ABSTRACT

Global change deals with large- and small-scale processes that modify the Earth’s atmosphere, land and ocean, and drive broad planetary changes in the Earth System. Using innovative geodetic space-borne sensor systems, dedicated gravity field and altimeter satellites monitor these processes over a range of spatial and temporal scales. The integrated analysis of these geometric and gravimetric Earth observation data shall improve the knowledge of system processes of the changing Earth. A few case studies elucidate the role of satellite geodesy in Earth system science.

1. INTRODUCTION

Geodetic satellite missions, both with gravimetric and with geometric observables, play a key role in quantifying processes in the Earth system. Examples of applications are manifold. In this contribution we present a number of case studies that elucidate the role of satellite geodesy in Earth system science.

- Satellite altimetry (ENVISAT, CryoSat-2, HY-2, TPM) is successfully used to quantify components of the hydrological cycle. Observations of river water level in the Yangtze are turned into discharge.
- The combination of lake level altimetry with surface water extent observations from optical or radar remote sensing provides volume changes of lakes and reservoirs over time.
- The GRACE mission still provides science data, allowing the continued monitoring of large-scale water storage changes.
- ESA’s magnetometry mission Swarm allows gravity field recovery through precise orbit determination. As such it could fill the gap between GRACE and its successor in terms of time-variable gravity monitoring, at least at the longest scales.
- GOCE orbit validation satellite laser ranging (SLR).

2. RIVER DISCHARGE OF UNGAUGED CATCHMENTS

River discharge data of all major catchments worldwide is generally available through the Global Runoff Data Centre (GRDC). However, the delivery of data to this database is showing a negative trend since the 1980s for several reasons, either politically or economically. An example is the Yangtze River basin. The GRDC contains several records of gauge stations along the Yangtze with decade-long time series. As Fig. 1 shows, data delivery stopped in the late 1980s, with an exception for the year 2004.

Although satellite altimeter missions have been designed classically for oceanographic purposes, satellite altimetry has proven itself to be a great tool to monitor inland water levels as well. Lakes, reservoirs and rivers can thus be observed from space at so-called virtual gauges, i.e. at locations where the altimeter groundtrack crosses a water body.

![Figure 1. Availability of Yangtze river discharge at Datong station in the GRDC database](image-url)
frame. It was recently demonstrated, however, that rating curves may be estimated by quantile function matching [1] under the assumption of cyclo-stationarity of hydrological behaviour. This approach greatly alleviates the above timeframe restriction and preserves heritage GRDC data into the satellite age.

Fig. 2 shows river discharge at a virtual station close to the Datong gauge from ENVISAT river heights through the quantile matching approach. Where the ENVISAT time series is interrupted, a Kalman filter predicts. The extrapolation after 2010 reveals that the Kalman filter takes over with the cyclo-stationary behaviour (mean annual cycle). Validation of this particular station can only be performed in 2004, with in situ discharge is available from GRDC. The estimated discharge matches the in situ data very well, except during the first months of 2004. Apparently the river is regulated during these months.

The Yangtze example above, together with other examples, cf. [1], clearly demonstrate the utility of spaceborne observations for quantifying the hydrological cycle.

3. LAKE LEVEL AND VOLUME MONITORING

Inland lakes are sensitive to global change processes, either through climate change or through anthropogenic pressure. Thus, long-term monitoring of lakes in terms of lake level and areal extension is key to the modelling of such global change processes. Satellite altimetry is a viable alternative for monitoring ungauged lake levels from space [2]. With careful data analysis lakes with surface areas down to about 100 km² could be observed. For China, for instance, that would imply a potential monitoring of about 130 lakes, provided they are covered by groundtracks.

