Satellite orbit and gravity field determination at AIUB

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The Satellite Geodesy Team of AIUB

Astronomical Institute, University of Bern, Switzerland

LEO Satellites

Plenty of satellites orbit Earth in **Low Earth Orbit (LEO)**, i.e., at an altitude of about 200 - 2'000 km. For many of them a very **accurate and precise knowledge of their positions** at any time is crucial. E.g., to reliably measure global and regional sea level by means of **satellite altimetry** (see Fig. 1), the LEO satellite orbits need to be know at a level of cm or even sub-cm accuracy.

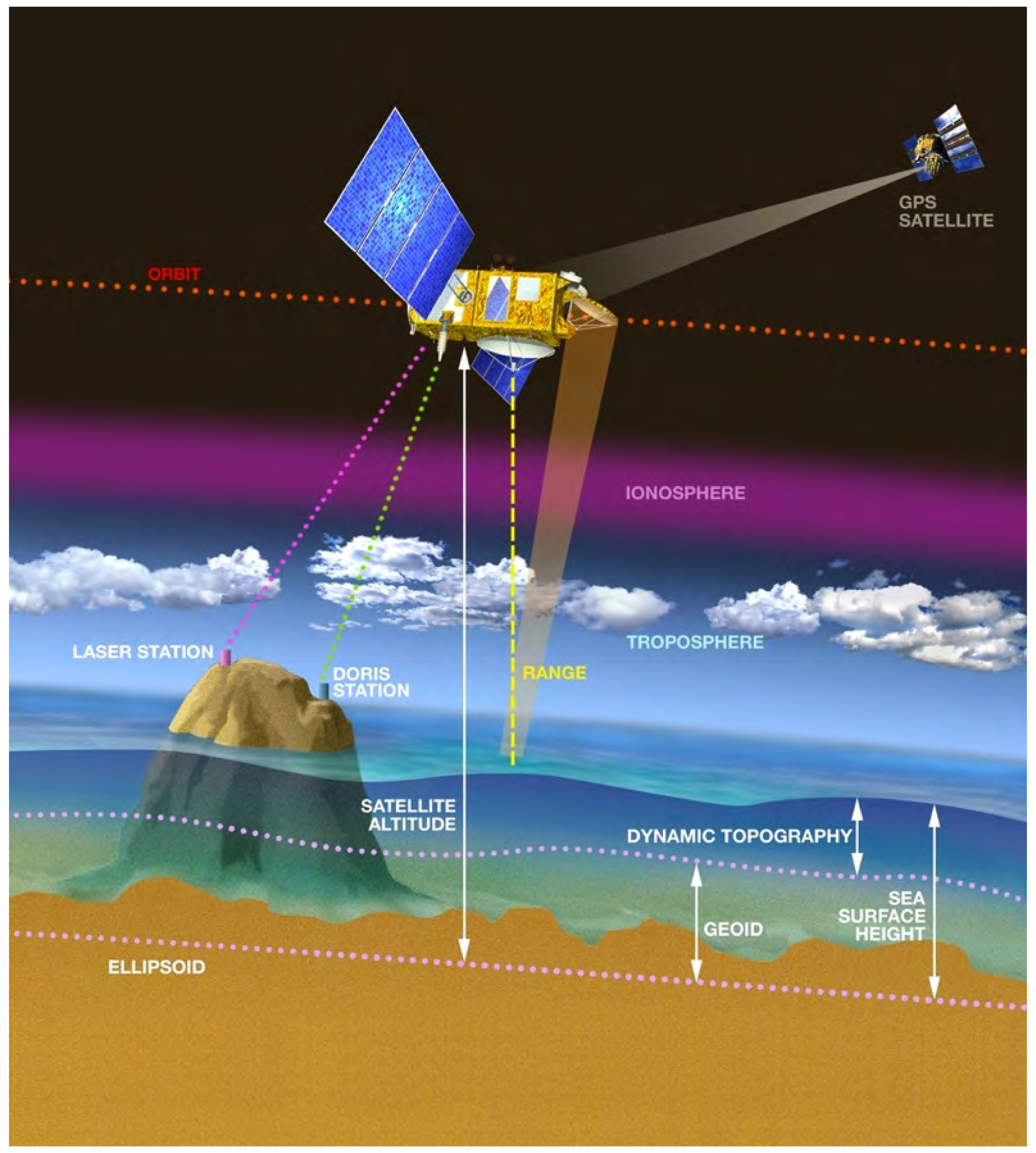

Figure 1: Principle of satellite altimetry. ©CLS/AVISO

Often such LEO satellites carry **GNSS (Global Navigation Satellite Systems) receivers** on board – most of them for GPS, but newer satellites also for other GNSS like the European Galileo. These GNSS measurements can be exploited to support a Precise Orbit Determination (POD) *if*

- high-quality information about the GNSS satellites (in particular their orbits, atomic clock corrections and signal biases) are known
- accurate information about LEO satellite geometry is available
- substantial effort for the modeling of satellite dynamics and of the GNSS measurements (including signal propagation and effects in transmitter and receiver) is conducted.

LEO POD at AIUB

