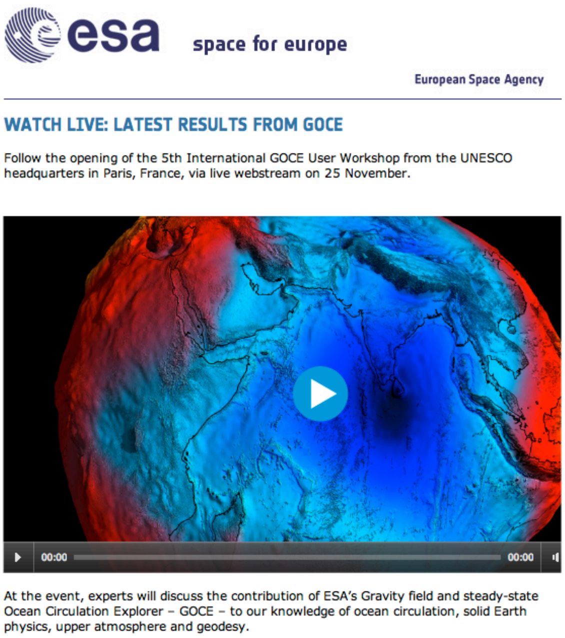
Goce gravity map traces ocean circulation

By Jonathan Amos
Science correspondent, BBC News

Floating buoys were used to validate the map of ocean circulation and speed

Figure 7: BBC News article on GOCE Gravity and Ocean Circulation

The opening session was broadcast live on Internet and is available on the ESA website (Fig. 8): http://www.esa.int/Our_Activities/Observing_the_Earth/GOCE/Watch_live_Latest_results_from_GOCE.



WATCH LIVE: LATEST RESULTS FROM GOCE

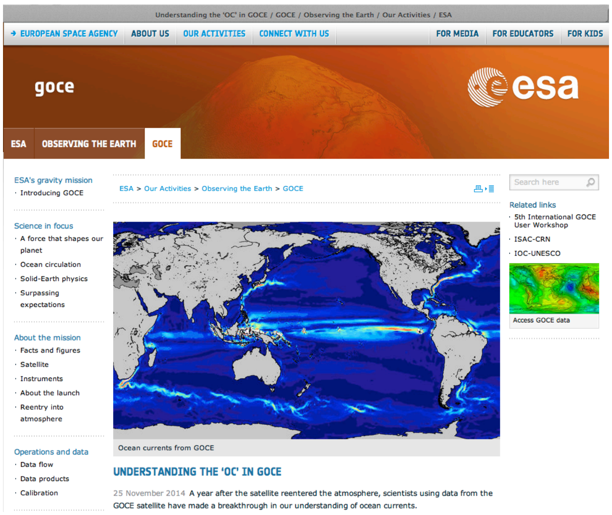
Follow the opening of the 5th International GOCE User Workshop from the UNESCO headquarters in Paris, France, via live webstream on 25 November.

At the event, experts will discuss the contribution of ESA's Gravity field and steady-state Ocean Circulation Explorer – GOCE – to our knowledge of ocean circulation, solid Earth physics, upper atmosphere and geodesy.

Figure 8: The opening session was broadcasted live on the web…

A Web story was published on the ESA web site during the Workshop entitled: Understanding the "OC" in GOCE (Fig 9). It reported the results presented during the keynote of the opening session. It can be reached at:

http://www.esa.int/Our_Activities/Observing_the_Earth/GOCE/Understanding_the_OC_in_GOCE



Ocean currents from GOCE

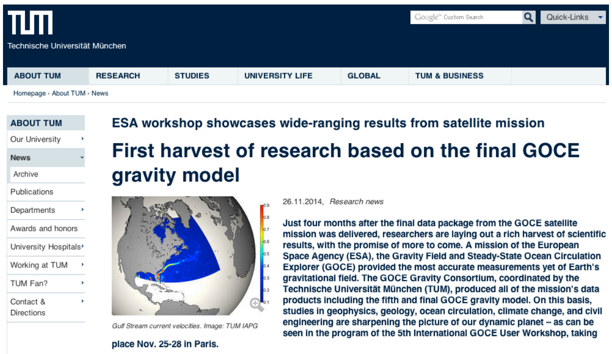
UNDERSTANDING THE 'OC' IN GOCE

25 November 2014 A year after the satellite reentered the atmosphere, scientists using data from the GOCE satellite have made a breakthrough in our understanding of ocean currents.

