Future Space Gravity Mission Architectures for Observing the Earth's Hydrology Signal

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Introduction

Numerous efforts for improving gravity field determination and hence mass variations from future space gravity missions (FSGM) beyond the GRACE/GRACE-FO (Gravity Recovery And Climate Experiment / Follow-On) missions have been proposed during the last decade. In this contribution, four FSGM, namely Bender-, Cartwheel-, Helix- and Pendulum-type, in addition to GRACE-FO as a reference mission are used to recover the mass variations represented by the hydrological signal globally and regionally. The results show a superiority of investigated configurations in retrieving the hydrological signal w.r.t. the GRACE-FO mission. Moreover, the Bender-type provides improved global hydrological recovery showing the least standard deviations (STD) of about 3.43cm in terms of equivalent water heights (EWH) at spatial resolution of 250 km. The Pendulum, Cartwheel and Helix missions provide STD of about 6.34cm, 8.35cm and 5.78cm in terms of EWH, respectively. In addition, the FSGMs provide improved regional hydrology recovery on the basin scale.

Future Space Gravity Mission Architectures

Figure (1) shows four designs of proposed future space gravity missions (FSGM) compared to the current GRACE-FO gravity mission (Fig. 1a). The Pendulum-type architecture (Fig. 1b) consists of two satellites in two orbital planes, where the orbital plane of follower satellite (Pendulum B) crosses orbital plane of leader satellite (Pendulum A) over the poles providing the maximum cross-track separation over the equator. The Bender-type architecture (Fig. 1c), whose design was firstly introduced by Bender et al. (2008), consists of two satellite pairs, each of them collects observations in along-track direction. One of these satellite-pairs (Bender A & B) flies in a polar orbit, while the second-pair (Bender C & D) flies in an inclined orbit. The concept of radial-oriented Cartwheel-type (Fig. 1d) is based on two satellites flying in two orbital planes and collecting observations in both radial (over equators) and along-track (over poles) directions. The Helix-type configuration (Fig. 1e) is a modified mission (i.e. radial-inclined) of Cartwheel-type, where the orbital plane of the follower satellite (Helix B) crosses the orbital plane of the leader satellite (Helix A) providing cross-track information beside along-track and radial information. The main difference between the radial-oriented Cartwheel-type and the radial-inclined Helix-type is that in former configuration the Cartwheel B satellite follows the leader satellite in the northern hemisphere but in the southern hemisphere it becomes the leader satellites (see Fig. 1d). In Helix-type configuration, Helix B satellite has different angle of right ascension of ascending node beside the argument of perigee and different mean anomaly allowing Helix A to be always the leader satellite (Fig. 1e).

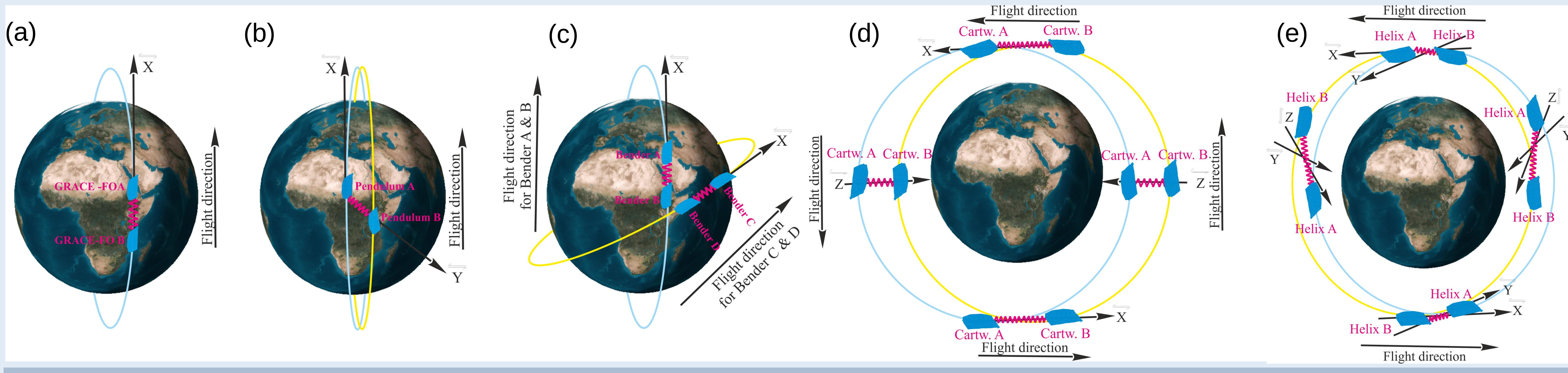

Figure 1. The investigated Future Space Gravity Missions showing satellite observables in different line-of-sight directions: (a) GRACE-FO as a reference mission, (b) Pendulum, (c) Bender, (d) Cartwheel and (e) Helix. Note: the X, Y, Z vectors stand for inter-satellite line-of-sight directions in along-track, cross-track and radial, respectively.

