Exploring the Earth’s Time-Variable Gravity Field using Satellite Observations

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Earth’s Gravity Field

Gravitational pull at the Earth’s surface

\[ g = 9.78 \frac{m}{s^2} \ldots 9.83 \frac{m}{s^2} \]

\[ \pm 0.0004 \frac{m}{s^2} \]

\[ 1 \text{ mGal} = 0.00001 \frac{m}{s^2} \]

1 millionth of the pull at the Earth’s surface
Earth’s Gravity Field in March
Earth’s Gravity Field in September
September – March
September – March
September – March
September – March
How do we measure these changes?
From Newton to satellites ...

Satellites at a height of 200 – 500 km

Measuring the trajectory, or
- the velocity
- the acceleration
Bahnspur des sowj. Erdkrabanten

Sternbild: Ursa Major
Aufnahme: Schulsternwarte Rodewisch 16h.
13. Okt. 1957 451h MEZ
Orbit Perturbations

Orbit perturbations caused by the Earth’s oblateness result in, e.g., a secular precession of the satellite’s orbital plane.

Observing satellites thus allowed it to determine the Earth’s oblateness based on very short time spans of observed orbital arcs – revolutionizing the work of decades of terrestrial surveying.
Dedicated Gravity Missions

- CHAMP (GFZ, 2000-2010)
- GRACE (NASA/DLR, 2002-2017)
- GOCE (ESA, 2009-2013)
- GRACE-FO (NASA/GFZ, 2018-2022)

- High-low satellite-to-satellite tracking (hl-SST)
- Low-low satellite-to-satellite tracking (ll-SST)
- Satellite gravity gradiometry (SGG)
Modeling the Earth’s Gravity Potential

\[
V(r, \theta, \lambda) = \frac{GM}{R} \sum_{l=0}^{l_{\text{max}}} \left( \frac{R}{r} \right)^{l+1} \sum_{m=0}^{l} P_{lm}(\cos \theta) \cdot \left[ \overline{C}_{lm} \cos(m\lambda) + \overline{S}_{lm} \sin(m\lambda) \right]
\]

(geoid heights)

A spherical harmonic expansion up to a certain maximum degree \(l_{\text{max}}\) is most commonly used to represent the Earth’s gravity potential.

<table>
<thead>
<tr>
<th>(l_{\text{max}})</th>
<th># Coeff.</th>
<th>(\lambda) [km]</th>
</tr>
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<tbody>
<tr>
<td>20</td>
<td>441</td>
<td>1000</td>
</tr>
<tr>
<td>100</td>
<td>10 201</td>
<td>200</td>
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<tr>
<td>200</td>
<td>40 401</td>
<td>100</td>
</tr>
<tr>
<td>250</td>
<td>63 001</td>
<td>80</td>
</tr>
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\(\lambda\) … spatial (half) wavelength
Measuring Satellite Motion

cm-precision

nm-precision (with additional laser link)

mm-precision

GRACE-FO Mission

LISA Technology Sheds Light on Climate Change
Swiss Optical Ground Station and Geodynamics Observatory in Zimmerwald

- Measuring distances to satellites equipped with retro-reflectors with Satellite Laser Ranging (SLR)
- Fully automated, 24/7 operations
- Telescope used for both SLR and optical astronomy
- One of the most productive SLR stations worldwide (and usually the most productive one on the Northern hemisphere).
Precise orbits for GPS, Galileo und other Global Navigation Satellite Systems are operationally computed at the Center for Orbit Determination in Europe located at the Astronomical Institute of the University of Bern.
The Bernese GNSS Software is a scientific software package for high precision analysis of various space geodetic data. It is developed since many years at the Astronomical Institute of the University of Bern and is meanwhile used by more than 700 institutions worldwide.
Modeling Satellite Motion

Equation of motion

\[ m \cdot \ddot{x} = \vec{F}(t, \vec{x}, ...) \]

\[ \Rightarrow \text{Numerical integration of the orbit} \]

Force modeling:
- Static gravity field
- Additional bodies (sun, moon, planets)
- Solid Earth tides
- Ocean tides
- Pol tides
- Ocean pole tides
- Atmospheric tides
- Dealiasing (atmosphere, ocean)
- Non-gravitational forces
- Relativistic effects
Measurement Principle
Measurement Principle

That's much more precise than measuring the absolute or relative position with GPS or SLR (cm or mm).
Challenging Data Processing