Figure 9: Understanding the "OC" in GOCE

The harvest of the results of the GOCE mission was announced on the website of the Technical University Munich (Fig. 10):

https://www.tum.de/en/about-tum/news/press-releases/short/article/31922/



ESA workshop showcases wide-ranging results from satellite mission

First harvest of research based on the final GOCE gravity model

26.11.2014, *Research news*

Gulf Stream current velocities. Image: TUM IAPG

Just four months after the final data package from the GOCE satellite mission was delivered, researchers are laying out a rich harvest of scientific results, with the promise of more to come. A mission of the European Space Agency (ESA), the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) provided the most accurate measurements yet of Earth's gravitational field. The GOCE Gravity Consortium, coordinated by the Technische Universität München (TUM), produced all of the mission's data products including the fifth and final GOCE gravity model. On this basis, studies in geophysics, geology, ocean circulation, climate change, and civil engineering are sharpening the picture of our dynamic planet – as can be seen in the program of the 5th International GOCE User Workshop, taking place Nov. 25-28 in Paris.

Figure 10: The Technical University Munich web report.

General Recommendations

Among all he recommendations expressed in each session discussion periods, one was recurrently formulated. It was highly recommended by the attendees that ESA organises a 6th GOCE International User Workshop in a couple of years in order to discuss and highlight the results of on-going studies exploiting the latest release of the GOCE products and the overall legacy of the GOCE Mission.

Closing Session

The session was chaired by R. Floberghagen and J. Benveniste.

The Fifth International GOCE User Workshop closed with a recall of the tribute by Fernando Sansò to Carl Christian Tscherning (Fig. 8), who's passing a month before left us all in shock. Carl Christian Tscherning's pioneering work, personal achievements and involvement in Geodesy were appraised.

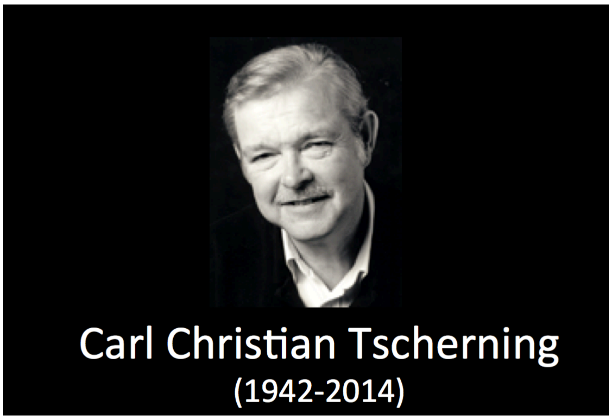


Figure 8: A tribute to Carl Christian Tscherning.

Acknowledgements

The scientific committee and co-chairs of the sessions are thoroughly thanked for their effort in reviewing the submitted abstracts, contributing to shape the programme and animating the GOCE Fifth International User Workshop. Co-chairs were asked to draft seed questions to be discussed by the community and to animate the discussion periods. Thereafter, their duty was to prepare a summary with the highlights, recommendations and conclusions of their session, which are the input to this paper. May they be thoroughly thanked again here for their valuable contribution.

15. Scientific Committee and Co-Chairs

B. Ailor
O. Andersen
G. Balmino
J. Benveniste
S. Bettadpur
R. Bingham
J. Bouman
C. Braitenberg
S. Bruinsma
M. Diament
E. Doornbos
J. Ebbing
R. Floberghagen
T. Flohrer
J. Forbes
T. Gruber
R. Haagmans
K. Haines
C. Hughes
M. Kern
H. Klinkrad
P. Knudsen
H. Krag
T. Lips
M. Mandea
J. Müller
R. Nasca
R. Pail
I. Panet
C. Pardini
M-H. Rio
R. Rummel
F. Sansò
H. Snaith
N. Sneeuw
H. Sünkel
C. C. Tscherning
M. van der Meijde
P. Visser
P. Woodworth
V. Zlotnicki