Two groups of lakes in China locate in the Tibet-Plateau and the Yangtze River basin (Fig. 3). The lakes over the Qinghai-Tibet Plateau, similar to the lakes of East Africa plateau, are an important part of the global lakes distributions. But their hydrological information is difficult to obtain due to the inaccessibility of the region, the sparse distribution of gauge stations, or the slow dissemination of such data. The Yangtze River basin, having five of the largest fresh water lakes, is one of the densest places of lake distribution in China. Many oxbow and regular lakes, dispersed in the form of a butterfly, are connected to the Yangtze River on both sides of it. The basin is characterized by floods and disasters for the water levels of the rivers in the middle and lower reaches of the Yangtze are as low as 10 m. Four of the severest floods causing the most devastating disasters in Chinese history took place in 1931, 1935, 1954, (cf. Fig.1) and 1998. The topography of the Yangtze River basin consists of undulating mountains and hills and plateaus covering about 85 percent of the total surface area. However, the terrain in the middle and lower reaches of the Yangtze is relatively flat, and hence most susceptible to flooding [3]. Moreover, some lakes are scattered across all over China from northwest to north-east, such as Bosten Lake, Qinghai Lake, Hulun Lake, and so on.

Since satellites have a limited life time, long-term monitoring of lake levels can be guaranteed only through multi-mission analysis. Fig. 4 shows groundtracks of several missions over Hulun Lake in Northern China. This multi-satellite sampling allows us to

![Figure 2. River discharge from ENVISAT (black solid line), interpolated and extrapolated using a Kalman filter (red) and validation (blue)](image)

![Figure 3. Two groups of lakes in China](image)

![Figure 4. Multi-satellite altimetry over Hulun Lake](image)
generate a height time series over more than 20 years, cf. Fig. 5, from Topex/Poseidon, Jason1/2, ENVISAT, SARAL and CryoSat-2 mission data. The time series shows that from 2000 to 2010 the lake lost water at an astounding rate of roughly 4 dm/year. Without any discussion on the causes and consequences of such drastic change, Fig. 5 underlines the relevance of satellite altimetry in monitoring change processes in the Earth system.

Figure 5. Hulun Lake level time series (in [m]) from multi-satellite altimetry

Satellite altimetry (here: Envisat and CryoSat-2) over the same time frame gives us an average height drop of 36 cm/year [4]. The combination of height with area variations, together with knowledge of the lake’s bathymetry, leads us to a complete monitoring of the absolute lake volume, cf. Fig. 8. And it leads to the drastic insight that the lake has lost water from a level of about 9 km³ to less than 2 km³ in a mere decade.

Figure 8. Total water volume variation of Urmia Lake

4. GRACE WATER STORAGE CHANGES

In the last decade, temporal variations of the gravity field from GRACE (Gravity Recovery and Climate Experiment) observations have become one of the most ubiquitous and valuable sources of information for geophysical and environmental studies. In the context of global climate change, mass balance of the Arctic and Antarctic ice sheets gained particular attention (cf. latest

The Urmia Lake in Northwestern Iran is a hypersaline lake that suffers from unprecedented desiccation over the past decade, due to groundwater abstraction in its catchment, reservoir construction in the nearby hills and mountains and compounded by a drought period after 2007 [4]. The desiccation process is clearly visible from the receding shorelines in the MODIS snapshots in Fig. 6. Although with limited spatial resolution, the good temporal resolution and the dry climate allow for the construction of a time series of Urmia Lake’s areal extent over the past decade. Fig. 7 reveals a drastic reduction in area of about 70%. Due to the shallow bathymetry in the southern part, the shoreline moves back and forth in an annual motion, leading to a strong annual amplitude in area after 2009.

Figure 7. Urmia Lake’s areal extent based on MODIS imagery

Unless a lake has steep topography around its shorelines, any change in height must lead to change in area, a quantity that may be observed by remote sensing. As successfully documented in the literature, spaceborne monitoring of the areal extent of lakes and reservoirs can be performed either through optical or by SAR-based imagery. Combination of area with height monitoring directly allows spaceborne observation of lake and reservoir volume time series.

Figure 6. Urmia Lake’s receding shoreline based on MODIS imagery
assessments report of the Intergovernmental Panel on Climate Change, IPCC).

Figure 9. GRACE long-term mass variation, expressed in rates of Equivalent Water Height

The power of spaceborne gravimetry for Earth science applications is exemplified in Fig. 9, which shows trends in mass changes over the lifetime of the GRACE mission (expressed, though, in equivalent water height). Melting of the Greenland and West-Antarctica ice caps is well discernible, as is glacial isostatic adjustment over the former Fenno-Scandian and Laurentide ice shields. Even the 2004 Sumatra earthquake leaves a trace in this mass trend map. See also the next section for a further discussion on mass trend estimates.

