SPACE-BORNE GRAVIMETRY: PROGRESS, PREDICTIONS AND RELEVANCE FOR SWARM

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ABSTRACT

In the beginning of the new millennium, a unique series of space-borne geo-potential missions is being realized, including the currently flying CHAMP and GRACE satellites (launched in respectively 2000 and 2002), and the future GOCE gravity field and Swarm magnetic field satellites (foreseen launches in 2007 and 2010, status April 2006).

The progress in global gravity field modeling achieved already by CHAMP and GRACE will be highlighted together with an outlook to the GOCE mission. In addition, the relevance of gravity field modeling for Swarm, or the role that Swarm can play itself in gravity field modeling, will be discussed.

1. INTRODUCTION

Global Earth gravity field modeling has seen considerable progress since the launches of respectively CHAMP in July 2000 [1] and GRACE in March 2002 [2]. Further enhancements are expected after the launch of the European Space Agency (ESA) Core Explorer GOCE [3], which is currently (May 2006) foreseen to be launched in 2007. All these missions rely on (enhanced) existing and new technologies including GPS receivers, high-precision accelerometers, very precise low-low satellite-to-satellite microwave tracking, gradiometry (triad of three orthogonal pairs of ultra-sensitive accelerometers) and micro-propulsion systems (Figure 1).

The CHAMP mission has proved for the first time the concept of separating gravitational from non-gravitational forces by combining continuous three-dimensional tracking (by GPS) with space-borne accelerometry. The GRACE mission has added the concept of very precise low-low satellite-to-satellite tracking, enhancing not only the achievable resolution of global gravity field models, but also opening the possibility to observe long-wavelength gravity field changes. GOCE will combine continuous three-dimensional tracking with space-borne accelerometry ("common-mode") and gradiometry ("differential mode"), further enhancing the achievable gravity field model resolution and accuracy.

2. RECENT EARTH GRAVITY FIELD MODELS

The CHAMP and GRACE missions have resulted already in a series of improved global gravity field models, including the EIGEN series from the GeoForschungsZentrum (GFZ) in Potsdam, Germany, and the GGM series from the Center for Space Research (CSR) in Austin, Texas. These models are typically provided as spherical harmonic expansions, truncated at a maximum degree of typically between 100 and 200 (spatial resolution of 200-100 km, where for the higher degrees the satellite observations need to be combined with for example ground based gravimetry and altimetry). In addition, the GRACE observations allowed the generation of time series of long-wavelength temporal gravity field variations that are typically significant to degree and order 15-20 (>1000 km resolution). A fascinating result is, amongst others, the observation of gravity field changes induced by continental hydrology [4].

The improvement of global gravity field models that became possible after the launches of CHAMP and GRACE is shown in Figure 3, where EGM96 [5] represents a state-of-the-art pre-launch model. It is clear that a significant improvement has been obtained in both accuracy and resolution. Also indicated is a predicted performance for GOCE from 2002 [6]. Since 2002, design changes have caused this GOCE curve to intersect the signal magnitude (black) at degree 200 leading to a cumulative geoid error of 1-2 cm at a resolution of about 100 km, still within the original objectives [3].

3. MODELING THE EARTH'S GRAVITY FIELD: FUTURE CHALLENGES

Even though significant progress has been made by the CHAMP and GRACE missions, and more progress is anticipated after completion of the GOCE mission, many more challenges lie ahead to fully comprehend all spatial and temporal scales of the Earth's gravity field and its impact in many application areas. Requirements have already been defined that have to be met by future GRACE and GOCE follow-on missions [7]. These requirements are presented in Figure 2. This figure includes the (predicted) performance of GRACE and GOCE and clearly shows that certain areas in the gravity field domain, spatially and temporally, are not covered by existing and currently planned missions.