At the Astronomical Institute of the University of Bern (AIUB) the GNSS-based LEO POD is advanced since many years. The orbits of numerous different LEO satellites have been and are being computed using our in-house developed **Bernese GNSS Software**, which is used by more than 700 other institutions worldwide. For the GNSS orbits and clock corrections we use our high-quality Center For Orbit Determination in Europe (CODE) products.
As an example, the AIUB is part of the **Copernicus POD Quality Working Group**, in the frame of which we perform POD for the ESA Sentinel-1, -2, -3, and -6 Earth observation satellite fleet (see Fig. 2) for intercomparison and cross-validation (see Fig. 3).

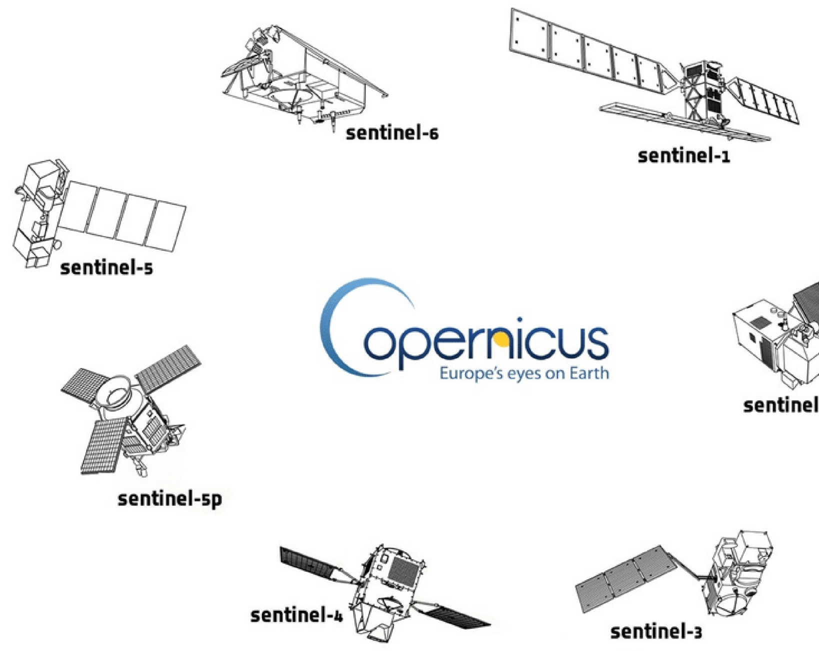

Figure 2: ESA's Sentinel satellites. ©ESA

For a typical 1-day reduced-dynamic (solution of a satellite equation of motion) and kinematic (purely geometric positioning) LEO POD with 10 s sampled GPS data from an 8-channel GPS receiver (e.g., Sentinel-1), we process about 250'000 GPS and 90'000 attitude measurements to estimate orbit and observation technique-specific parameters. The number of estimated parameter is in the range of 10'000 for the reduced-dynamic orbit and about 40'000 for the kinematic one. The processing time (including data pre-processing) amounts to 20-40 minutes and the maximum memory consumption to about 150 MB. Processing GPS data at 1 Hz sampling and/or from GPS receivers with more channels increases these numbers. The POD is usually performed on UBELIX, for extended tests or reprocessing purposes typically many (50-100) days are processed in parallel.