- Process GRACE data to a time series of monthly gravity field solutions
- Processing is challenging
  - Interaction of multiple instruments
  - Different noise characteristics
  - Environmental disturbances
    - Ionosphere
    - Atmosphere
    - Ocean currents
    - Tides
- There is not one „true“ solution
... and even more challenging with laser

LISA: Laser Interferometer Space Antenna, launched in May 2018
Which changes can be measured
Time Variations

[ 1km³ = 1Gt water ]
ΔTWS(t) = ΔGW(t) + ΔSW(t) + ΔSWE(t) + ΔSM(t) - ΔRO(t)

ΔTWS(t) = Total Water Storage
ΔGW(t) = Ground Water
ΔSW(t) = Surface Water
ΔSWE(t) = Snow Water Equivalent
ΔSM(t) = Soil Moisture
ΔRO(t) = Run Off

Can only be measured by GRACE!

Separation needs further measurements
Time Variations

Thank you for your attention.
Melting Ice in Greenland

Mass Loss: ≈ 250 Gt/year
Melting Ice in Greenland

30 June, 2019: "Bern im All", Quiz on Bundesplatz:

How many of these blocks are melting in Greenland every second?
Melting Ice in Greenland

30 June, 2019: "Bern im All", Quiz on Bundesplatz:

≈10,000 of these blocks are melting in Greenland every second
Melting Ice in Antarctica
Melting Ice in Greenland

Greenland: ~7 m sea level equiv.
Antarctica: ~60 m sea level equivalent.

GRACE weighs the ice sheets and identifies loss and gain on regional level.

Continuous measurements ensure we identify regional change and long term vs short term variations which ensures an “early warning system”
SEA LEVEL RISE
CONTRIBUTIONS
& IMPACTS

GLOBAL MEAN SEA LEVEL
BY 2100

-2 meters
People impacted by flooding per year if not mitigated

-1 meter
-50-575 millions for 0.6-1.2m

-0.3 meters
-25-400 millions for 0.3-0.5m

GLACIERS

GROUNDWATER

ICE SHEETS

Proxy records
Tide Gauge Data
Satellite Data

-0.01 - +0.09mm/yr
2100: no change

TODAY: 0.4 - 1.1mm/yr
2100: 0.7 - 2.6mm/yr

TODAY: 0.4 - 0.8mm/yr
2100: -2mm/yr to >12mm/yr

ANNUAL CONTRIBUTIONS

TEMPERATURE CHANGES

TODAY: 1 - 2 mm/yr
2100: 1 - 5mm/yr

Potential Rate at Year 2100
Rate Today
Availability of Water

Emerging Trends in Water Distribution & Availability

Rodell et al., 2018
Example: Drought in California
Example: Drought in California

Actual Water Storage Variations

‘Normal’ range of Water Storage Variations

Difference to ‘normal’ dry conditions

Thomas et al. (2014)
Example: Floods
Hydrological Extreme Events as Seen by GRACE

November 01, 2005

Total Water Storage Anomaly [cm]
(seasonal and secular variations removed)
Could these data be helpful for early warning?
Potentially yes, …

Saturated soils  →  One factor, which may favor the development of floods

Unusual developments in Total Water Storage may serve in the future as an additional indicator for the potential development of floods.
Potentially yes, ...


Usually this information is only available two months later, and only with a time resolution of one month.

In May 2007 actually occurring floods.

In order to be useful, it will be necessary to have this information in near real-time and significantly improved (daily) time resolution.

Reager and Famiglietti (2009)
Wetness index for early flood warning

Retrospective analysis of daily solutions for the Danube basin.

Particularly relevant with respect to early flood warning is the build-up of basin-wide water storage of several weeks duration prior to the larger flood events.
An operational test run of near real-time gravity field solutions has been demonstrated in the final months of the GRACE mission.
Rapid Mapping

ZKI: Center for satellite-based crisis information

Possible idea for the future:
Earlier alarms thanks to gravity based indicators

Data provision → Pre-processing → Analysis → Map generation → Transfer

alarm
European initiatives and future perspectives
GRACE-FO Analysis Centers

European Analysis Centers

Chinese Analysis Centers

Jet Propulsion Laboratory (JPL):
- Level 1-3, US Project and Science Management
- SDS Lead

GeoForschungsZentrum (GFZ):
- Level 2-3, German Project Management, incl. spacecraft operations (at DLR-GSOC)
- Geophysical background models

CSR:
- Level 2-3
- Science Operations Management

Goddard SFC (GSFC):
- Level 2-3 & Ancillary data support

SDS Analysis Centers
European Gravity Initiatives

The University of Bern coordinated the H2020 project EGSIEEM (2015-2017). It was explicitly mentioned in NASA’s Decadal Survey and paved the way for the current activities.

