Hochpräzise Bahnbestimmung von Satelliten: Was man aus Satellitenbahnen über Umweltveränderungen lernen kann

Adrian Jäggi

Universität Bern

Im Namen der COST-G und G3P Teams

COST-G Combination Service for Time-variable Gravity Models

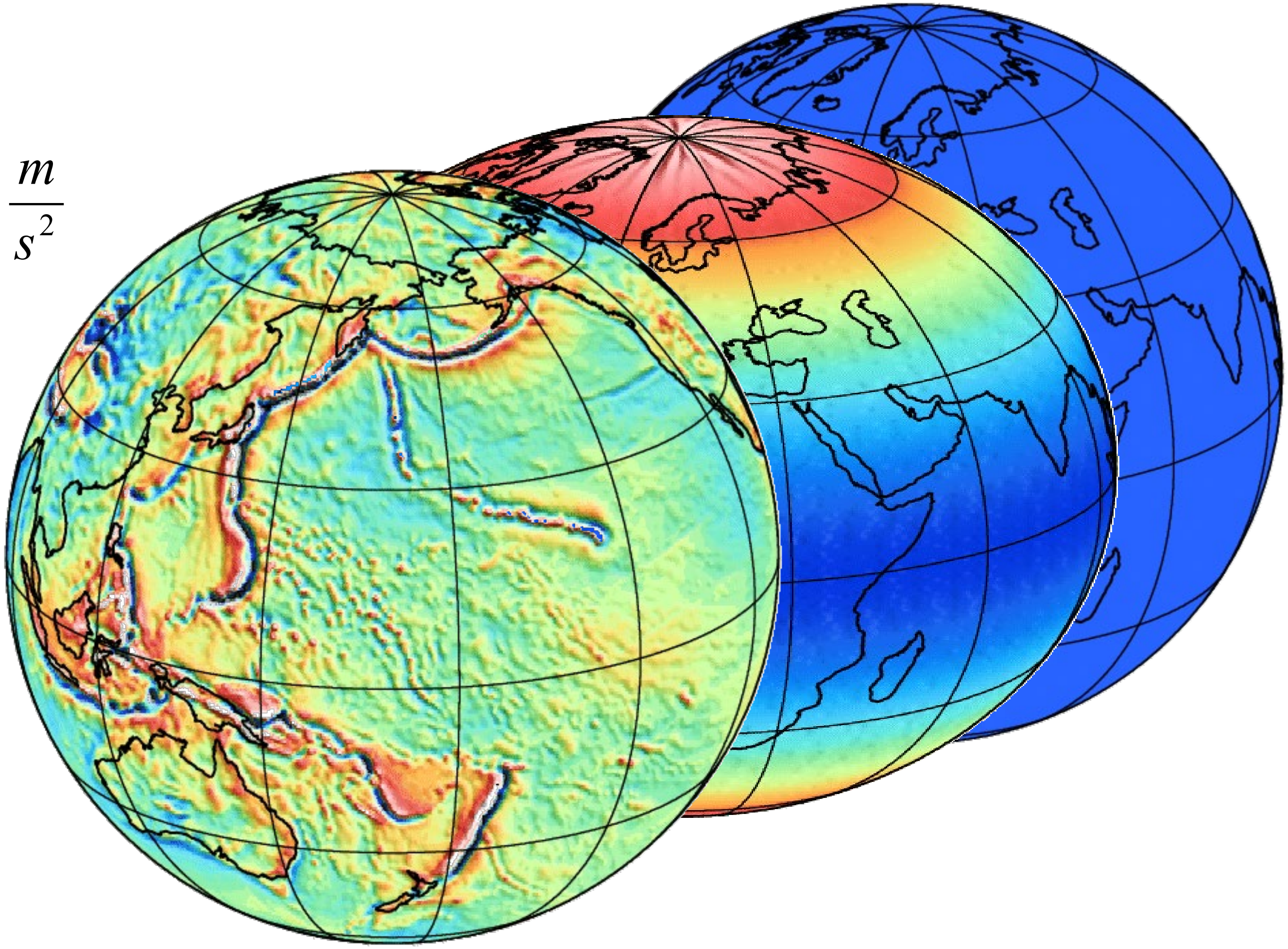
G3P

Earth's Gravity Field

Gravitational pull at the Earth's surface

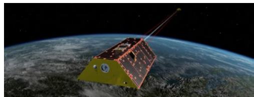
$$g = 9{,}78\frac{m}{s^2}\ldots 9{,}83\frac{m}{s^2}$$

$$\pm 0{,}0004\frac{m}{s^2}$$

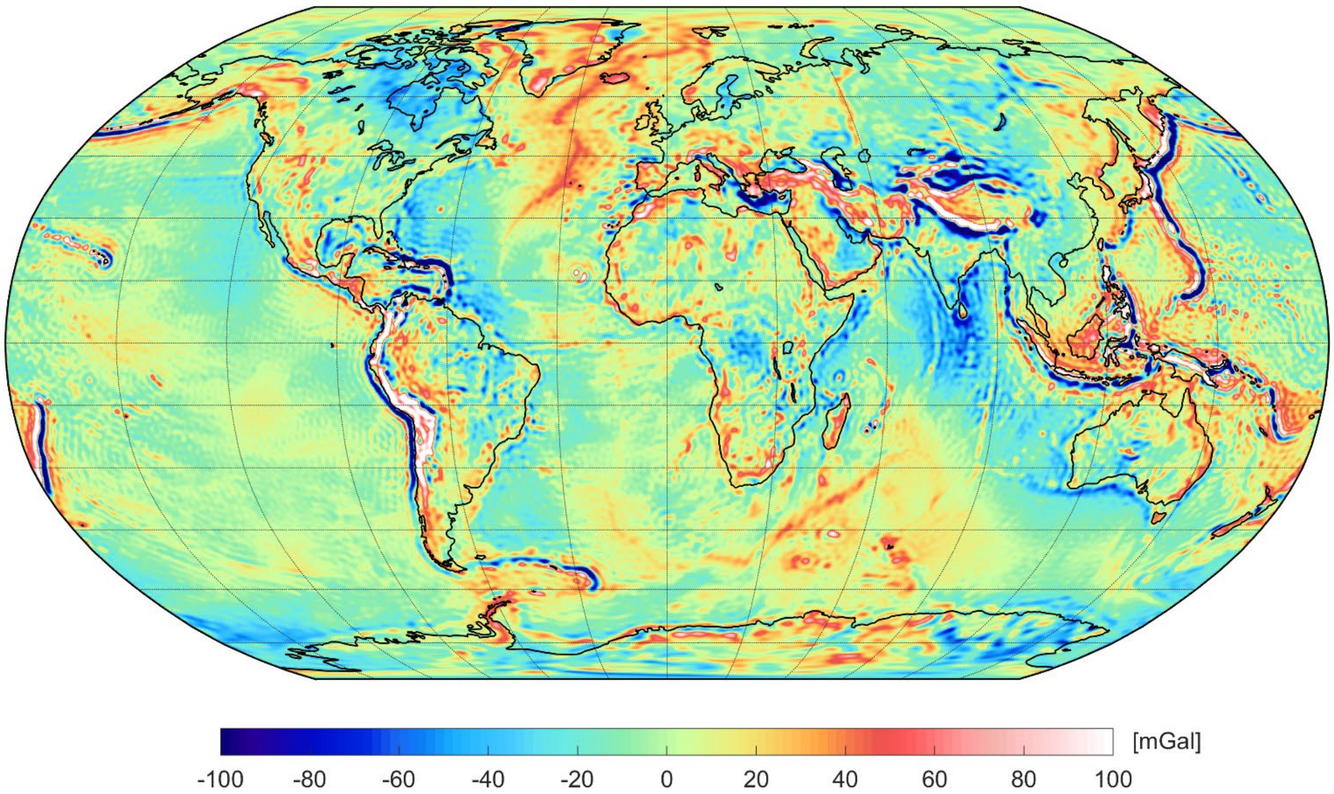


$$\left[1\,\mathrm{mGal} = 0{,}00001\frac{m}{s^2}\right]$$

1 millionth of the pull at the Earth's surface



Earth’s Gravity Field in March



$$\left[1\,\mathrm{mGal} = 0{,}00001\frac{m}{s^2}\right]$$

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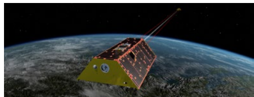
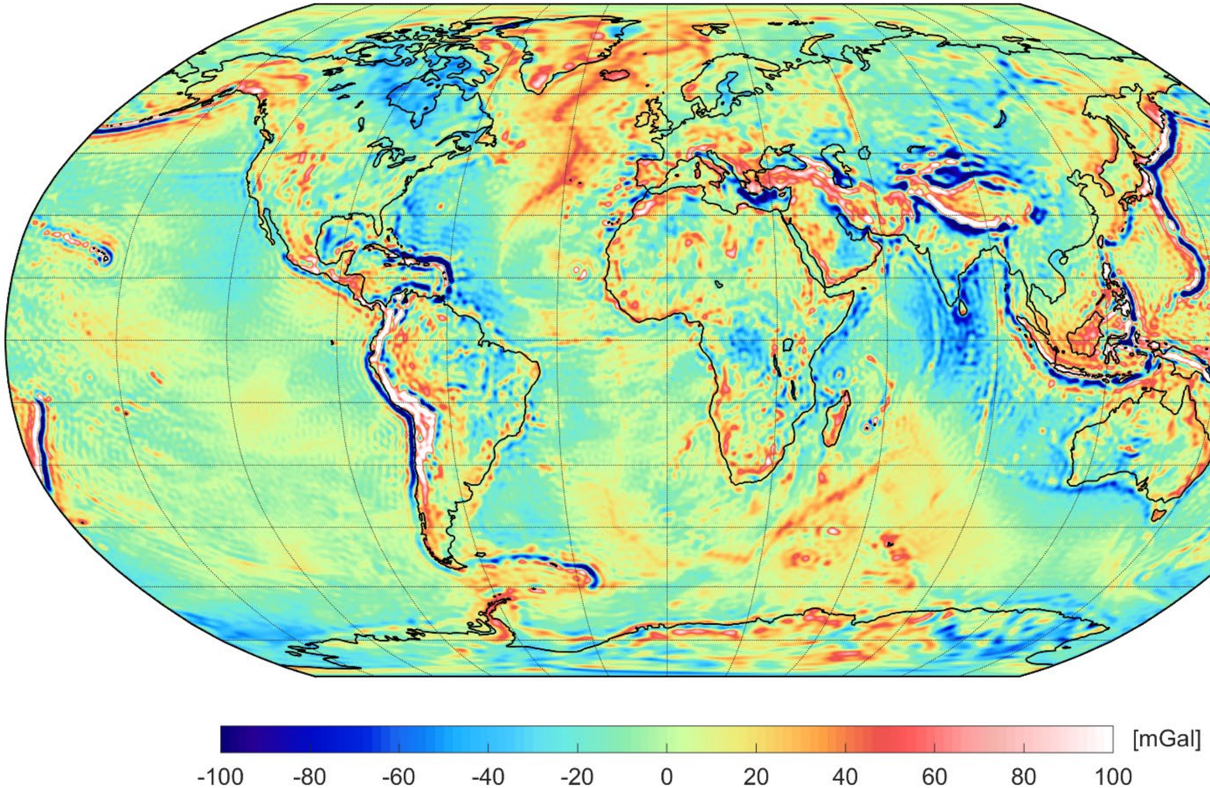


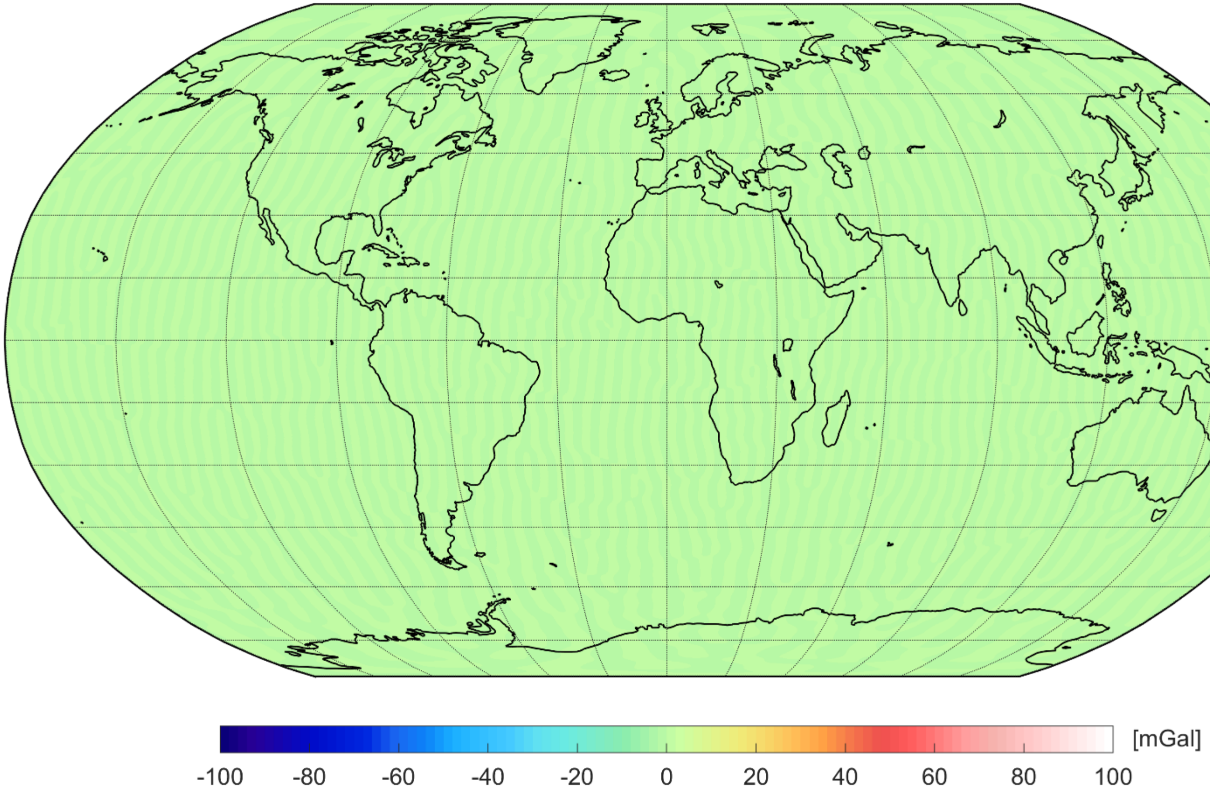
Earth’s Gravity Field in September



$$\left[1\,\text{mGal} = 0{,}00001 \frac{m}{s^2} \right]$$

1 millionth of the pull at the Earth‘s surface

September – March



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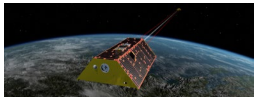