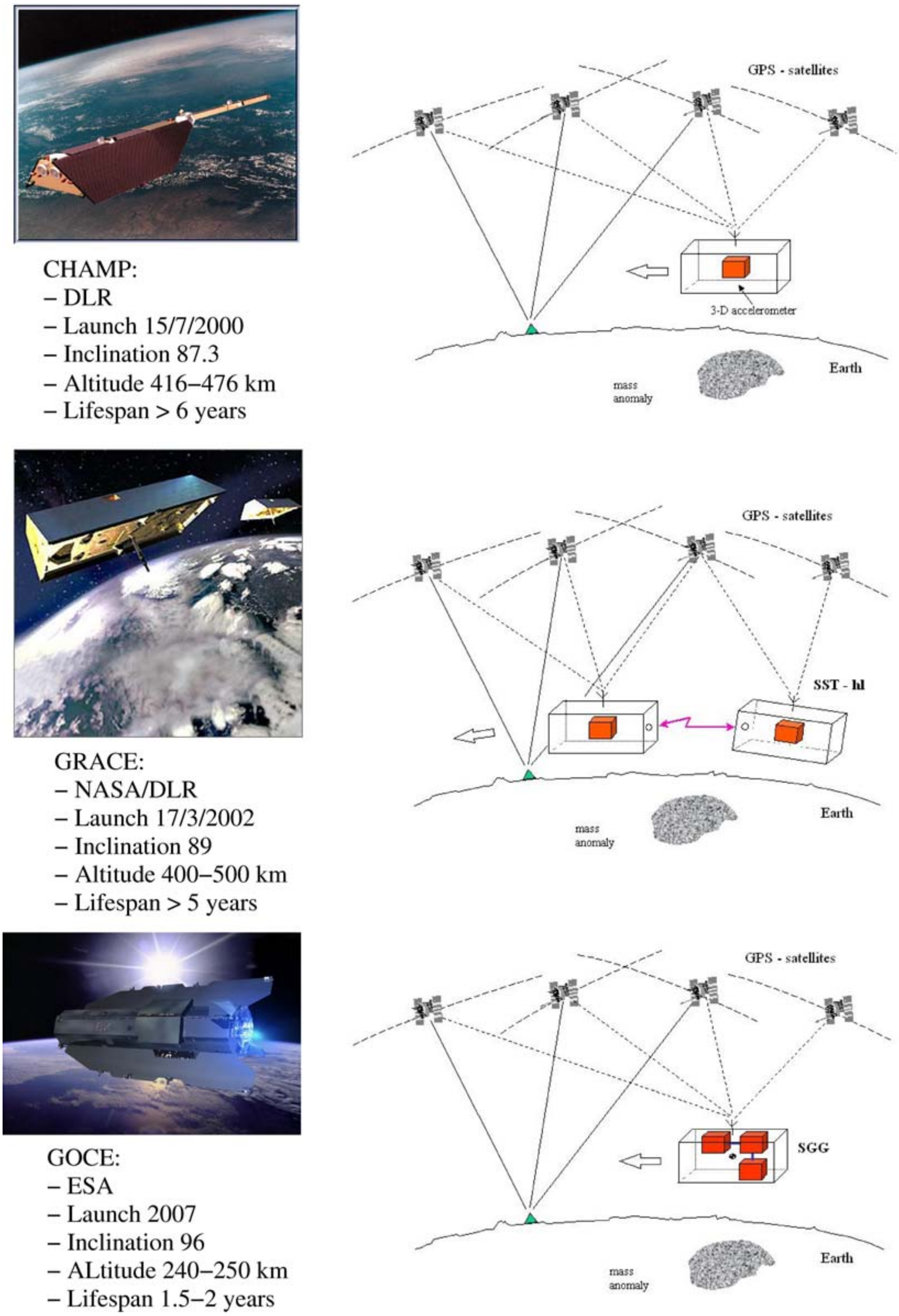

Figure 1. Satellites observing the Earth's gravity field and their respective observation technique