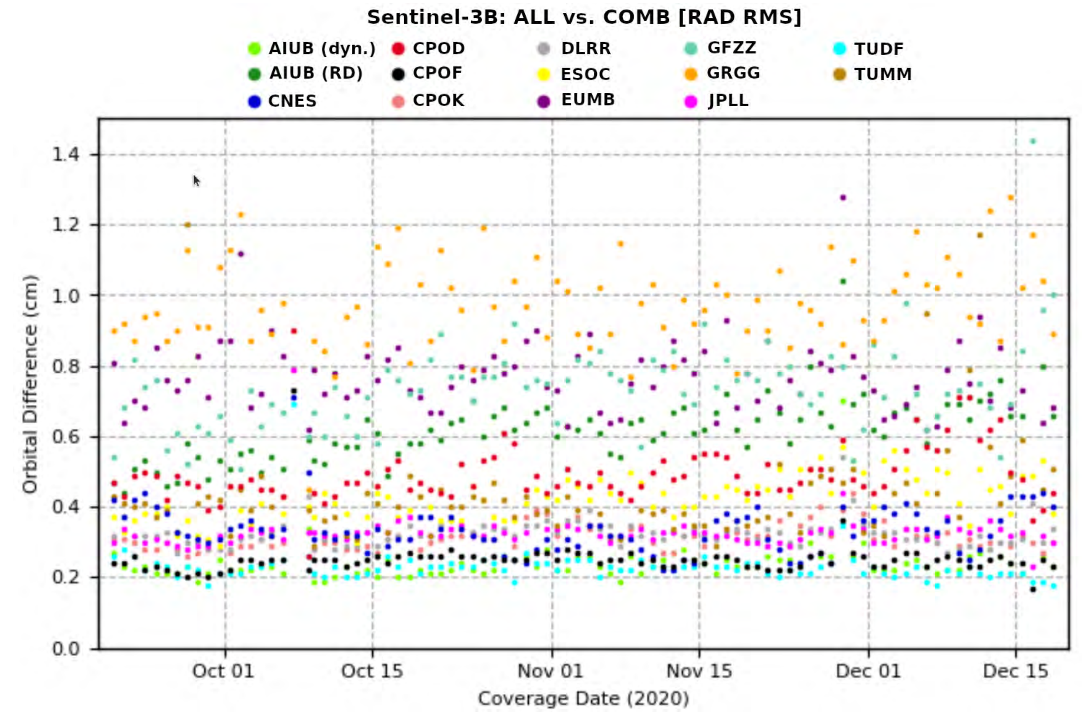

Figure 3: Radial differences of numerous orbit solutions for Sentinel-3B w.r.t. a combined solution in the Copernicus Regular Service Review #19. AIUB is delivering dynamic (light green) and a reduced-dynamic (dark green) solutions. The former one belong to the highest-performing solutions within the Quality Working Group.