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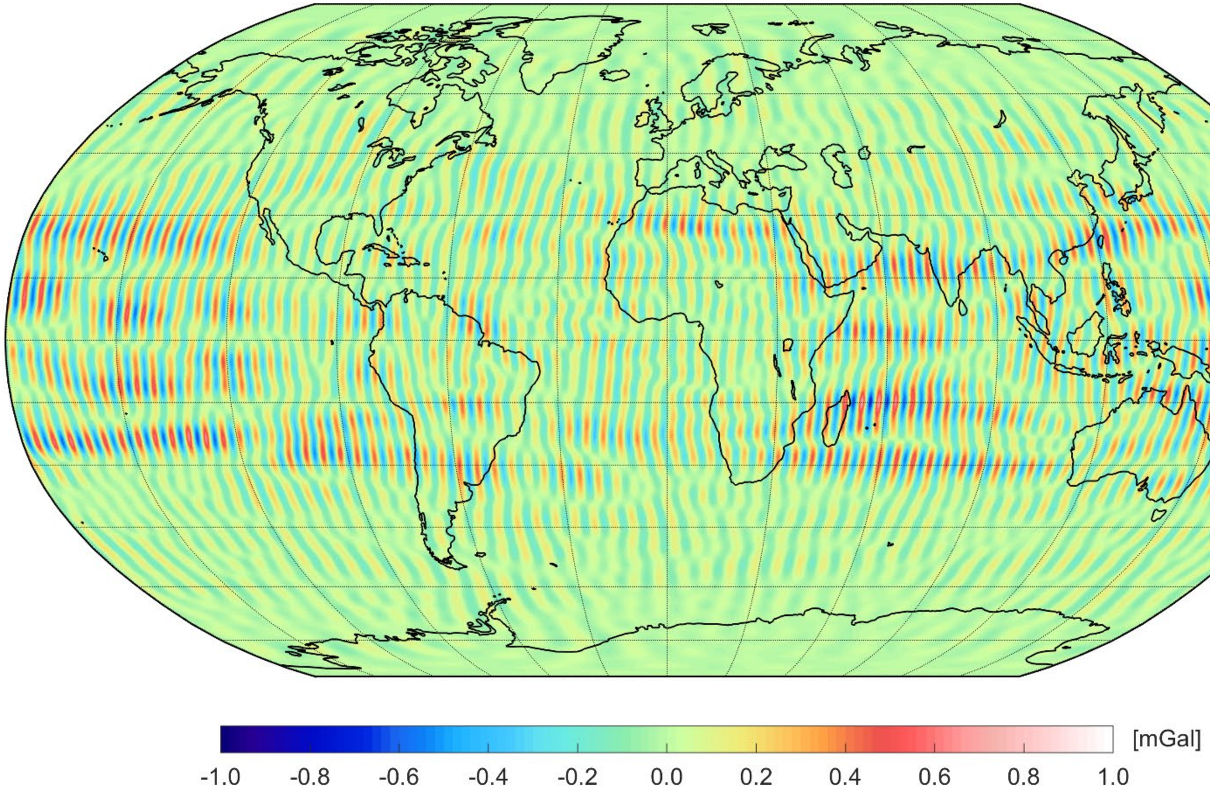

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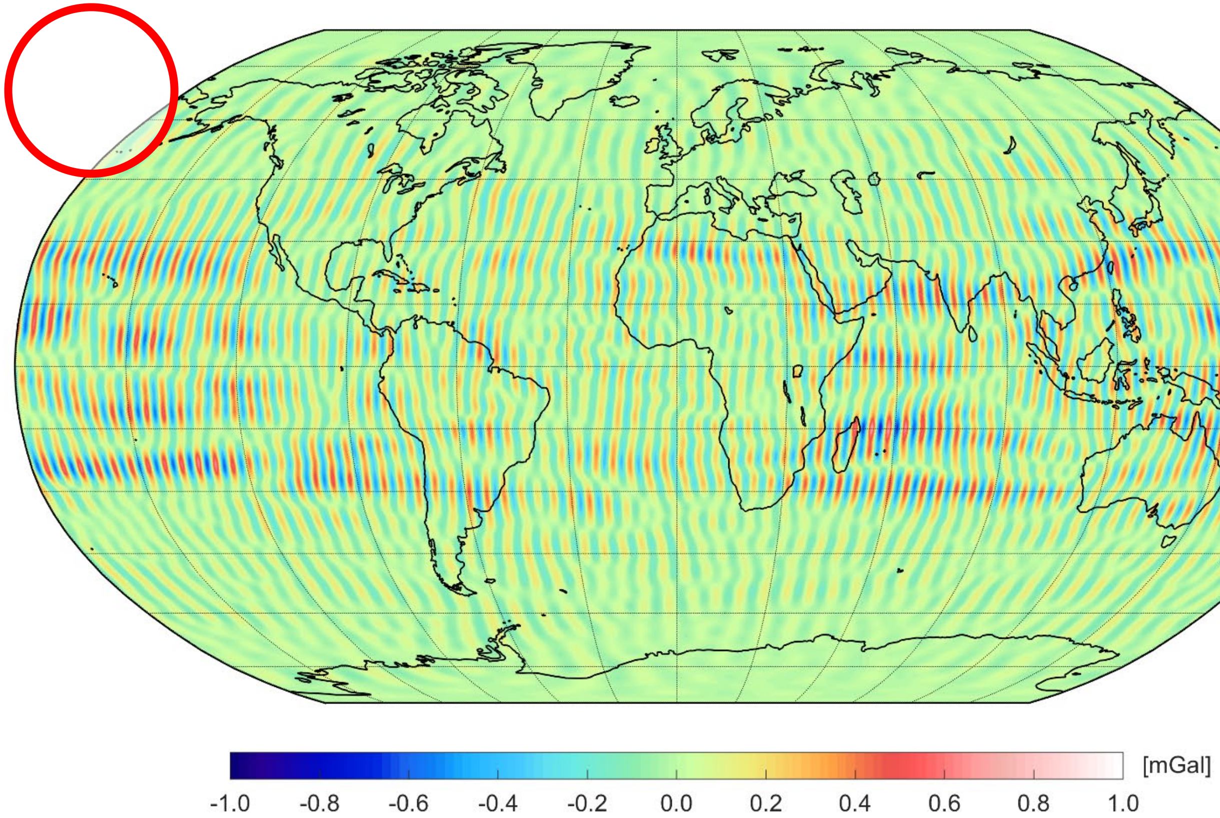

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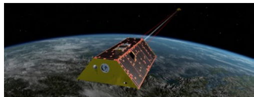

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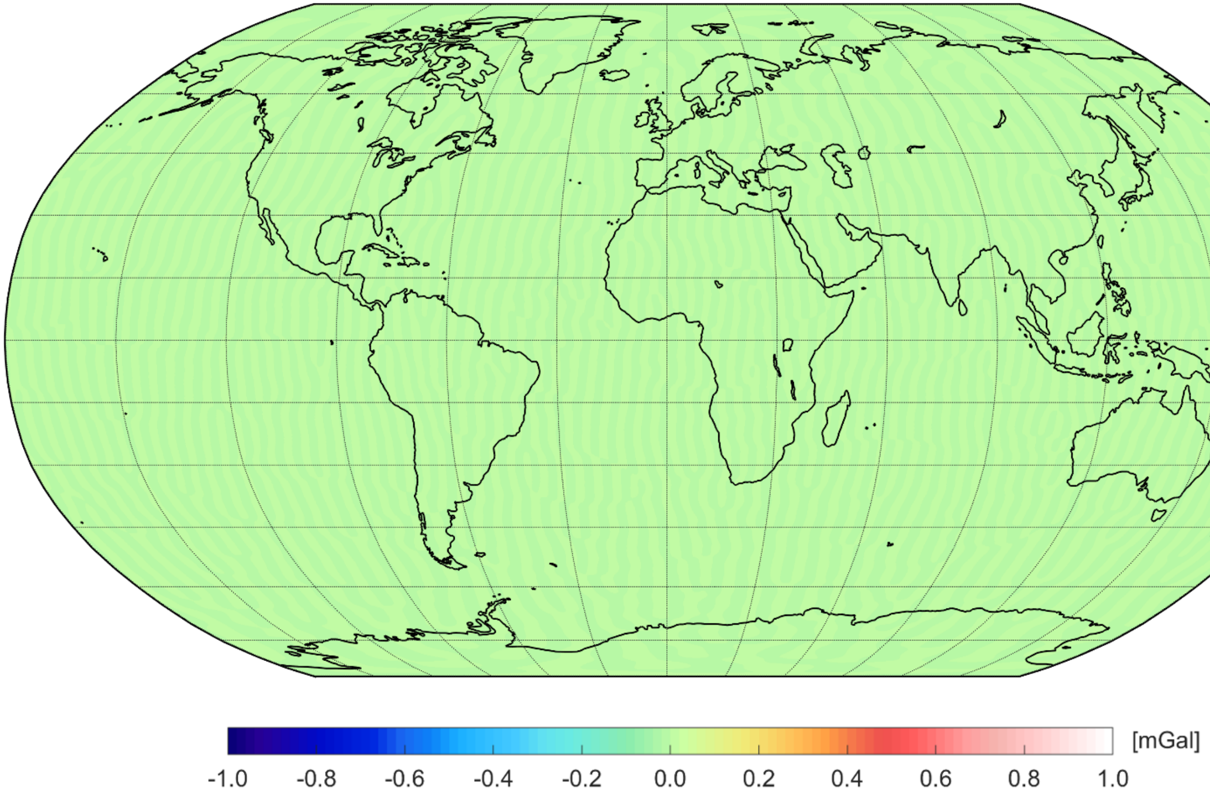

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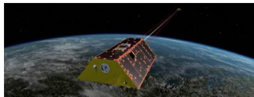

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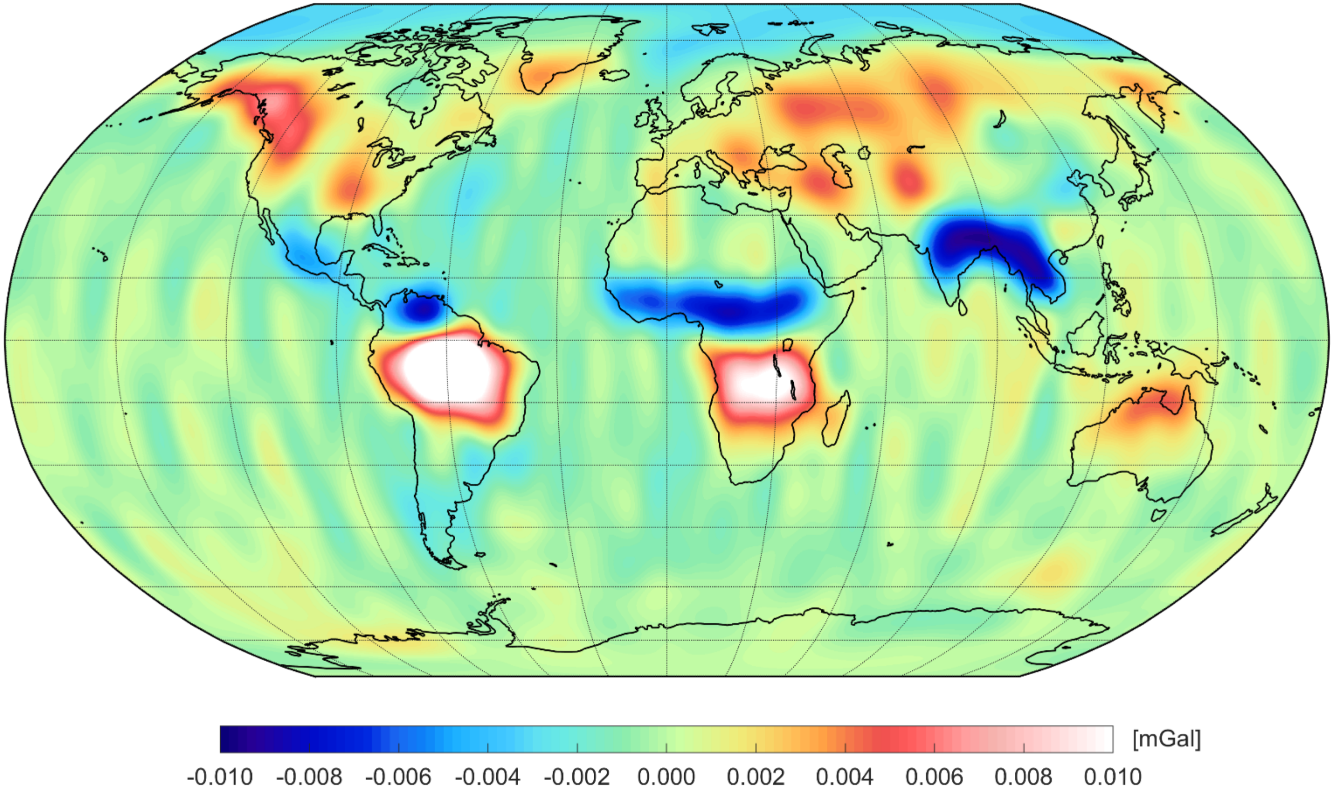

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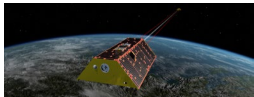
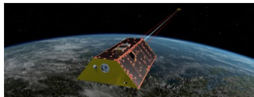
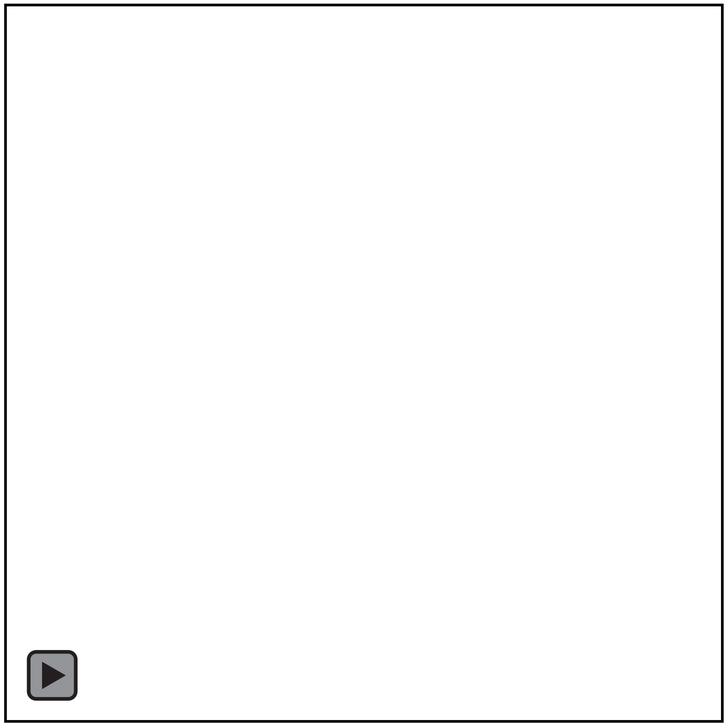
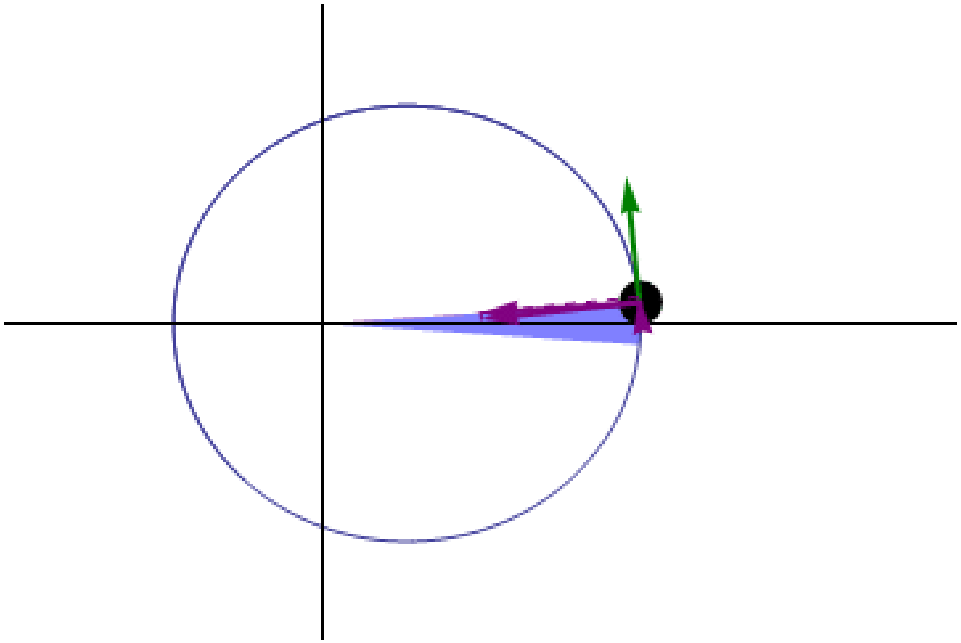


How do we measure these changes ?