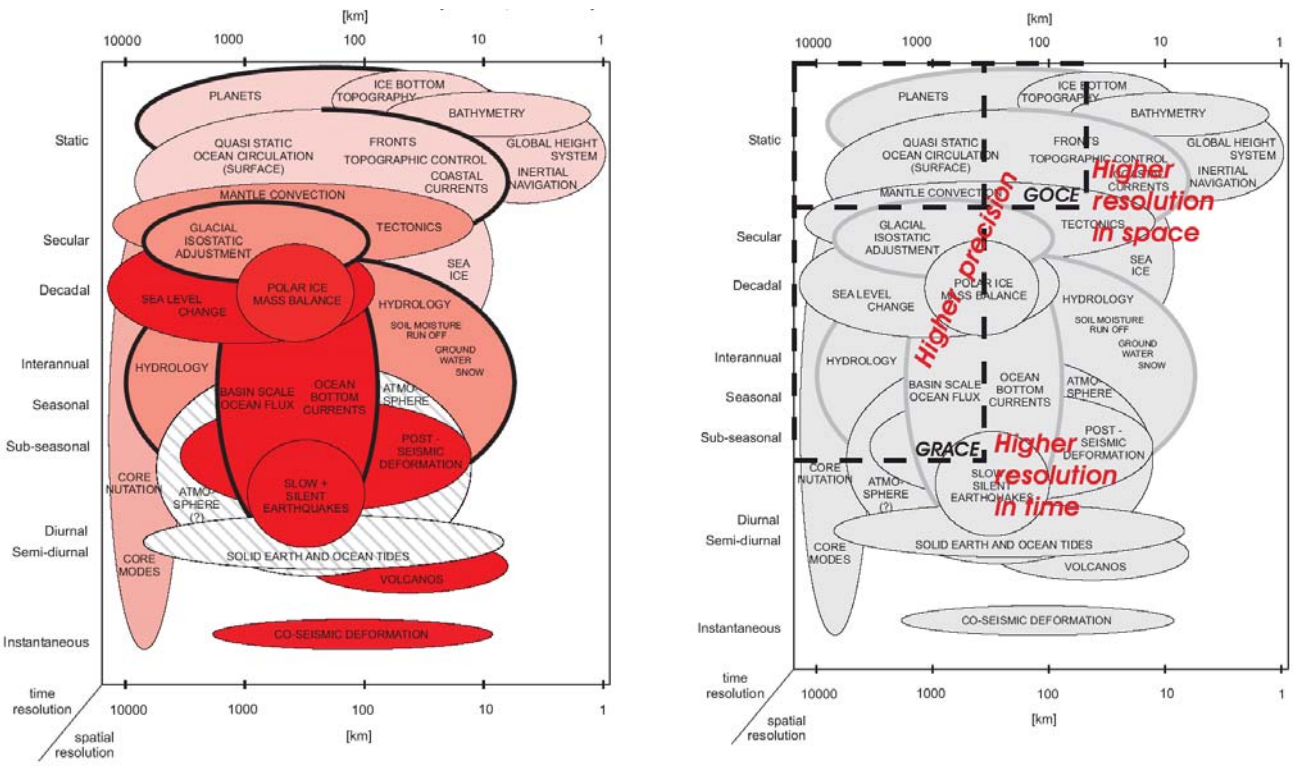

Figure 2. Required mission duration (left) and spatial/temporal resolution after GRACE and GOCE [7]

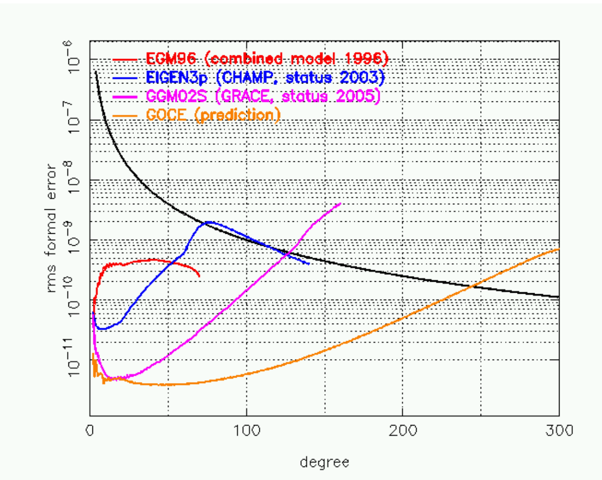

Figure 3. Accuracy assessment of past, recent and future gravity field models. The decreasing (black) line represents an estimate of the signal magnitude

4. POSSIBLE ROLE OF SWARM IN EARTH GRAVITY FIELD MODELING

Swarm will consist of two satellites flying "en echelon" at 450 km altitude and a third one at 530 km altitude [8]. It is currently foreseen that all the Swarm satellites will be equipped with high-precision, dual-frequency GPS receivers and accelerometers for atmospheric density retrieval. The CHAMP mission has proved that this combination allows the observation of long to medium wavelength gravity field phenomena. The altitude range for Swarm is comparable to what is flown during the first years of the CHAMP and GRACE missions.

4.1. GRACE heritage

Although the primary instrument on board of GRACE is the low-low satellite-to-satellite tracking device, referred to as KBR, this mission could serve as a test bed for high-precision relative positioning by GPS ("space-borne differential GPS") as well. The KBR offered the possibility to validate the ranges that are obtained from the GPS observations. It was found that a consistency between GPS-derived ranges ("baselines") and the KBR observations (claimed precision of a few µm at 1 Hz) could be obtained better than 1 mm [9]. Although the KBR observations are a few orders of magnitude more precise, a 1-mm precision level for inter-satellite ranges allows to recover/monitor at least the long wavelength part of the gravity field as well. As an example, a 100-day time series of GRACE baseline solutions by space-borne differential GPS was analyzed.

First, the relative velocity was derived from this time series to enhance the high-frequency content and second, a high-pass filter was applied to eliminate the dominant low frequency orbit perturbations. Finally, the resulting time series was geographically averaged. The resulting geographical signature (Figure 4, bottom) strongly resembles the geographically averaged and high-pass filtered KBR observations (Figure 4, top). Clearly visible are for example gravity field structures above the Himalayan region and the Indonesian archipelago. This result clearly demonstrates the potential of space-borne differential GPS of formations of low-flying Earth orbiters for gravity field recovery.