Several of the other coloured areas indicate interannual changes in hydrological behaviour. Note for instance the reddish area around Urmia Lake. Using GRACE data we quantified the large scale mass loss over the Urmia catchment [4]. Fig. 10 shows the corresponding time series. Because the catchment is wider than the lake area alone, the annual variation, which represents soil moisture and other hydrological storages, shows a larger amplitude than the lake’s volume variation as in Fig. 8. However, the GRACE-derived trend in equivalent water height multiplied by catchment area is in the same range of 0.8–0.9 km³/year as the volumetrically determined trend of the previous section.

Table 1: Mass trends in selected regions

<table>
<thead>
<tr>
<th>Region</th>
<th>Mass trend (Gt/yr)</th>
</tr>
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<tbody>
<tr>
<td>Greenland</td>
<td>-232</td>
</tr>
<tr>
<td>West Antarctica</td>
<td>-73</td>
</tr>
<tr>
<td>Canadian Shield</td>
<td>193</td>
</tr>
<tr>
<td>Amazon basin</td>
<td>76</td>
</tr>
</tbody>
</table>

We assessed the capability of the (non-dedicated) mission Swarm for mass variation detection in a real-case environment (opposed to simulation studies). For this purpose, we "approximated" the Swarm scenario by the GRACE+CHAMP constellation (Fig. 12, left), referred to as pseudo-Swarm in the sequel. These results are compared to the findings obtained from mass variation detection exploiting RL05 gravity fields provided by the Center for Space Research (CSR) (Fig. 12, right); because of their superior quality (which is due to the fact that they are derived from inter-satellite GRACE measurements), the CSR-RL05 solutions serve as benchmark.

We found that mass trends (cf. Tab. 1) and annual amplitudes (not shown here) from the pseudo-Swarm constellation agree up to about 90% with results obtained from GRACE inter-satellite ranging. From this we conclude that Swarm may act as "gap filler" for surface mass variation monitoring. However, it should be kept in mind that any bridging technique is inferior to the performance that can be reached with inter-satellite tracking (with regard to both accuracy and resolution).

5. SWARM SURFACE MASS VARIATION

Because GRACE has outlived its predicted lifetime by several years already, it is very likely that a gap between GRACE and its successor GRACE follow-on (supposed to be launched in 2017, at the earliest) occurs. The ESA mission Swarm – launched on November 22, 2013 – is the most promising candidate to bridge this potential gap, i.e., to directly acquire large-scale mass variation information on the Earth’s surface in case of a gap between the present GRACE and the upcoming GRACE follow-on projects.

Although the magnetometry mission Swarm has not been designed for gravity field purposes, its three satellites have the characteristics for such an endeavour:

(i) low, near-circular and near-polar orbits,
(ii) precise positioning with high-quality GNSS receivers,
(iii) on-board accelerometers to measure the influence of non-gravitational forces.

Hence, from an orbit analysis point of view the Swarm satellites are comparable to the CHAMP (CHAllenging Minisatellite Payload), GRACE and GOCE (Gravity field and steady-state Ocean Circulation Explorer) spacecraft [5,6].
6. GOCE ORBIT VALIDATION BY SLR

Space-based monitoring and modelling of the system Earth requires precise knowledge of the orbits of artificial satellites. In this framework, since decades Satellite Laser Ranging (SLR) contributes with high measurement accuracy and robust tracking data to the acquisition of precise orbit information. One essential role of SLR tracking is the external validation of (kinematic) orbit solutions derived from Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS). This valuable task of external validation is performed by the comparison of computed ranges based on orbit solutions and unambiguous SLR tracking data (observed ranges).