From Newton to satellites …



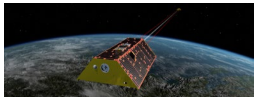


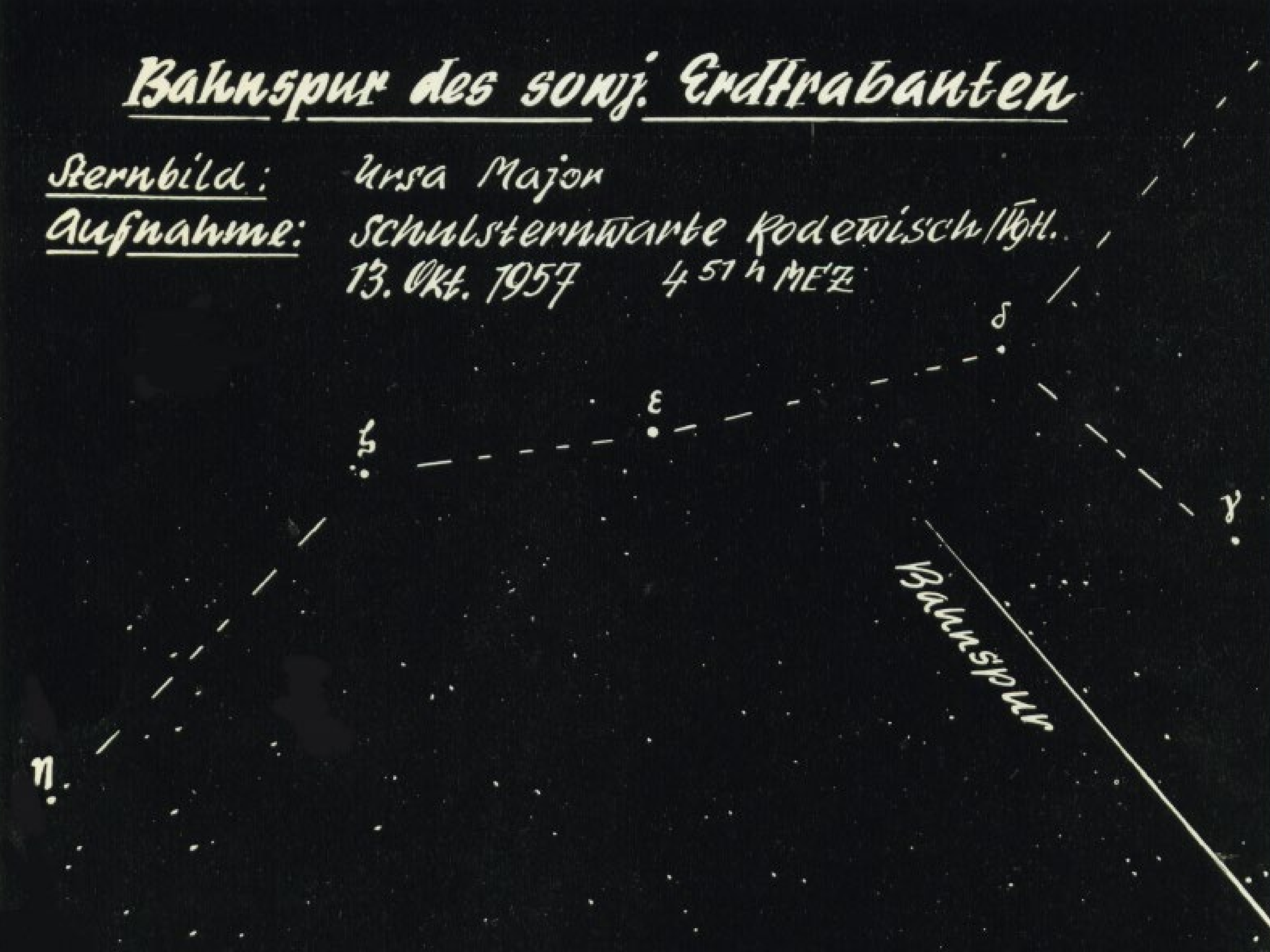
Satellites at a height of

200 – 500 km

Measuring the trajectory, or

- the velocity
- the acceleration




Bahnspur des sowj. Erdtrabanten
Sternbild: Ursa Major
Aufnahme: Schulsternwarte Rodewisch/Vgtl.
13. Okt. 1957 4 57 h MEZ
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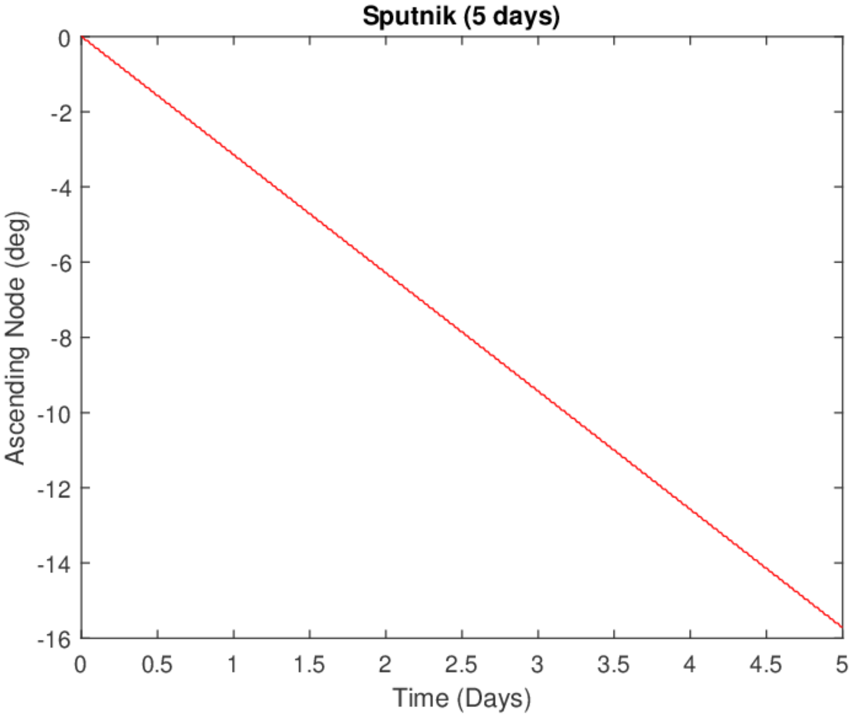
Bahnspur

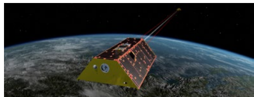
Orbit Perturbations



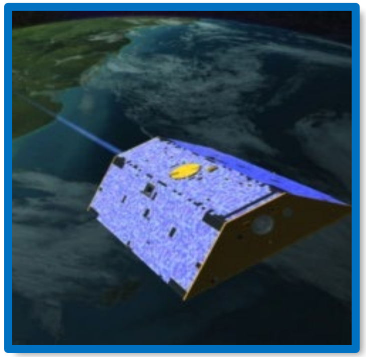
a: semi-major axis
e: numerical eccentricity
i: inclination
Ω: right ascension of ascending node
ω: argument of perigee
u_0: argument of latitude at t_0

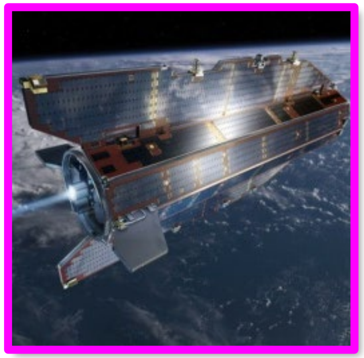
Orbit perturbations caused by the Earth's oblateness result in, e.g., a **secular precession** of the satellite's orbital plane.

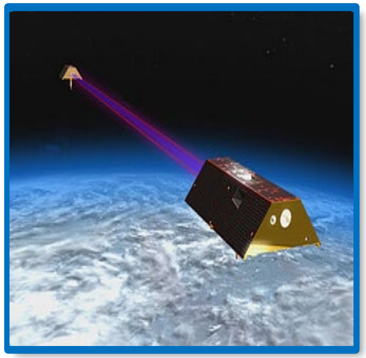
Observing satellites thus allowed it to determine the Earth's oblateness based on very short time spans of observed orbital arcs – revolutionizing the work of decades of terrestrial surveying.

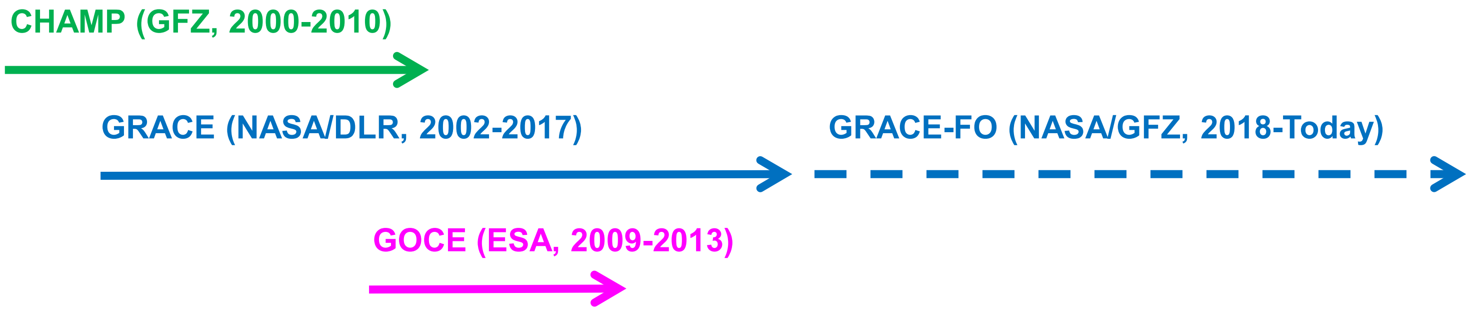


Dedicated Gravity Missions

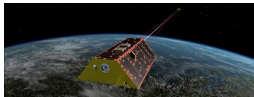






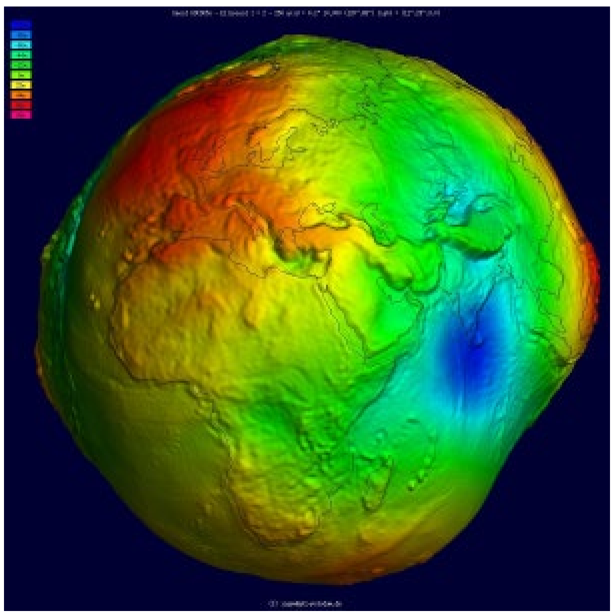


- High-low satellite-to-satellite tracking (hl-SST)
- Low-low satellite-to-satellite tracking (ll-SST)
- Satellite gravity gradiometry (SGG)



Modeling the Earth's Gravity Potential

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

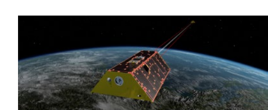


(geoid heights)

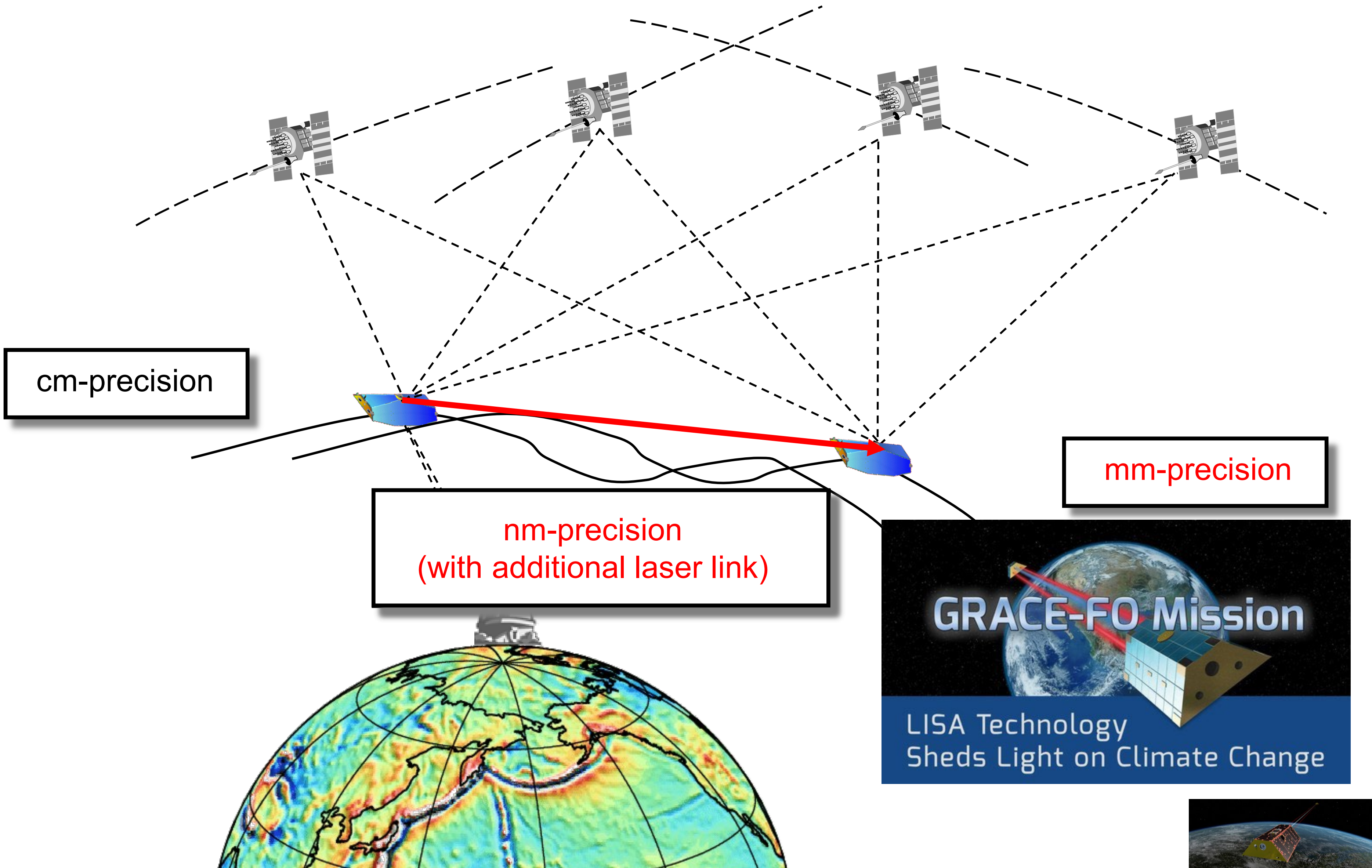
l_{max}	# Coeff.	λ [km]
20	441	1000
100	10 201	200
200	40 401	100
250	63 001	80

λ … spatial (half) wavelength

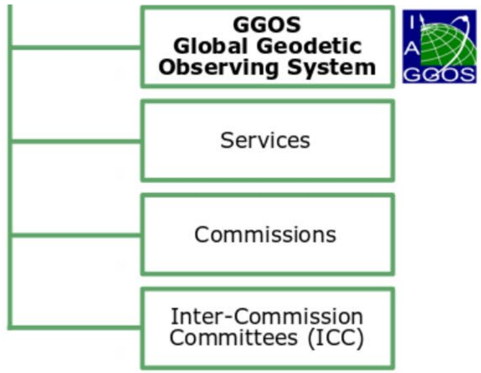
A spherical harmonic expansion up to a certain maximum degree l_{max} is most commonly used to represent the Earth's gravity potential.