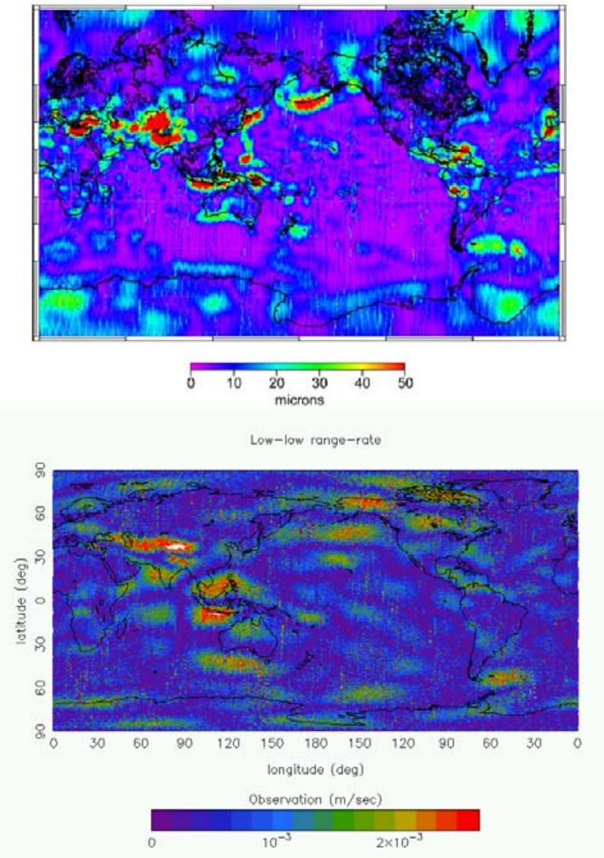

Figure 4. High-pass filtered KBR observations (top, courtesy Jet Propulsion Laboratory, Pasadena, California) and high-pass filtered inter-satellite velocities derived from GPS (bottom)

Although the GPS-based GRACE baseline solutions have a precision which is a few orders of magnitude less than the KBR observations, it has to be mentioned that GPS provides a 3-dimensional solution, i.e. not only the relative position along the line of sight of the GRACE satellites could be obtained, but also in perpendicular directions (predominantly radial and cross-track). Such a 3-dimensional solution will enhance the possibilities for gravity field recovery (in a way similar as claimed for the 3-axes GOCE gradiometer [3]).

4.2. Role of SWARM

The Swarm mission will provide a unique constellation for observing the Earth's magnetic field and its changes, allowing to separate the different sources that contribute to this field [8]. Likewise, Swarm offers a unique constellation for deriving gravity field models by space-borne differential GPS. The orbital geometry of the low-flying pair of satellites, including both a separation in the argument of latitude and the right ascension of ascending node, provides an enhanced sensitivity to cross-track gravity field induced orbit perturbations compared to GRACE. In addition, the higher flying third Swarm satellite provides the opportunity to also explore the possible value of inter-satellite baseline solutions when this satellite is in view of the lower pair. Finally, it is interesting to investigate the spatial and temporal sampling of the gravity field by the three Swarm satellites.

It is well known from orbit perturbation theory that every low Earth orbit has its own unique sensitivities ("resonances") to certain parts of the gravity field spectrum ("lumped coefficients") [10]. In general, for each new satellite or formation of satellites, precise orbit determination can be improved by adjusting the gravity field model. Tracking observations to these satellites (such as provided by GPS) are then used to update/improve existing gravity field models, possibly using accelerometer observations as well (provided the satellites carry such an instrument). Especially for Swarm, a combined analysis of GPS tracking and accelerometer observations will not lead only to valuable gravity field models, but also enhance the interpretation and calibration/validation of the accelerometer observations themselves and in conjunction improve the retrieval of neutral density and thereby support the primary mission objectives of the Swarm mission.

5. CONCLUSIONS

The ESA Swarm mission offers not only a unique constellation for observing the Earth's magnetic field, but also provides a unique possibility for exploring gravity field recovery by space-borne differential GPS. The concept of very precise (mm-level) relative positioning by GPS has been proved by the GRACE tandem mission.

The special orbital geometry of the Swarm constellation might have an impact on both achievable gravity field recovery precision in space and in time. It is anticipated that using Swarm tracking and accelerometer observations for an integrated gravity field and orbit determination will support the primary objectives of Swarm as well, as a minimum improving the analysis of the accelerometer observations themselves.

6. REFERENCES

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