Methodology of Hydrology Recovery

The satellite observations (i.e. the orbits, inter-satellite range-rate and accelerometer data) of the FSGM (see Fig. 1) have been numerically simulated besides simulated noises to mimic the real state of gravity field as given in Elsaka et al., (2014a). The background models applied in the gravity analysis step to recover the hydrological signal are as same as those given in Elsaka et al., (2014b). The spherical harmonic coefficients (SHC) up to degree/order (d/o) 80/80 estimated from the simulated observations are used to compute the equivalent water heights (EWH). The mass variations of the hydrology signal are estimated using the following formulae:

$$TWS_{(\varphi,\lambda)} = R_E \frac{\rho}{3} \sum_{n=0}^{N_{max}} \left(\frac{2n+1}{1+k_n} \right) \sum_{m=0}^{n} \bar{P}_{nm}(\sin\varphi)(C_{nm} \cos m\lambda + S_{nm} \sin m\lambda)$$

where the terms (r,φ,λ) are spherical coordinates (distance to the geocenter, geodetic latitude and longitude, respectively) of a point, R_E is the mean radius of the Earth (applied in our study as 6387136.3 m), ρ is the average density of the Earth (5517 kg/m³), k_n is the load love numbers, $P_{nm}(\sin\varphi)$ is the fully normalized associated Legendre function, and n, m are degree and order of spherical harmonics, respectively, and N_{max} the maximum applied degree which is set at 80. The differences between the fully normalized spherical harmonic coefficients obtained from the FSGM and those from the hydrological model WGHM (WaterGap Global Hydrology Model) as shown in Figure 2.

Results: Global Hydrology Recovery

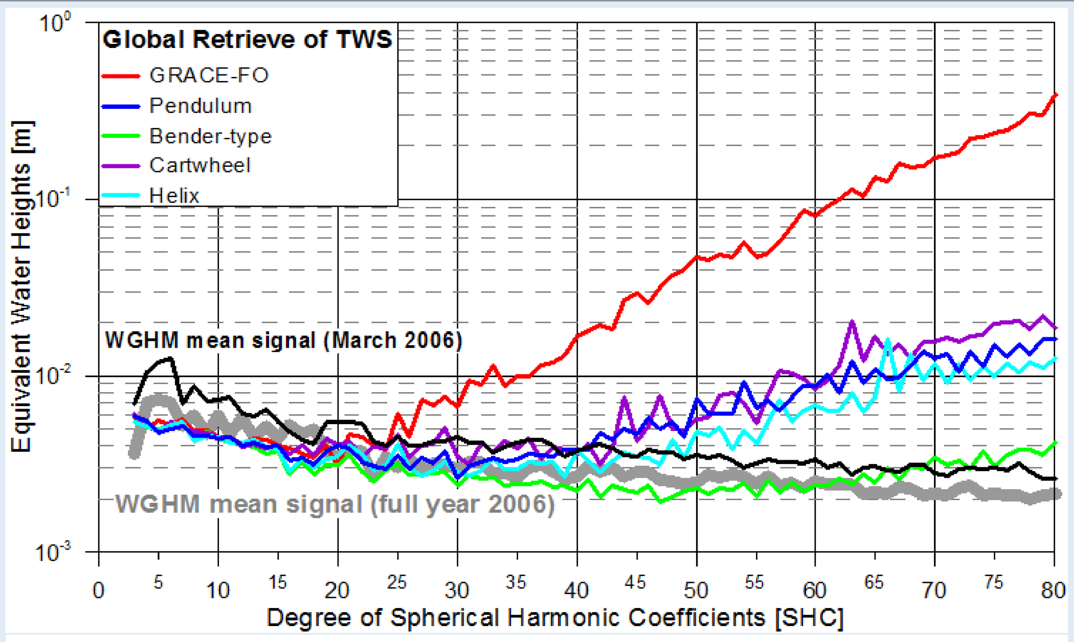

Figure 2. Difference degree variances [DDV] of the retrieved hydrological solutions in terms of EWH [m] from the investigated FSGM: GRACE-FO, Pendulum, Bender-type, Cartwheel and Helix.