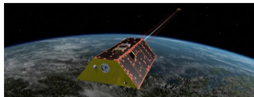
Measuring Satellite Motion



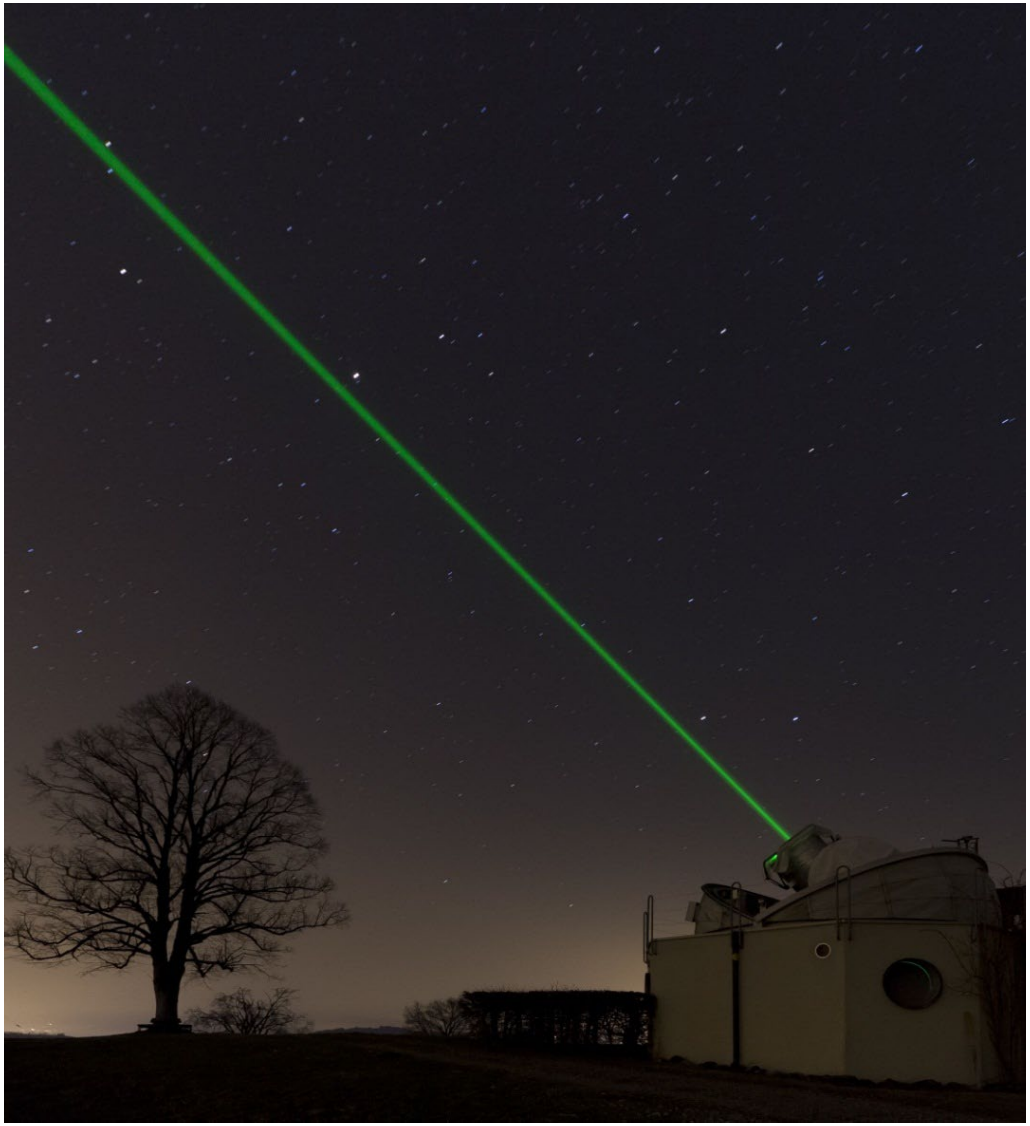
Global Geodetic Observing System (GGOS)



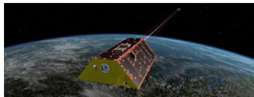
The **Global Geodetic Observing System** (GGOS) is the metrological basis for all global change research and for essential questions dealing with global deformation and mass exchange within the System Earth consisting of solid Earth, hydrosphere, atmosphere, and cryosphere (see https://ggos.org/).



Swiss Optical Ground Station (SwissOGS) and Geodynamics Observatory in Zimmerwald

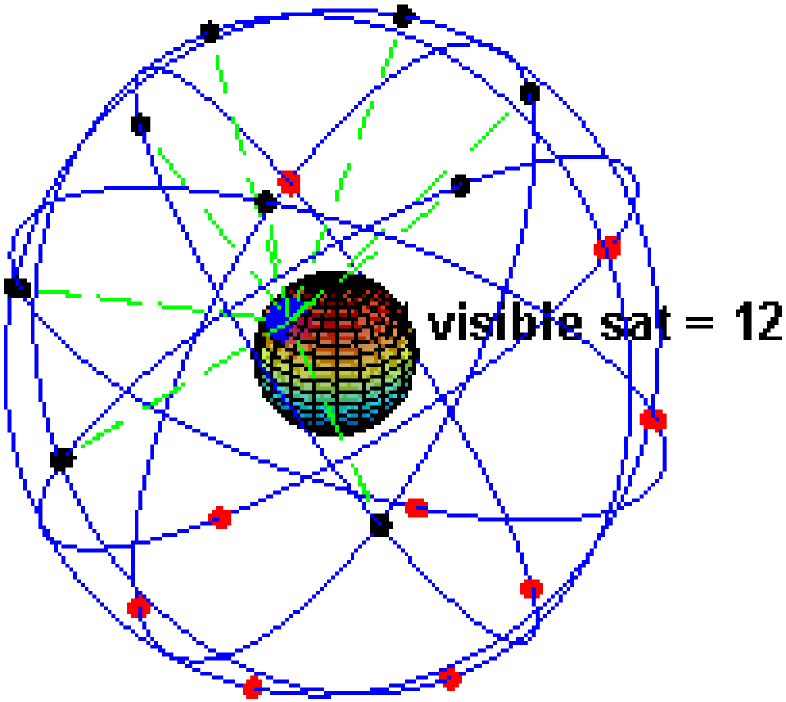


- Measuring distances to satellites equipped with retro-reflectors with **Satellite Laser Ranging (SLR)**
- Fully automated, 24/7 operations
- Telescope used for both SLR and optical astronomy
- One of the most productive SLR stations worldwide (and usually the most productive one on the Northern hemisphere).
- AGUZ member Prof. Lucia Kleint Vice-Director of SwissOGS since 2022.

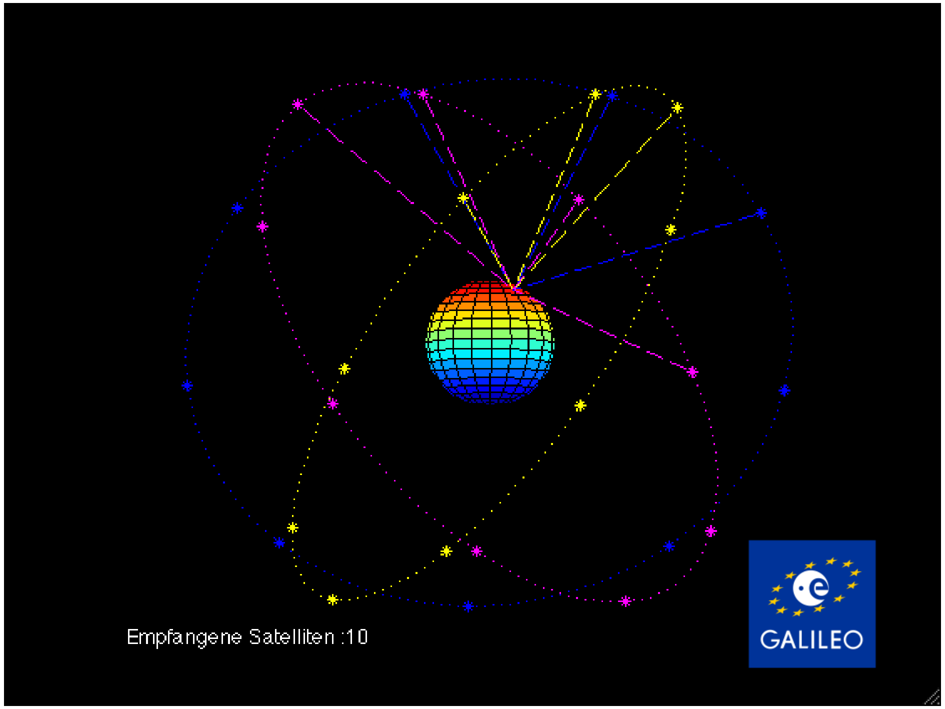


Global Navigation Satellite Systems (GNSS)

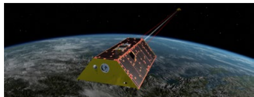
Global Positioning System (GPS)



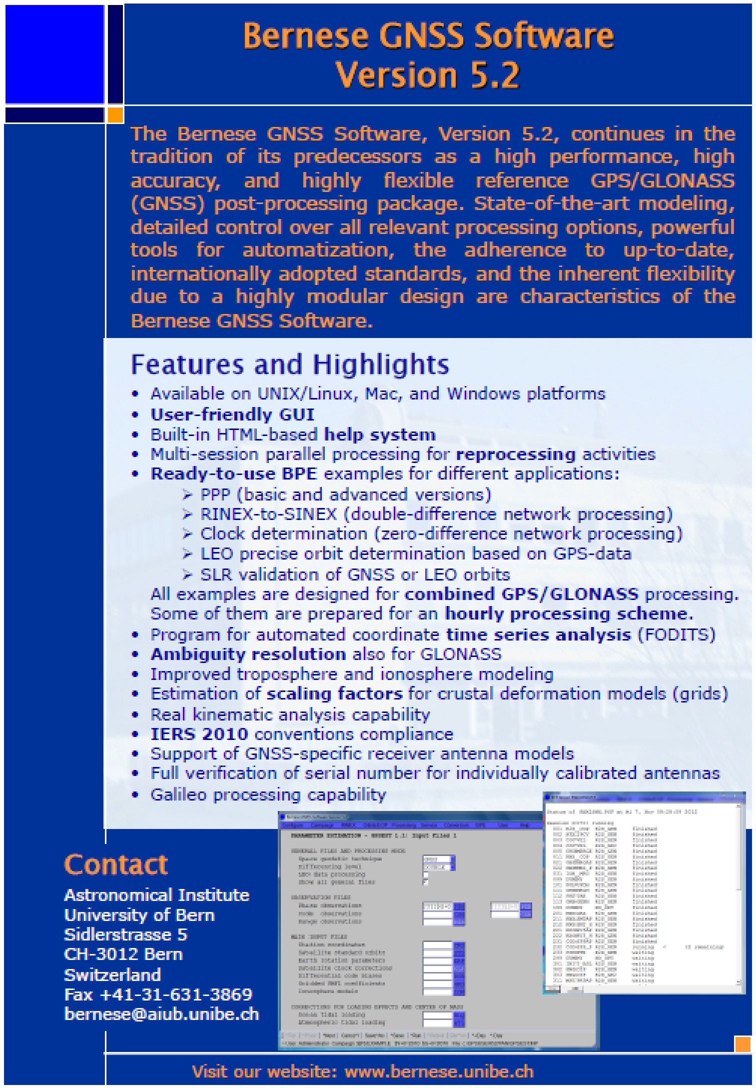
Galileo



Precise orbits for GPS, Galileo und further Global Navigation Satellite Systems (GNSS) are operationally computed for different product lines of the **International GNSS Service (IGS)** at various analysis centers.



Bernese GNSS Software



Bernese GNSS Software Version 5.2

The Bernese GNSS Software, Version 5.2, continues in the tradition of its predecessors as a high performance, high accuracy, and highly flexible reference GPS/GLONASS (GNSS) post-processing package. State-of-the-art modeling, detailed control over all relevant processing options, powerful tools for automatization, the adherence to up-to-date, internationally adopted standards, and the inherent flexibility due to a highly modular design are characteristics of the Bernese GNSS Software.

Features and Highlights

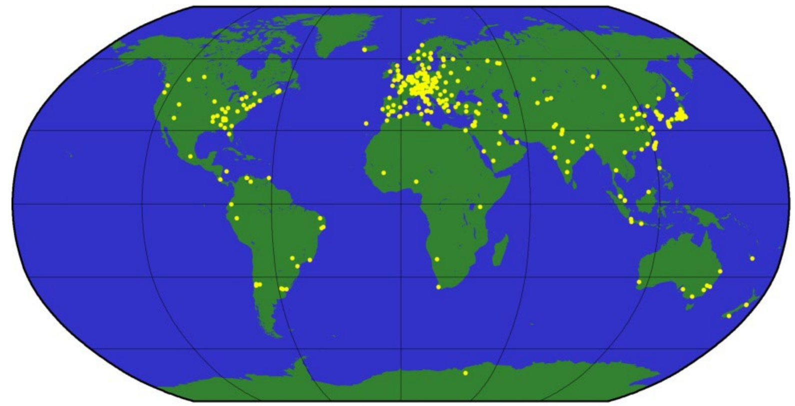
- Available on UNIX/Linux, Mac, and Windows platforms
- **User-friendly GUI**
- Built-in HTML-based **help system**
- Multi-session parallel processing for **reprocessing** activities
- **Ready-to-use BPE** examples for different applications:
  - PPP (basic and advanced versions)
  - RINEX-to-SINEX (double-difference network processing)
  - Clock determination (zero-difference network processing)
  - LEO precise orbit determination based on GPS-data
  - SLR validation of GNSS or LEO orbits

  All examples are designed for **combined GPS/GLONASS** processing. Some of them are prepared for an **hourly processing scheme**.
- Program for automated coordinate **time series analysis** (FODITS)
- **Ambiguity resolution** also for GLONASS
- Improved troposphere and ionosphere modeling
- Estimation of **scaling factors** for crustal deformation models (grids)
- Real kinematic analysis capability
- **IERS 2010** conventions compliance
- Support of GNSS-specific receiver antenna models
- Full verification of serial number for individually calibrated antennas
- Galileo processing capability

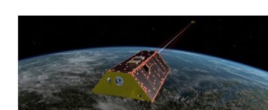
Contact

Astronomical Institute
University of Bern
Sidlerstrasse 5
CH-3012 Bern
Switzerland
Fax +41-31-631-3869
bernese@aiub.unibe.ch

Visit our website: www.bernese.unibe.ch



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 **800 institutions** worldwide.