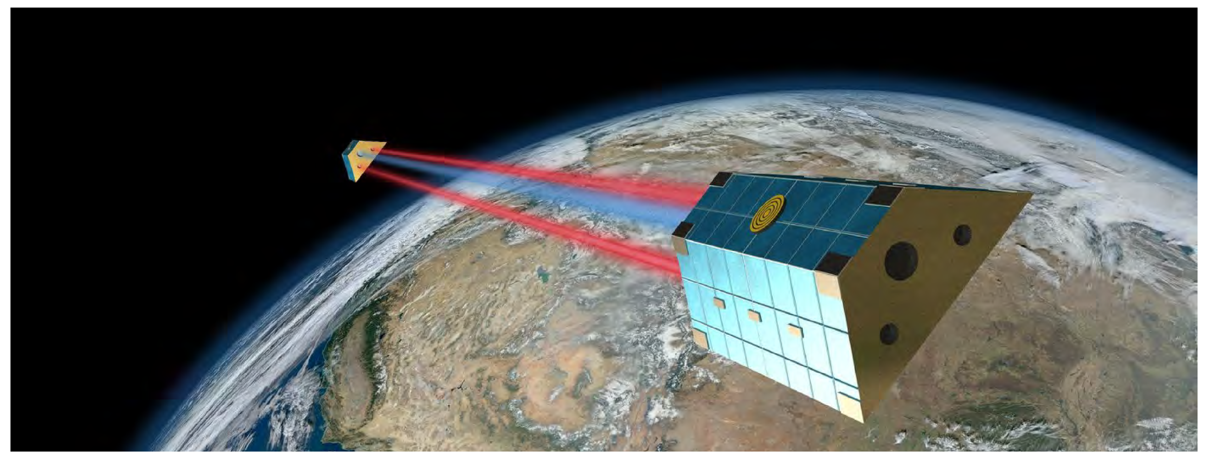

Figure 4: The GRACE Follow-On mission to measure Earth's time variable gravity field. ©NASA

From orbits to gravity field

The Earth's gravity field causes the main force acting on the satellite's orbit and defines its shape. This process may be reversed, thus, precisely measuring the motion of an artificial satellite in LEO allows to deduce **information about Earth's gravity field**. The latter is constant neither in space nor in time, but changes due to all-present mass re-distributions above, on or below the Earth surface. In short time scales, e.g., monthly, mostly water re-distributes, which means one is able to measure through satellite orbits the sea level rise, ice capes melting, floods or draughts (see Fig. 5).
Several missions dedicated to observe tiny mass variations through the Earth's gravity field have been launched in the last two decades. Primary focus is the most accurate determination of the orbit and consequently the gravity field through GPS, accelerometers and other dedicated measurements such as an ultra precise inter-satellite link between two satellites flying 200 km apart. This concept is applied in GRACE and GRACE Follow-On (see Fig. 4) where the latter uses a laser link with a precision resolving the 200 km distance with less than $\frac{1}{10}$ nm (1^{-10} m).
Gravity field processing is performed on UBELIX in monthly batches, running an orbit integration for each day in parallel, making heavy use of BLAS and LAPACK routines with a memory consumption of ~500 GB (~16 GB per day) where ~1'300'000 observations are processed (5 s sampling) and 28'000 unknown parameters are determined. Typical processing time (aiub-queue) is less than 1 h.