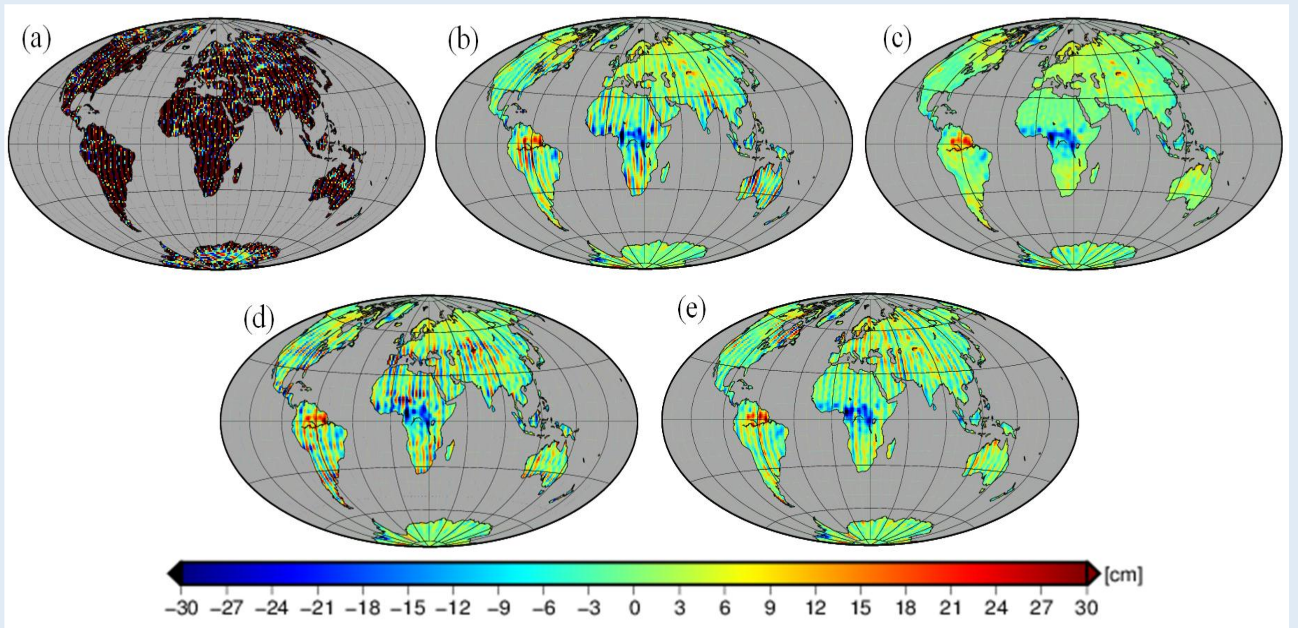

Figure 3. Global hydrological signals as determined from the investigated FSGM: (a) GRACE-FO as a reference mission, (b) Pendulum, (c) Bender-type, (d) Cartwheel and (e) Helix.

Statistics off FSGM	STD (EWH)	Mean (EWH)	min. (EWH)	max. (EWH)
GRACE-FO	93.007	-0.220	-488.57	467.62
Pendulum	6.348	0.0651	-46.087	35.964
Bender-type	3.430	0.0251	-36.246	28.356
Cartwheel	8.353	0.0385	-49.884	43.975
Helix	5.789	0.0760	-37.876	37.270

Table 1. Statistics in terms of STD, mean, min., max. values of the global hydrological recovery given in EWH [unit in cm] from the investigated FSGM represented in Figure 3. The gray cells represent the smallest values.