Modeling Satellite Motion

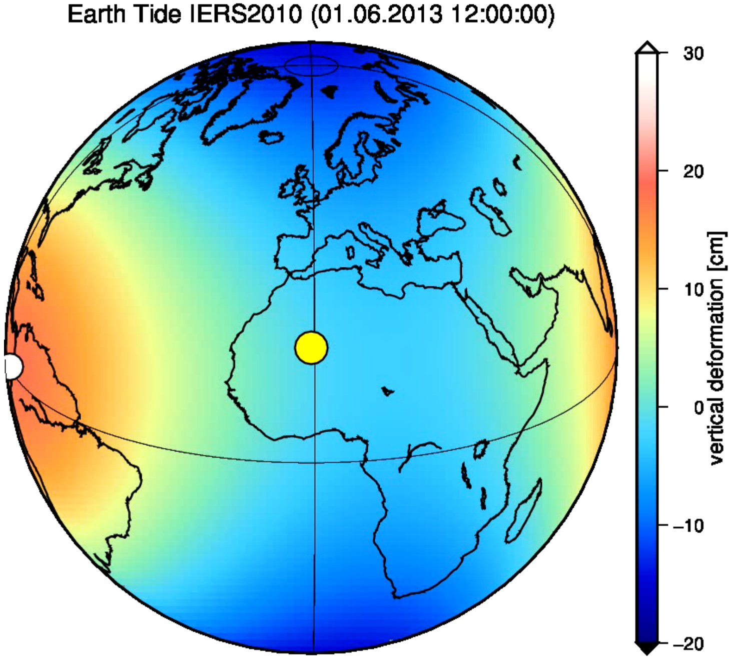
Equation of motion

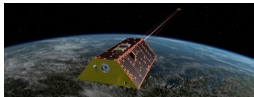
$$m \cdot \ddot{\vec{x}} = \vec{F}(t, \vec{x}, ...)$$

=> Numerical integration of the orbit

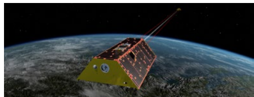
Force modeling:

- 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





GRACE Measurement Principle



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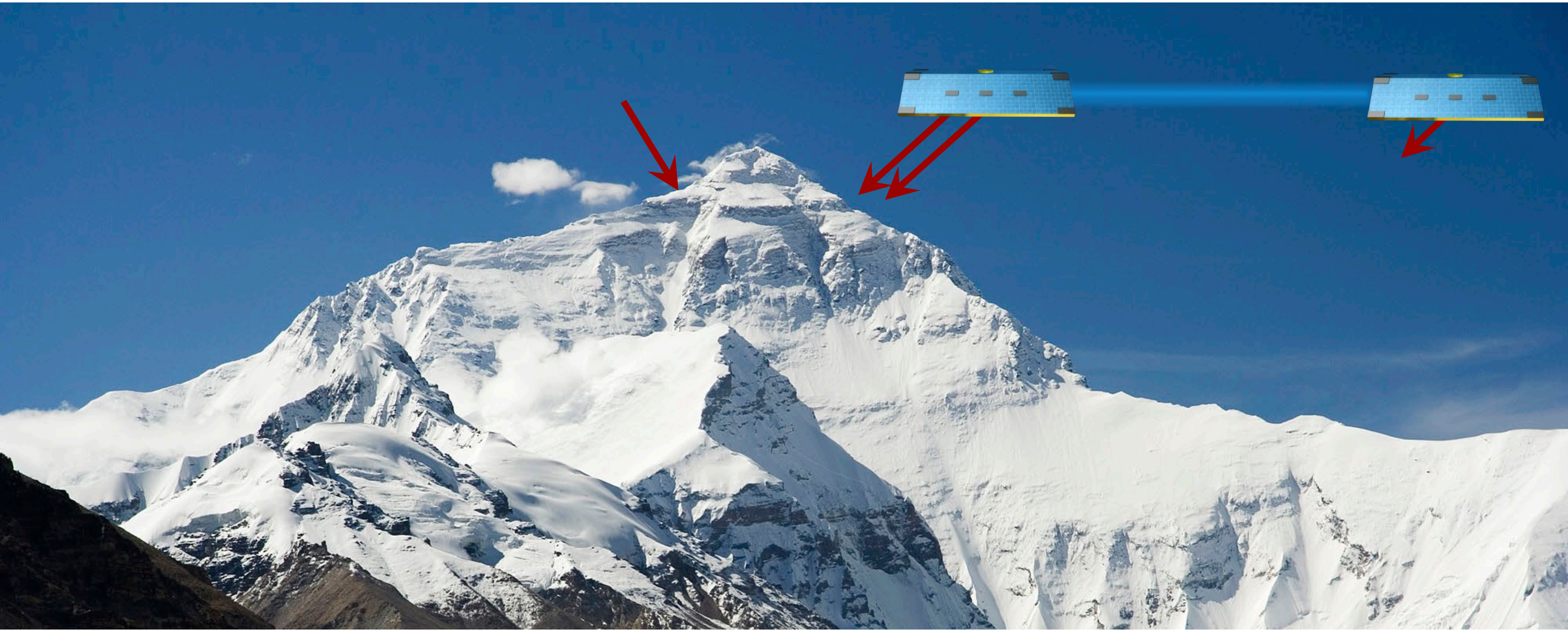

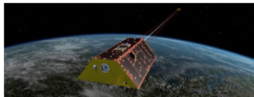

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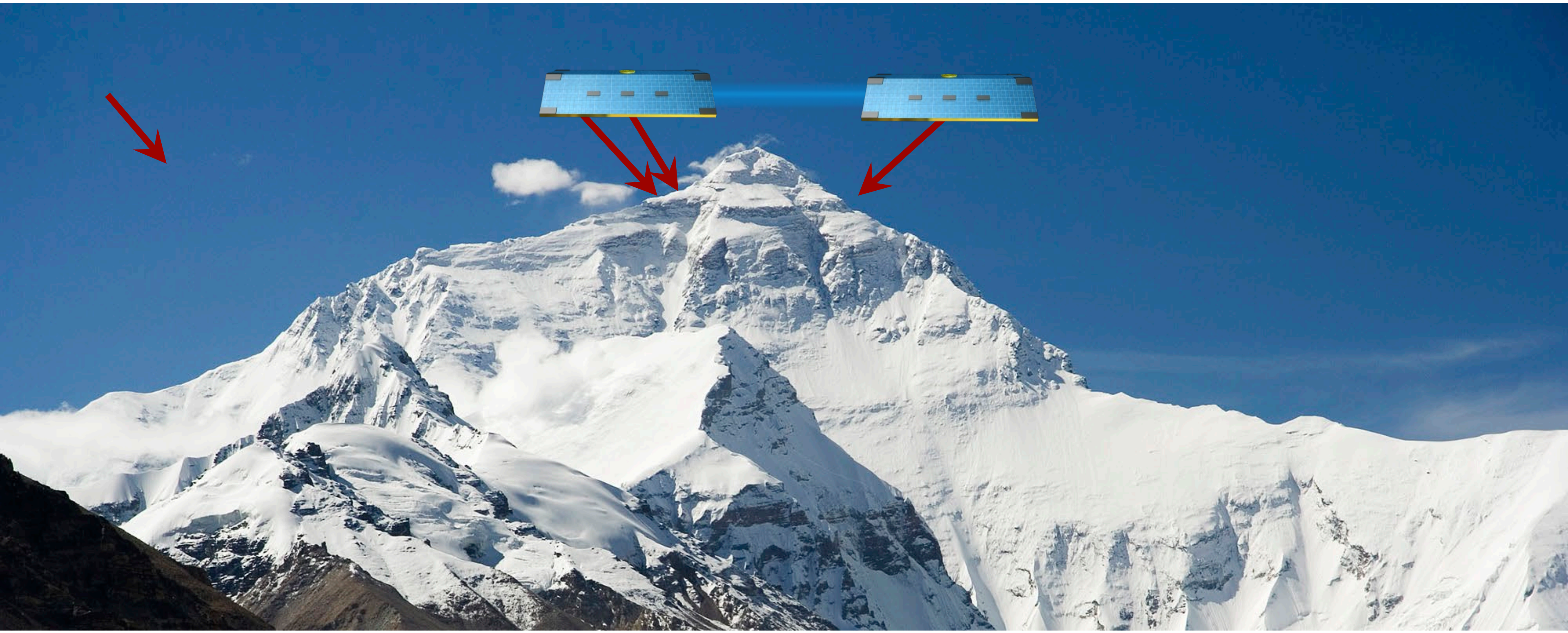
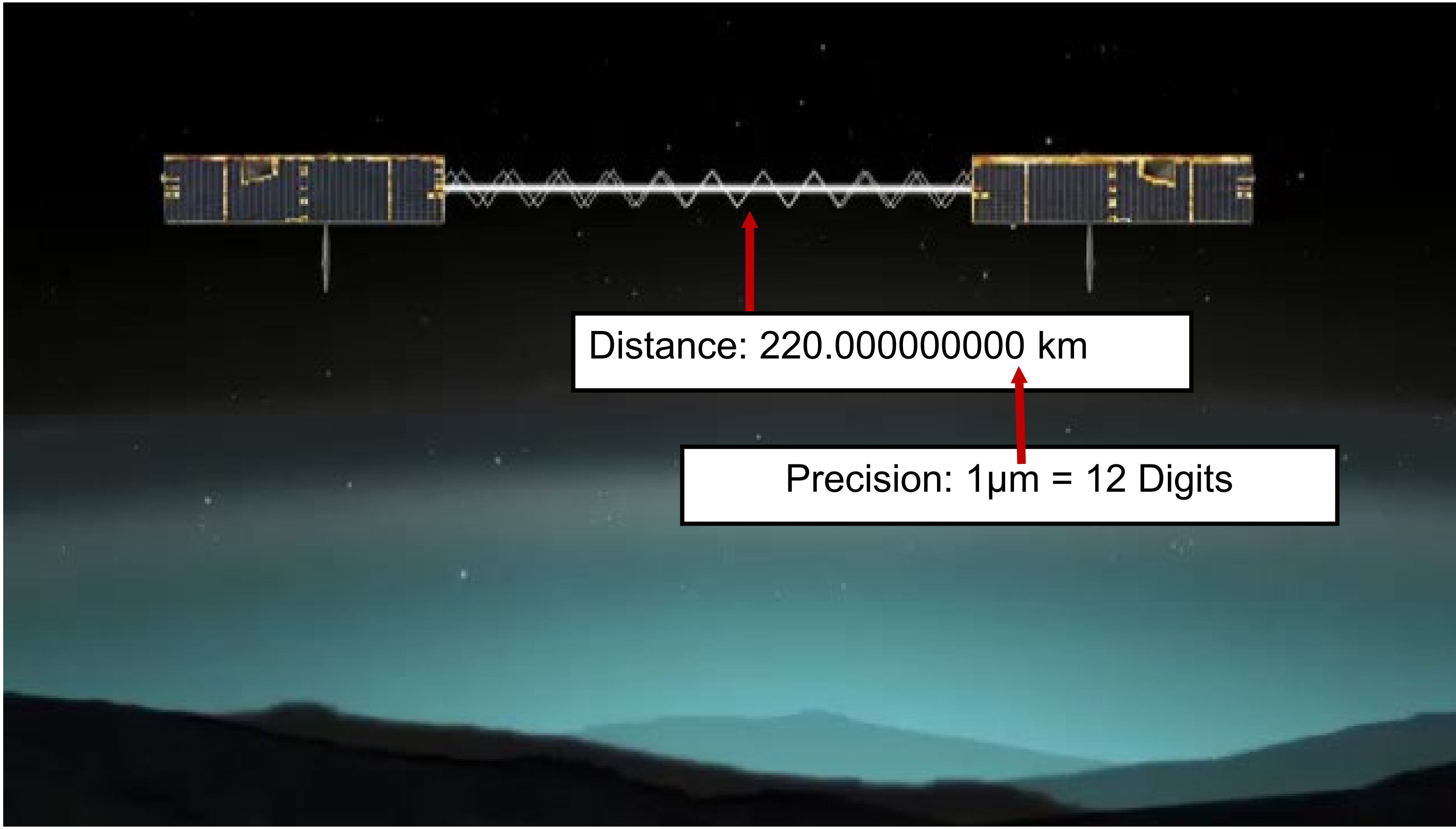
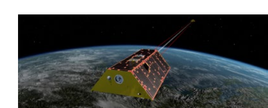


GRACE Measurement Principle

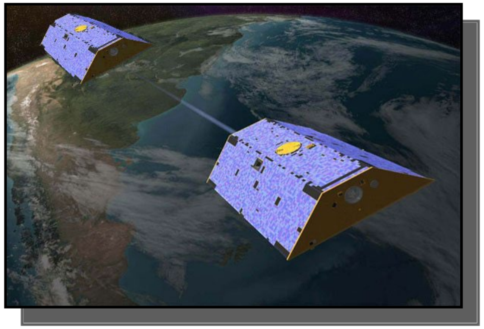


Terrestrial Water Storage (TWS) variations:

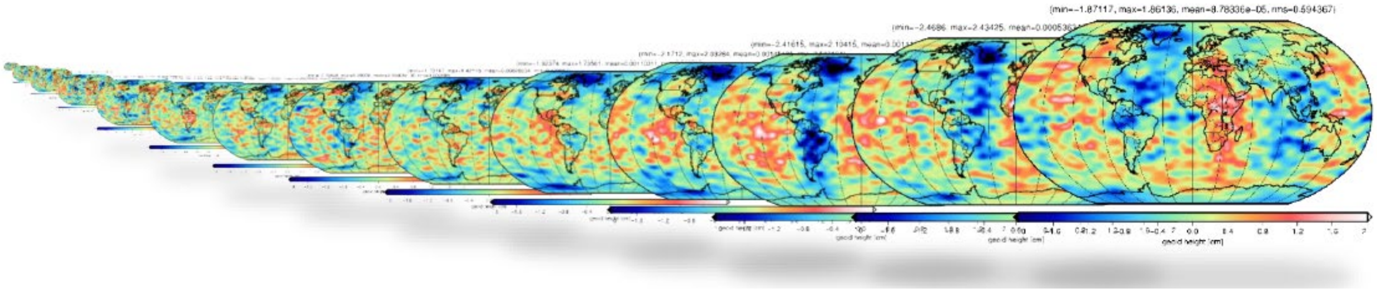
Estimation from GRACE and GRACE-FO data.