![Figure 11. SLR residuals of kinematic GOCE orbits as computed at AIUB (top) and ITSG (bottom). Colours indicate 25 different SLR tracking stations. Black solid line: mean; black dashed line: RMS](image)

Figure 11 presents the external validation of orbit solutions of the Gravity field and steady-state Ocean Circulation Explorer (GOCE) spacecraft. The GPS-derived kinematic orbits have been provided by the Astronomical Institute of the University of Bern (AIUB) and the Institute of Theoretical Geodesy and Satellite Geodesy (ITSG) at Graz University of Technology. The differences between the SLR-observed ranges and the computed ranges based on these orbit solutions reveal a level of agreement of a few cm (Table 2), corresponding well with the mission requirements.

The computed ranges are subject to the SLRF2008 station coordinates, including station displacement due to loading effects (solid Earth tide loading, ocean tide loading, pole tide loading) and a time-dependent offset between the satellite’s center of mass and the laser retro reflector (LRR) of the spacecraft. In order to form SLR residuals, the atmospheric delay of SLR-observed ranges was corrected with the Mendes-Pavlis model, and relativistic effects were considered. Furthermore, the LRR consists of several reflectors, thus an elevation-dependent retro reflector offset correction was taken into account.

![Table 2: Statistics of SLR residuals shown in Fig. 11 (outliers larger than 20 cm were discarded)]

<table>
<thead>
<tr>
<th>year(s)</th>
<th>AIUB orbits (cm)</th>
<th>ITSG orbits (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean RMS</td>
<td>mean RMS</td>
</tr>
<tr>
<td>2009</td>
<td>-0.25 1.54</td>
<td>0.63 1.87</td>
</tr>
<tr>
<td>2010</td>
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<td>-0.10 1.89</td>
</tr>
<tr>
<td>2011</td>
<td>-0.21 2.76</td>
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<tr>
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<td>-0.22 3.12</td>
<td>0.27 2.69</td>
</tr>
<tr>
<td>2013</td>
<td>-0.61 3.31</td>
<td>-0.18 2.62</td>
</tr>
<tr>
<td>2009-2013</td>
<td>-0.37 2.94</td>
<td>0.17 2.50</td>
</tr>
</tbody>
</table>

7. CONCLUSIONS

The case studies in this contribution have demonstrated that both geometric (height, area) and gravimetric (mass) satellite techniques provide a powerful monitoring tool for climate changes studies. Especially in situations where in situ data are sparse or non-existent, spaceborne sensors are an indispensable alternative. Oftentimes in situ data do exist but are simply not accessible to researchers worldwide. This is particularly the case for hydrological data over the Chinese land mass. It was demonstrated that the quantile matching approach can salvage pre-altimetry discharge data, unless anthropogenic influences change the statistical characteristics of the hydrological regime. The altimetric case study of Hulun Lake showed that long-term monitoring is feasible beyond the life span of single satellite missions.

We also emphasize the complementarity of the geometric techniques (satellite altimetry and remote sensing) as opposed to satellite gravimetry. Particularly their combination has the potential to give deeper insight into physical properties of global change processes, as the Urmia case study revealed. The desiccation of this lake over a 10-year time interval could be followed.

Although the GRACE mission, i.e. dedicated spaceborne gravimetry, may come to an end soon, the capability of non-dedicated missions to provide time variable gravity was assessed. The exercise with CHAMP and GRACE orbit data alone, without any inter-satellite ranging data GRACE, provided high correlations with GRACE solution, at least at the largest spatial scales. Hence, ESA’s magnetometry mission Swarm is a strong contender to fill in the gap until the GRACE-Follow On mission is launched.

The case study of GOCE orbit validation serves as a reminder that high quality satellite data requires high quality orbit determination. As such, satellite laser
ranging can independently validate GPS-based orbit determinations and improve the ties to the terrestrial reference frame.

Acknowledgements
Kinematic orbits have been provided by Adrian Jäggi (AIUB) and Torsten Mayer-Gürr (ITSG). We thank Matthias Weigelt for the computation of the pseudo-Swarm gravity fields, Balaji Devaraju (Institute of Geodesy, University of Stuttgart) gratefully provided the GRACE-derived water storage changes.

8. REFERENCES


Figure 12. Global maps of secular equivalent water height variations (top) and annual amplitude (bottom) from January 2006 to December 2009. Gaussian smoothing with a radius of 750 km applied. Left: results based on pseudo-Swarm; right: results based on CSR -RL05 gravity fields.