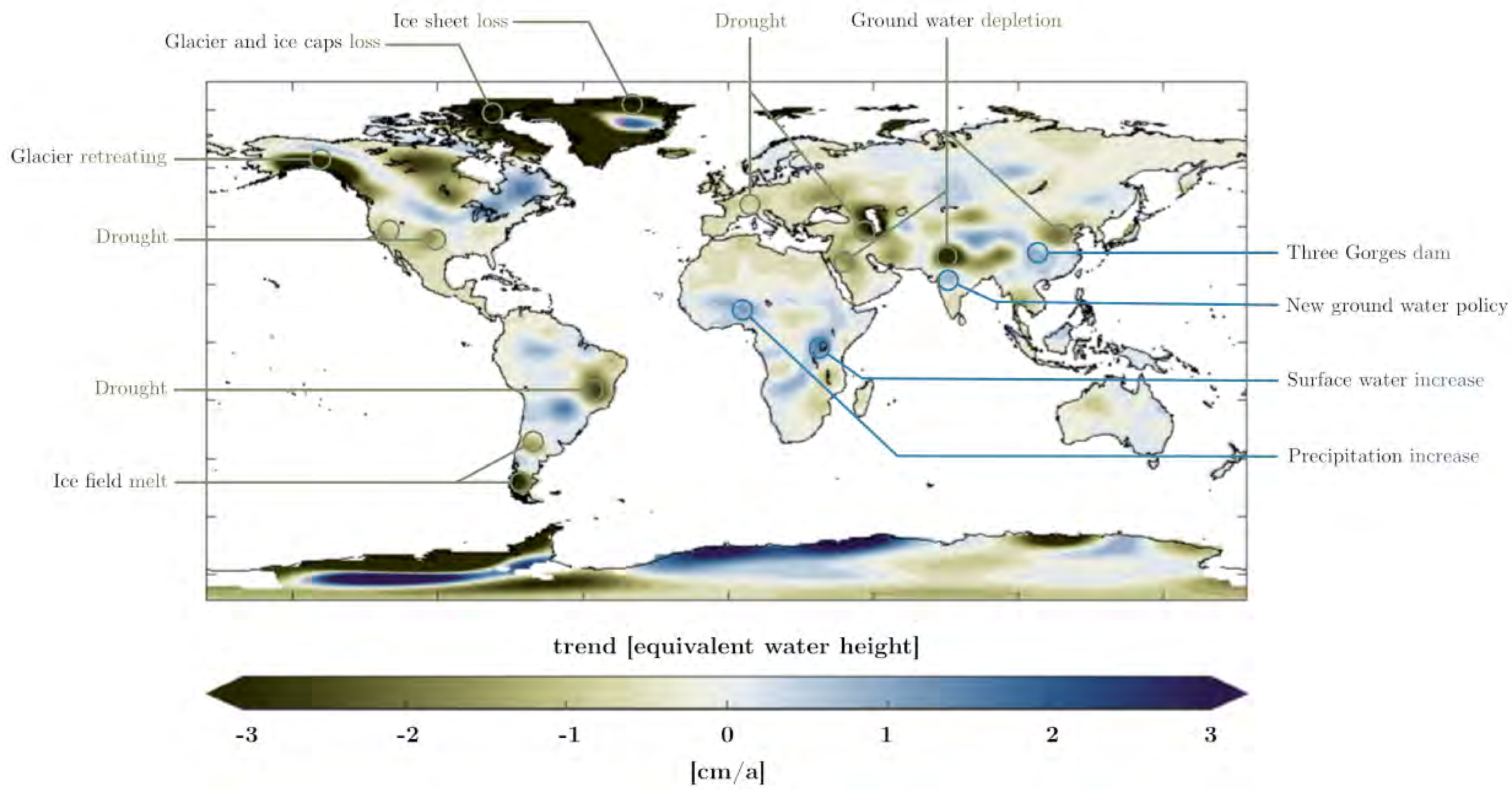

Figure 5: Geophysical signal observed by GRACE and GRACE Follow-On since 2002. Brown represents a loss of mass, e.g., caused by the ice capes melting or heavy use of ground water and droughts. Blue indicates a gain of water mass, e.g., through precipitation or man-made structures.

The procedure of determining the gravity field and consequently gaining insight into the inner structure of the planet may not only be applied to the Earth but to any celestial body with a probe orbiting (or even just flying by). The NASA mission GRAIL performed most sensitive gravity field measurements for the Moon (see Fig. 6), which is now the celestial body with the most accurately known gravity field! At AIUB these data have been analyzed to generate lunar gravity field models up to degree and order 350 in spherical harmonic expansion, involving the estimation of more than 150'000 parameters. The resulting daily normal equations only for the gravity field parameters consume about 60 GB of disk space and the solutions are based on about 90 days.