Challenging Data Processing (Level 2)

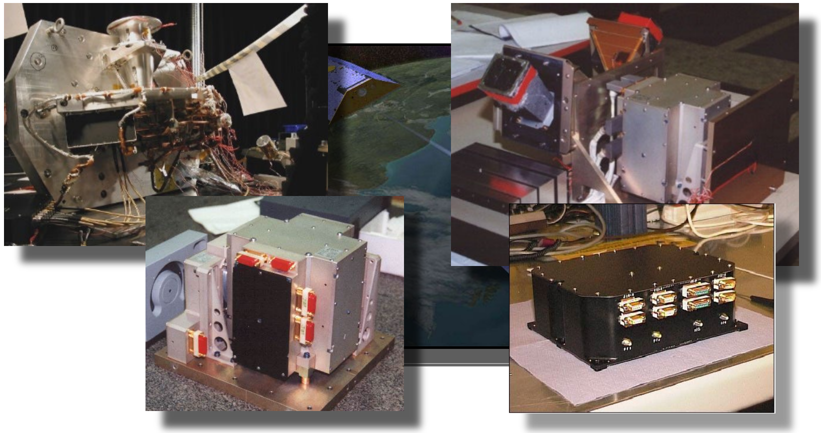


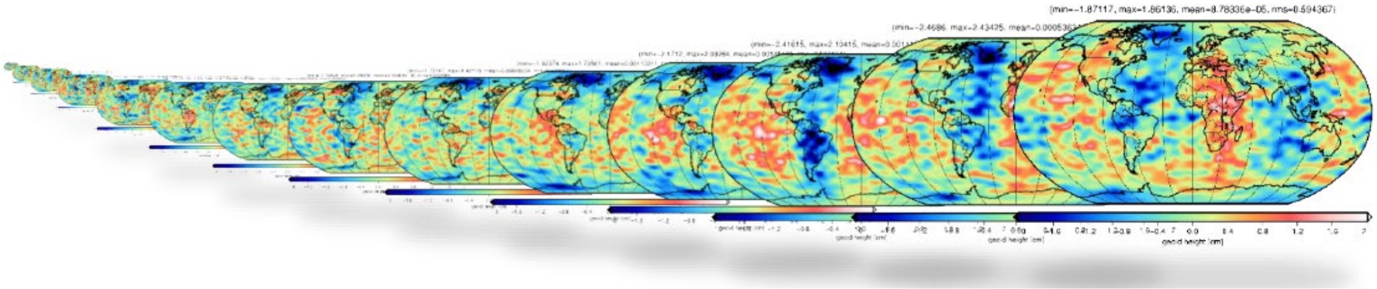
- Process GRACE/GRACE-FO data to a time series of monthly gravity field solutions
- Processing is challenging



Challenging Data Processing (Level 2)

- Process GRACE/GRACE-FO data to
  a time series of monthly gravity field solutions
- Processing is challenging
  - Interaction of multiple instruments





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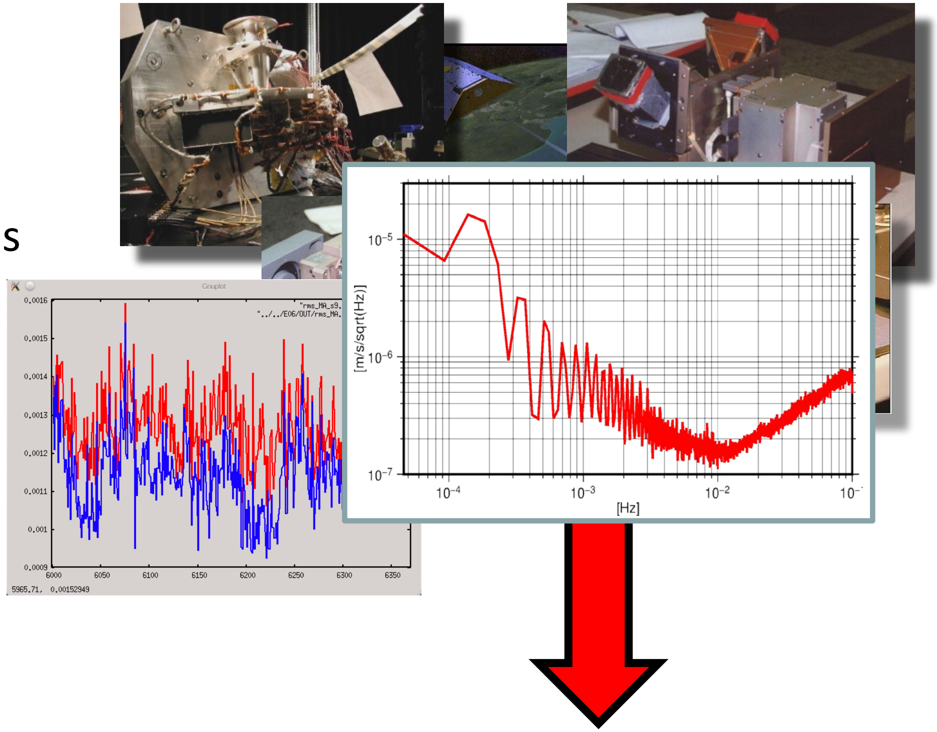
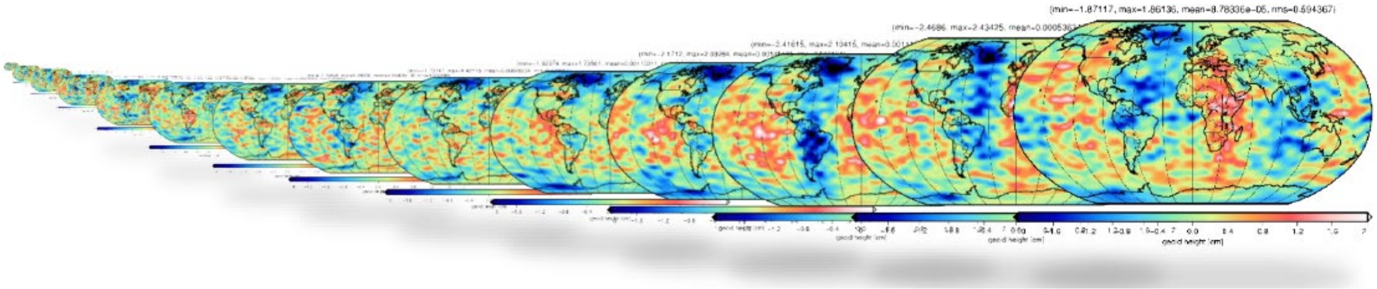
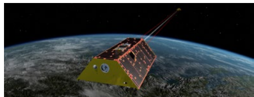


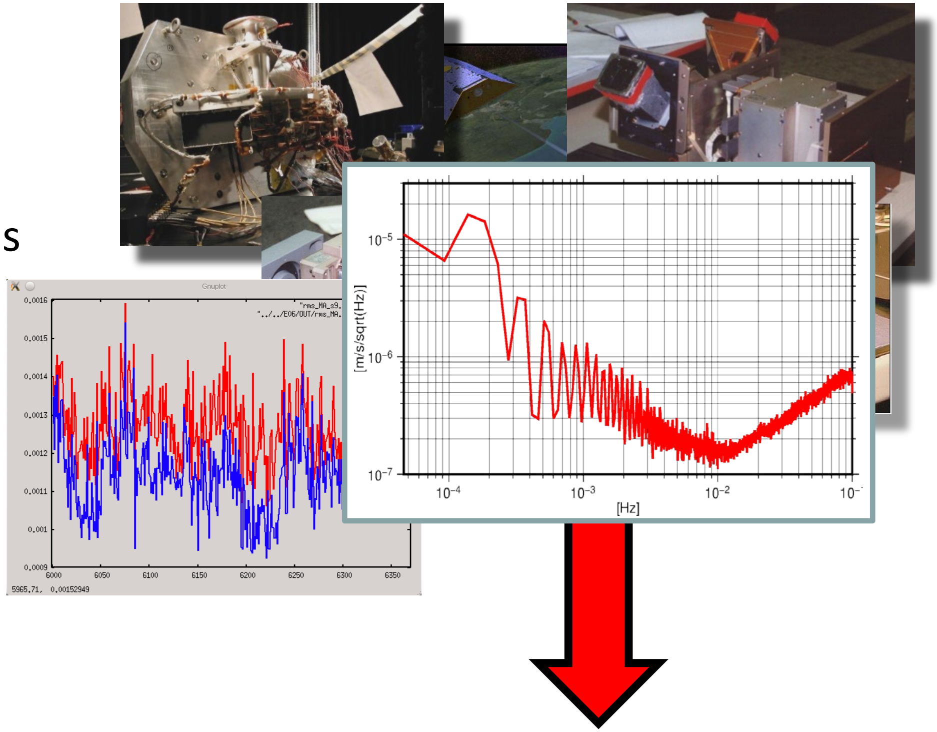
- Process GRACE/GRACE-FO data to
  a time series of monthly gravity field solutions
- Processing is challenging
  - Interaction of multiple instruments
  - Different noise characteristics

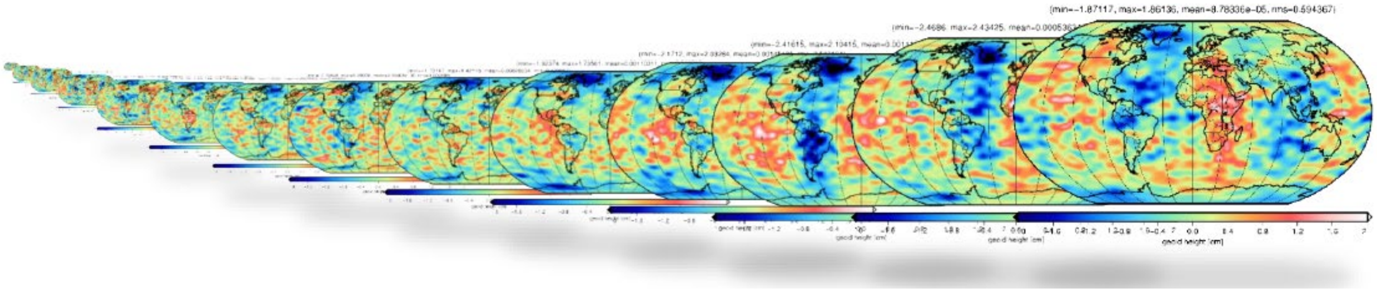


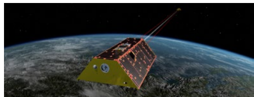


Challenging Data Processing (Level 2)

- Process GRACE/GRACE-FO data to a time series of monthly gravity field solutions
- Processing is challenging
  - Interaction of multiple instruments
  - Different noise characteristics
  - Environmental disturbances

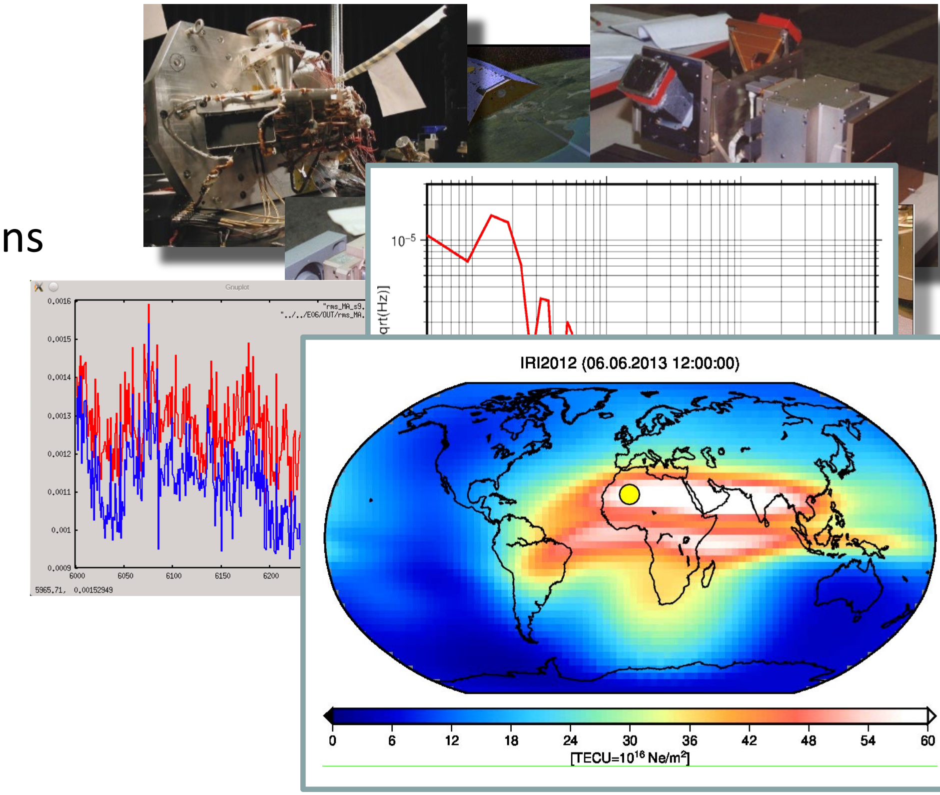


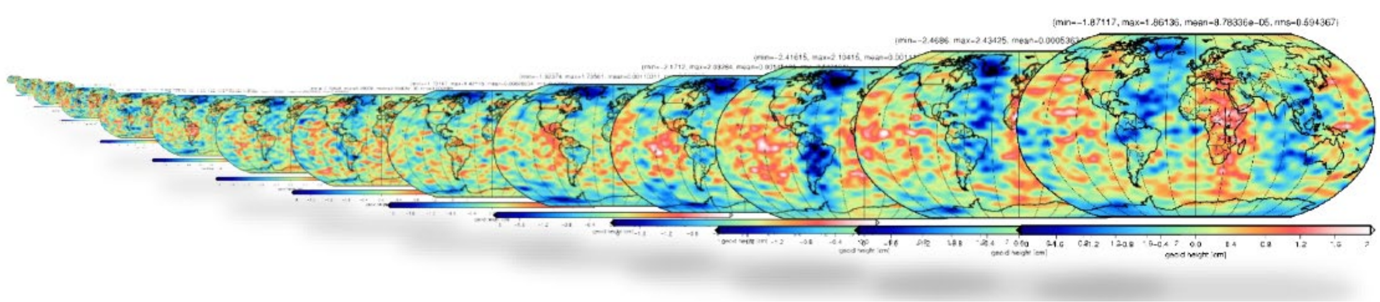




Challenging Data Processing (Level 2)