Parts of EGSIEEM are now continued as a new IAG activity called COST-G, coordinated again by the University of Bern.

The University of Bern initiated to strive for a H2020 follow-up of EGSIEEM with the same gravity core-group as in EGSIEEM: Global Gravity-based Groundwater Product (G3P), a H2020 project coordinated by GFZ (2020-2022).
Improved and consolidated product integrating the strengths of all ACs
Welcome to COST-G

The International Combination Service for Time-variable Gravity Fields (COST-G) is a product center of the International Gravity Field Service (IGFS) and is dedicated to the combination of monthly global gravity field models. COST-G stems from the activities of the former I2020 project European Gravity Service for Improved Emergency Management (EGSIEM) and is further developed within the follow-up project Global Gravity-Based Groundwater Product (G3P), which is funded from the European Union’s Horizon 2020 Research and Innovation Programme under Grant Agreement no. 870353 (funding period 2020-2022).

Please use the top menu to visit the various parts of our website!

Best regards,
Your COST-G Team.

Latest GRACE-FO combination results

Weights

https://cost-g.org/
Missing solutions are caused by the gap between GRACE and GRACE-FO, battery saving measures in the final years of the GRACE mission, or instrument issues.
Basin-integrated Greenland/Antarctic Ice Sheet (GIS/AIS) mass changes based on the sensitivity kernel approach by TU Dresden.

Trends are calculated from GRACE and GRACE-FO results (from a fitted linear, quadratic and seasonal model).
Consistency of Input Products

- Basin numbers:
  - 29: Ant. Peninsula (AP)
  - 30: East Ant. (EAIS)
  - 31: West Ant. (WAIS)
  - 32: AIS
Institutional Support

- **International Space Science Institute (ISSI):**
  - International Team funded from 2019 to 2021: Set-up of initial COST-G structures, computation of initial GRACE release and operational GRACE-FO release

- **ESA / Swarm DISC:**
  - Funded from 2020 to 2021: Operational provision of Swarm release

- **International Space Science Institute Beijing (ISSI-Beijing):**
  - Funded from 2021 to 2022: Extension with Chinese Analysis Centers
Meeting with the Chinese delegation in Bern just before the pandemic started (16-17 Jan., 2020) to discuss future collaborations. There, the idea was born for a further team supported by ISSI-Beijing.
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- **H2020:**
  - Funded from 2020 to 2022: Optimization and Operationalization of COST-G workflow within G3P
Groundwater and the Earth’s Gravity Field

- Satellite gravimetry with GRACE (2002 - 2017) and GRACE-FO (2018 -) is the only technique to observe Total Water Storage (TWS) variations

- A prototype for a global groundwater product shall be established for the Copernicus Climate Change Service.

Groundwater = TWS - glaciers - snow - soil moisture - storage in surface water bodies
Perspectives in Terms of Missions

Courtesy: ESA
Europe’s Earth Observation Programme

- Atmosphere monitoring
- Marine environment monitoring
- Emergency management
- Land monitoring
- Climate change
- Security

https://www.copernicus.eu/
The Global Climate Observing System (GCOS) defines several **Essential Climate Variables** (ECVs):

- an ECV is a variable that is critical for characterizing the climate system and its changes
- ECV datasets provide the empirical evidence needed to understand and predict the evolution of climate, to assess risks, to guide adaptation measures, to underpin climate services, …

Latest News: New ECV Terrestrial Water Storage is now approved by GCOS
Sustainable Satellites are serving Society

Data processing and dissemination

Gravity: one of the missing links in the Copernicus Earth Observation

Service evolution:

- Atmosphere monitoring
- Marine environment monitoring
- Emergency management
- Land monitoring
- Climate change

Copernicus
Europe’s eyes on Earth
Gravity missions enabled spectacular results:

- insights into the global water cycle
- polar and mountain ice mass loss
- changes in ocean surface currents
- unification of height systems
- sea level rise

→ There is a strong need for sustained observation.
Thanks a lot for your attention!