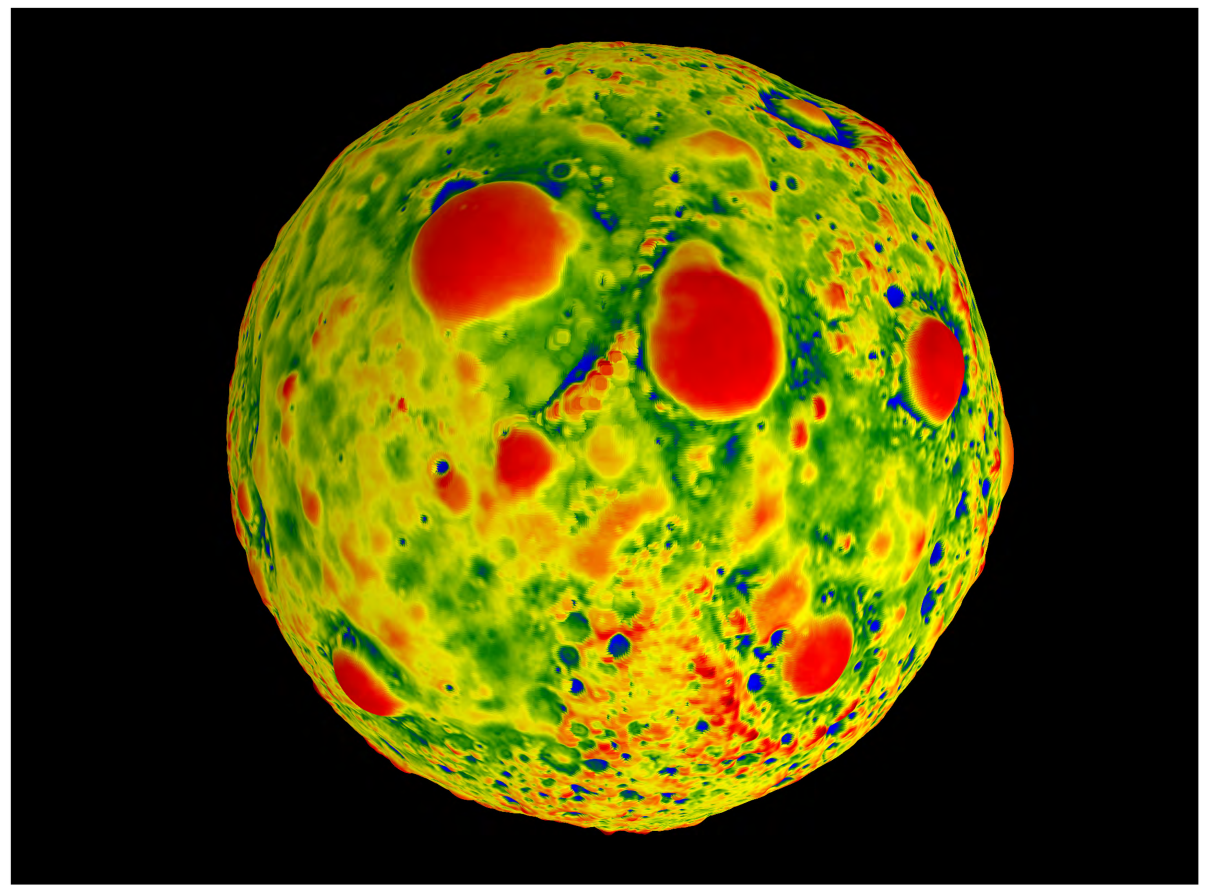

Figure 6: Representation of a high-resolution lunar gravity field model produced at AIUB by analyzing data from the NASA mission GRAIL. High areas in red indicate stronger gravity, low areas in blue weaker gravity.

Computational limitations and accuracy

Present computational challenges in the orbit and gravity field determination come with the significant increase in measurement precision over the last years. These observations meanwhile require more significant digits than 64-bit floats provide. Thus, at least critical components of the software dealing with these observations need to be extended to **quadruple precision**, ideally without significantly increasing computation time. A first example of such a bottleneck is the processing of the aforementioned ultra-precise laser data for GRACE Follow-On, the full exploitation of which requires a much more precise orbit integration. This is yet to be implemented in our software. A second example is light time computation in the processing of Doppler tracking data of planetary probes. E.g., for a probe around the Jupiter moon Europa light time to Earth amounts to 32-54 minutes. Changing carefully selected core pieces of code to quadruple precision allows to increase light time precision by a factor 2-3 to $2.5 \cdot 10^{-13}$ s, while increasing the computation time only by about 10 %.

Acknowledgement

We want take the opportunity to thank the UBELIX team for their exceptional flexibility and high motivation in maintaining the system. We are looking forward to continue the close cooperation in future.

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