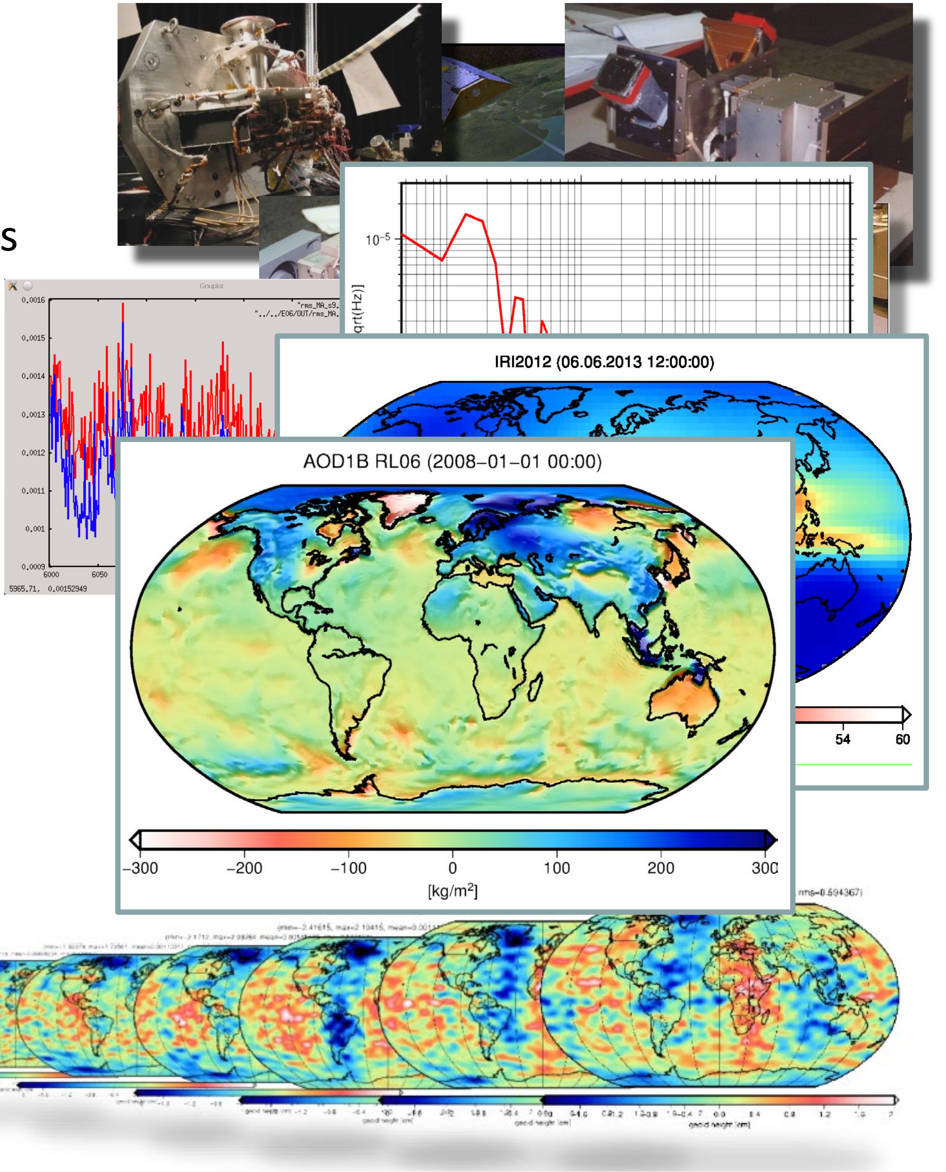
- Process GRACE/GRACE-FO data to
  a time series of monthly gravity field solutions
- Processing is challenging
  - Interaction of multiple instruments
  - Different noise characteristics
  - Environmental disturbances
    - Ionosphere

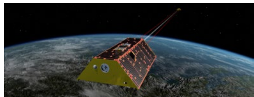




Challenging Data Processing (Level 2)

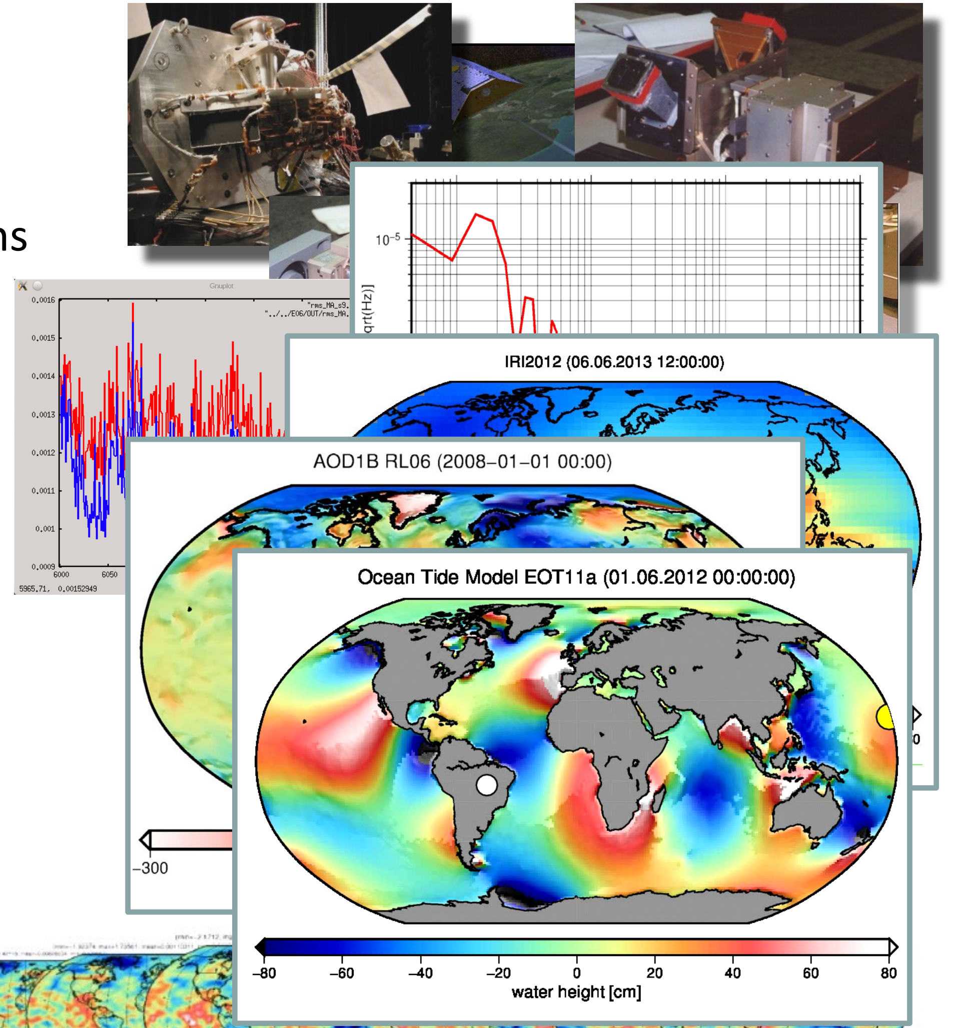
- Process GRACE/GRACE-FO data to
  a time series of monthly gravity field solutions
- Processing is challenging
  - Interaction of multiple instruments
  - Different noise characteristics
  - Environmental disturbances
    - Ionosphere
    - Atmosphere
    - Ocean currents

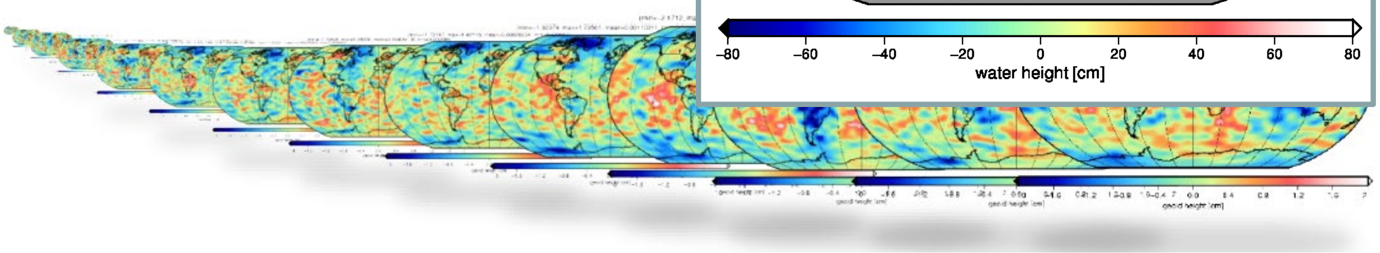


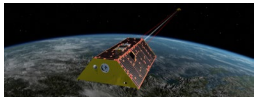


Challenging Data Processing (Level 2)

- Process GRACE/GRACE-FO 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

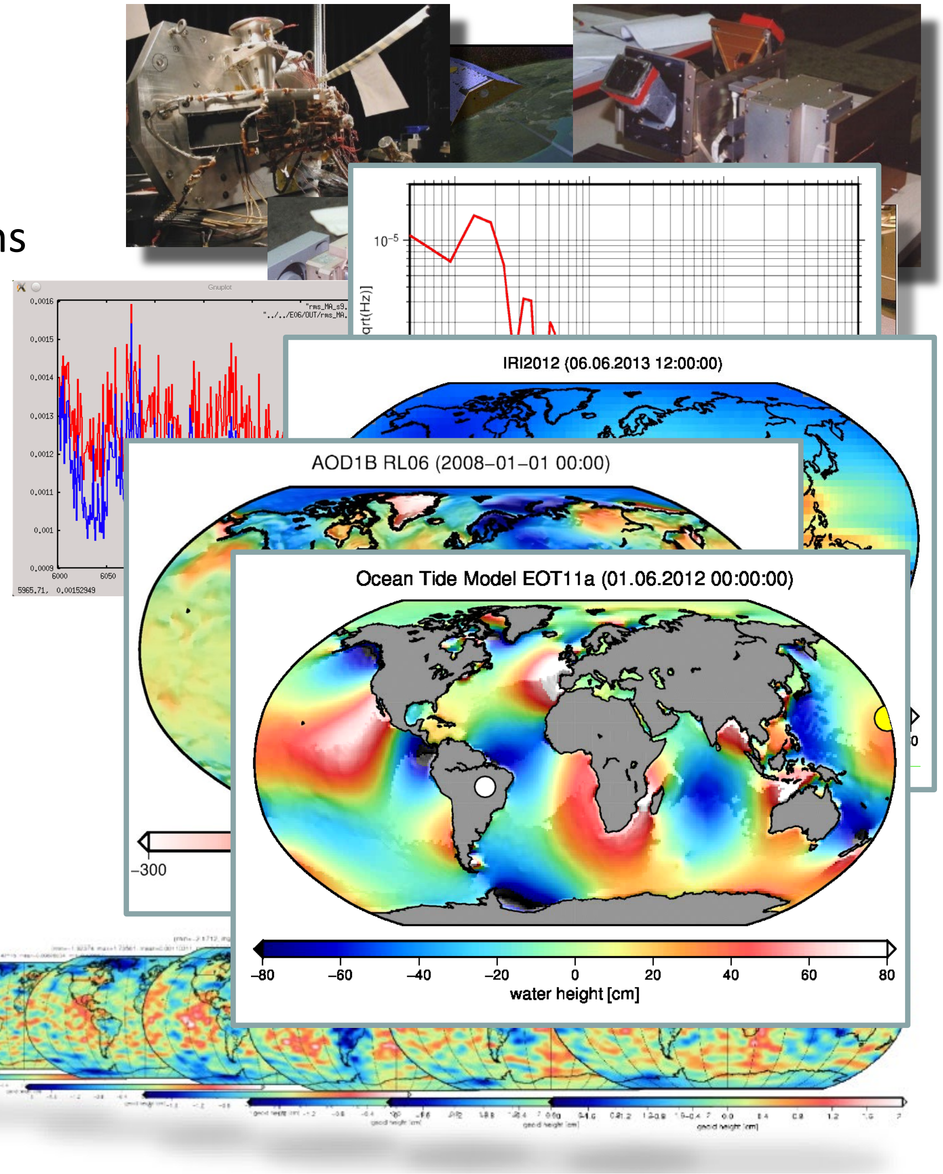


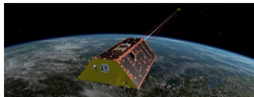




Challenging Data Processing (Level 2)

- Process GRACE/GRACE-FO 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

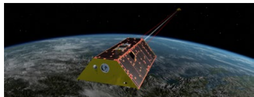




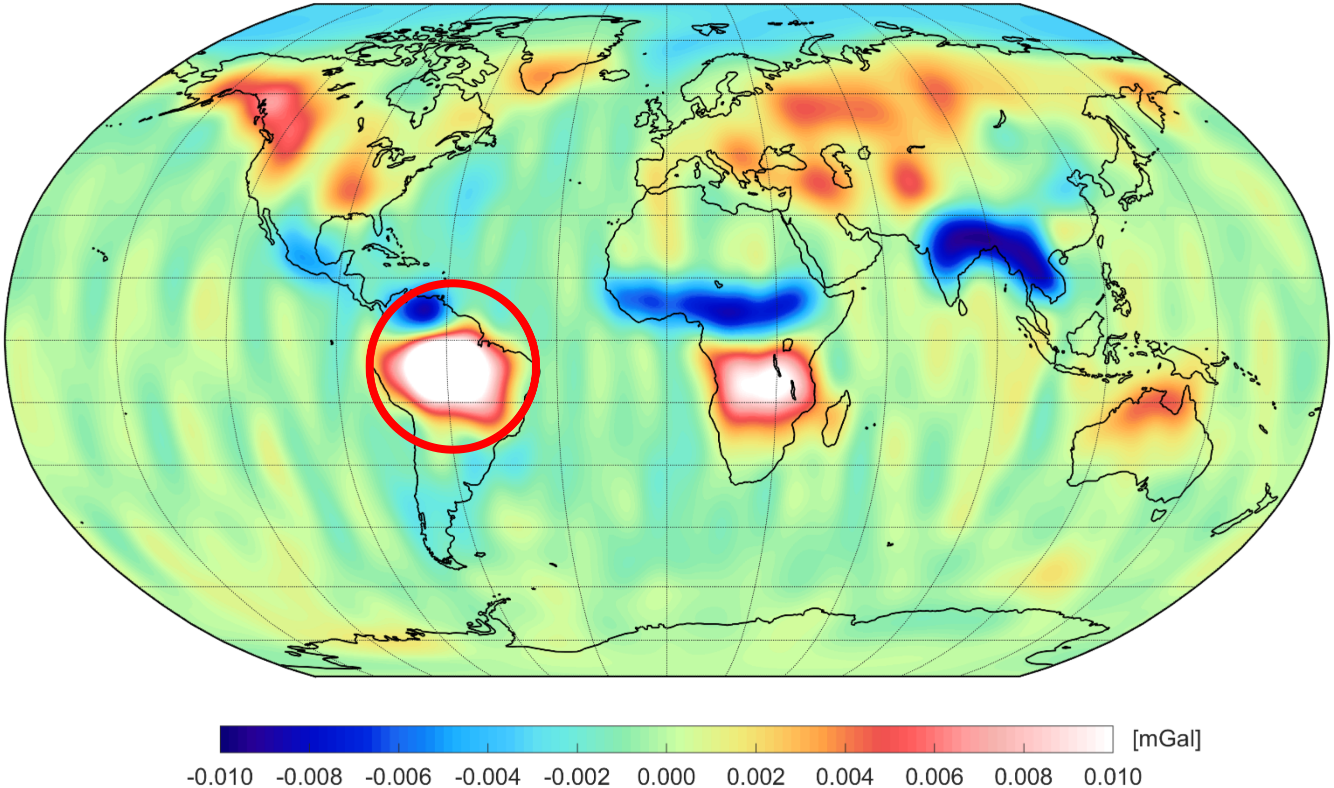
... and even more challenging with laser

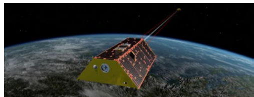
LISA: Laser Interferometer Space Antenna, launched in May 2018

Which changes can be measured ?