Results: Regional Hydrology Recovery over some major River Basins

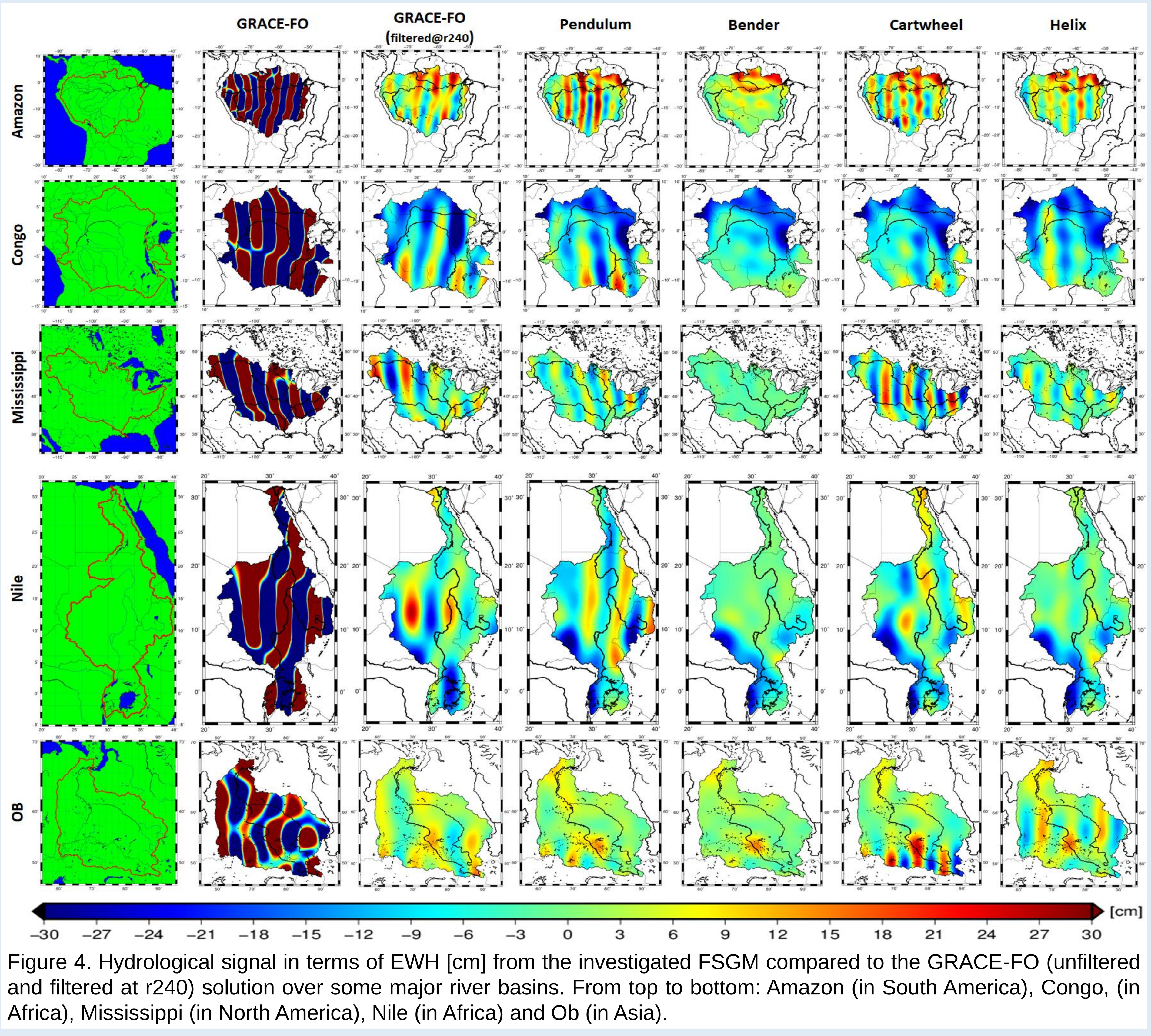

Figure 4. Hydrological signal in terms of EWH [cm] from the investigated FSGM compared to the GRACE-FO (unfiltered and filtered at r240) solution over some major river basins. From top to bottom: Amazon (in South America), Congo, (in Africa), Mississippi (in North America), Nile (in Africa) and Ob (in Asia).

Discussion of Results

On the global scale (Fig. 3), it is possible to obtain better hydrology recovery as seen spectrally in Fig. 2 and spatially in Fig. 3. In fact, the recovery of the hydrological signal is affected by the striping error behavior of the GRACE-FO mission (see Fig. 3 a), which was the same issue of the former GRACE mission. Whereas, the hydrology signal are clearly seen by the other mission scenarios, especially for the Bender-type mission (see Table 1) without any stripes.

On the regional scale (Fig. 4), the hydrological signal derived from GRACE-FO solutions are hardly to be identified due to the associated striping errors. Therefore, post-processing procedures (e.g. applying suitable filtering technique) are required for reducing the high frequency noise in GRACE-FO mission and for damping these striping errors. On the contrary, there is no demand to filter the hydrology solutions derived from the FSGMs, since the recovered TWS signal is clearly detected without any distortion of the striping errors.

Conclusion

- The results obtained within this poster demonstrate clearly the benefit of merging additional information (i.e. combining satellite observations flying in different directions; along-track; cross-track and radial components (see Fig. 1).
- The MAGIC mission which is foreseen for launch around 2028-2032 (Massotti et al., 2021) will realize the Bender concept. Our results suggest that the MAGIC surface mass fields will thus have a significantly higher accuracy (at the same spectral resolution) as compared to the unfiltered GRACE-FO data.

References

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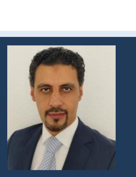

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