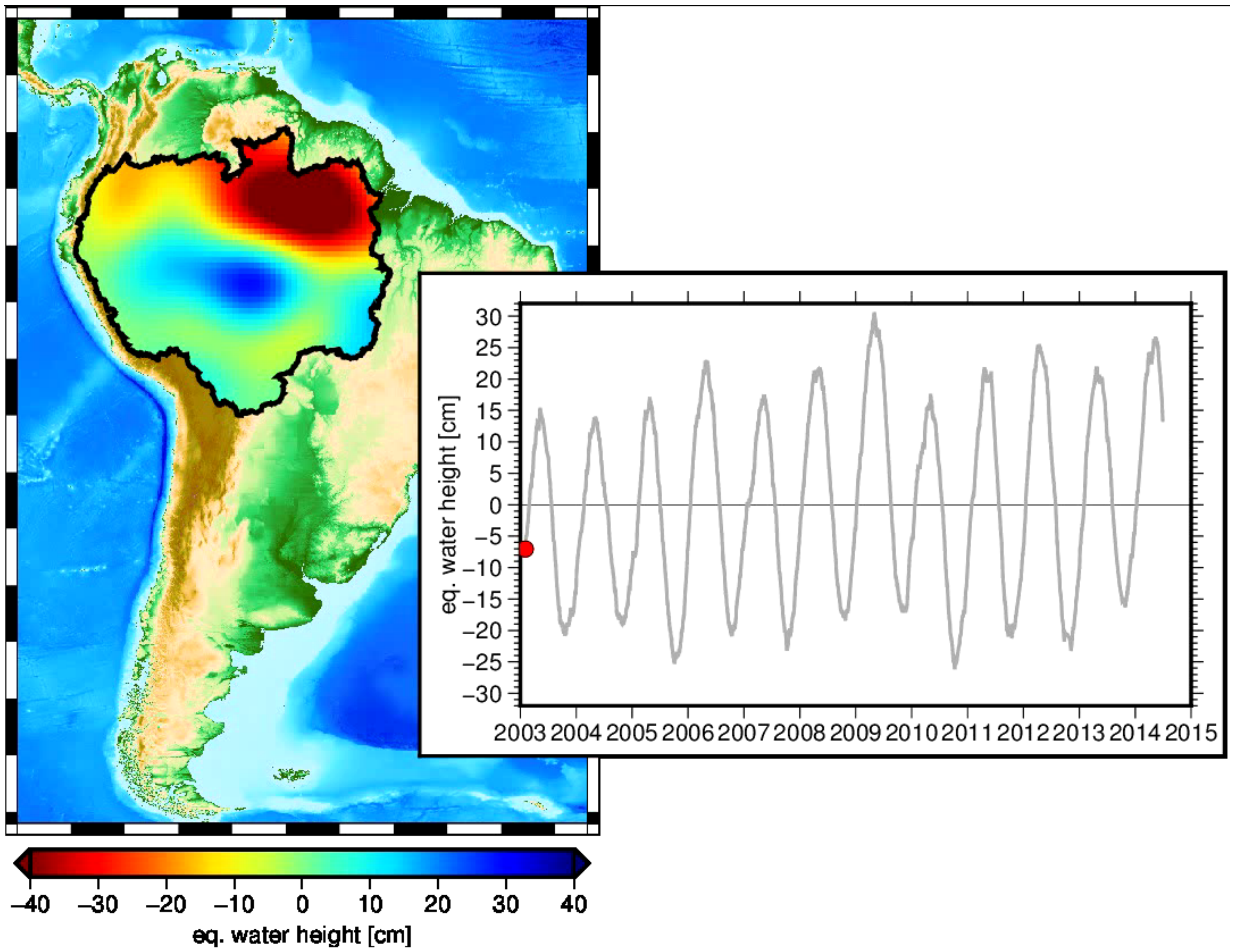


September – March



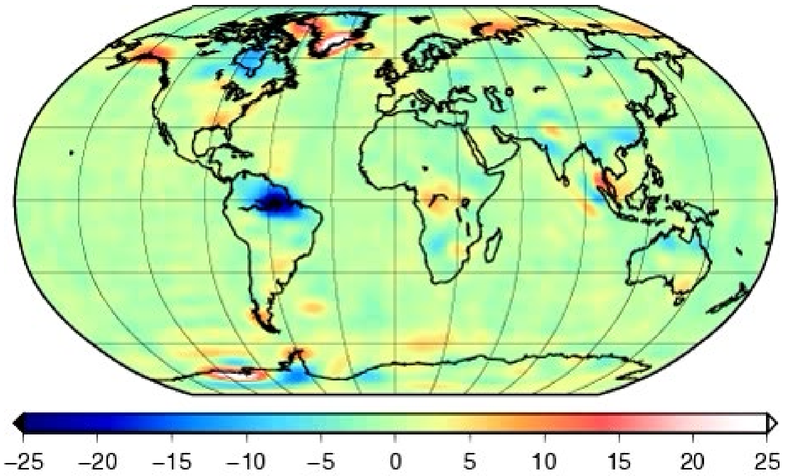


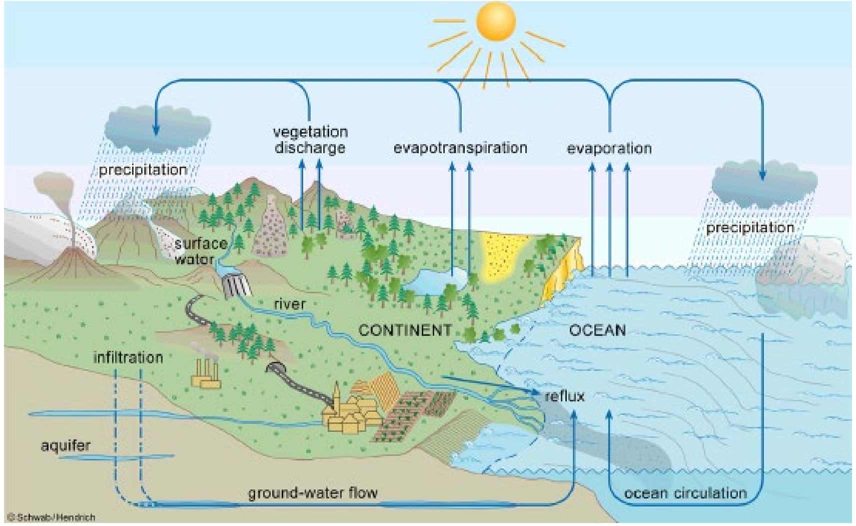
Water Cycle



eq. water height [cm]
–40 –30 –20 –10 0 10 20 30 40
eq. water height [cm]
30 25 20 15 10 5 0 −5 −10 −15 −20 −25 −30
2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015

Global Water Cycle





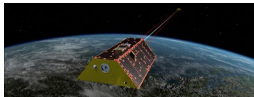
ΔTWS(t) = ΔGW(t) + ΔSW(t) + ΔSWE(t) + ΔSM(t) - ΔRO(t)

ΔTWS(t) = Total Water Storage **Can only be measured by GRACE!**

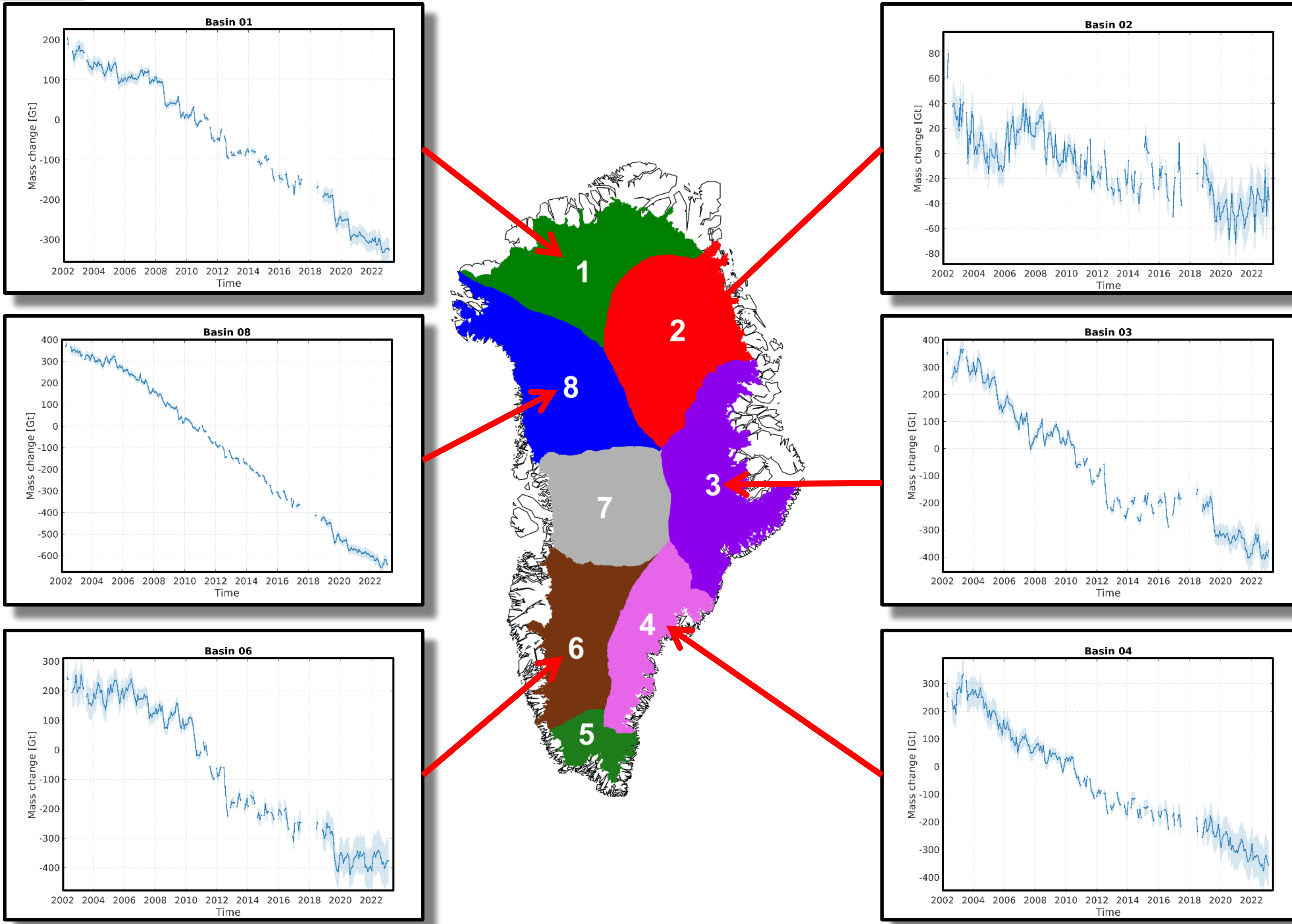
ΔGW(t) = Ground Water
ΔSW(t) = Surface Water } ΔAW(t) = Accessible Water
ΔSWE(t) = Snow Water Equivalent

ΔSM(t) = Soil Moisture
ΔRO(t) = Run Off

} **Separation needs further measurements**



Melting Ice in Greenland



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Combination Service for Time-variable Gravity Models

Melting Ice in Greenland

"Bern im All", Quiz on Bern Bundesplatz:

How many

of these blocks are melting
in Greenland

every second ?

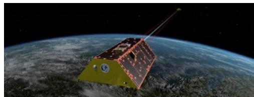
Melting Ice in Greenland

"Bern im All", Quiz on Bern Bundesplatz:

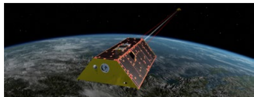
≈10´000

of these blocks are melting in Greenland

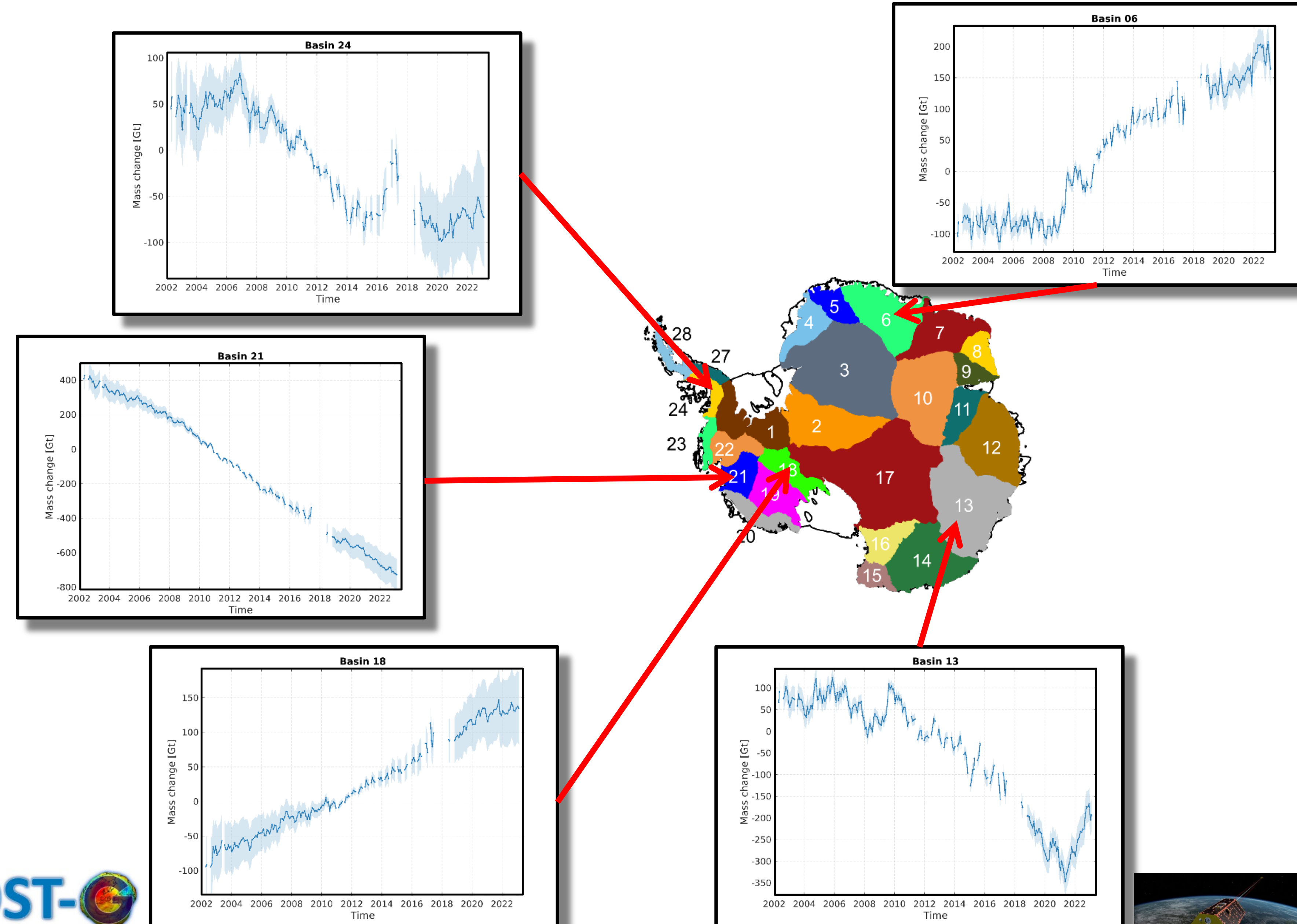
every second



Melting Ice in Greenland



Melting Ice in Antarctica



COST-G
Combination Service for Time-variable Gravity Models

Melting Ice in Greenland

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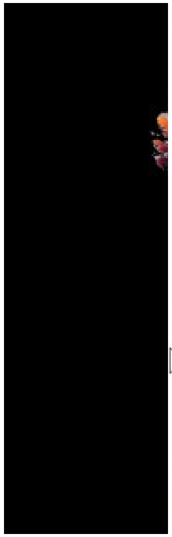
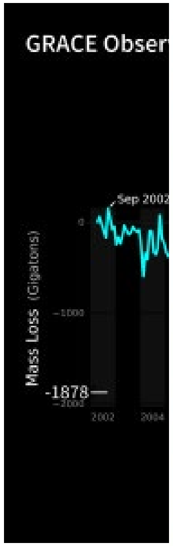
Satellitenmessungen

Meeresspiegel steigt immer schneller

Die Erhöhung des Meeresspiegels beschleunigt sich, berichten Klimaforscher unter Berufung auf

DPA





level eqv.
a level

ice sheets
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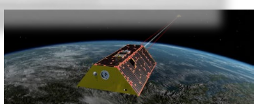
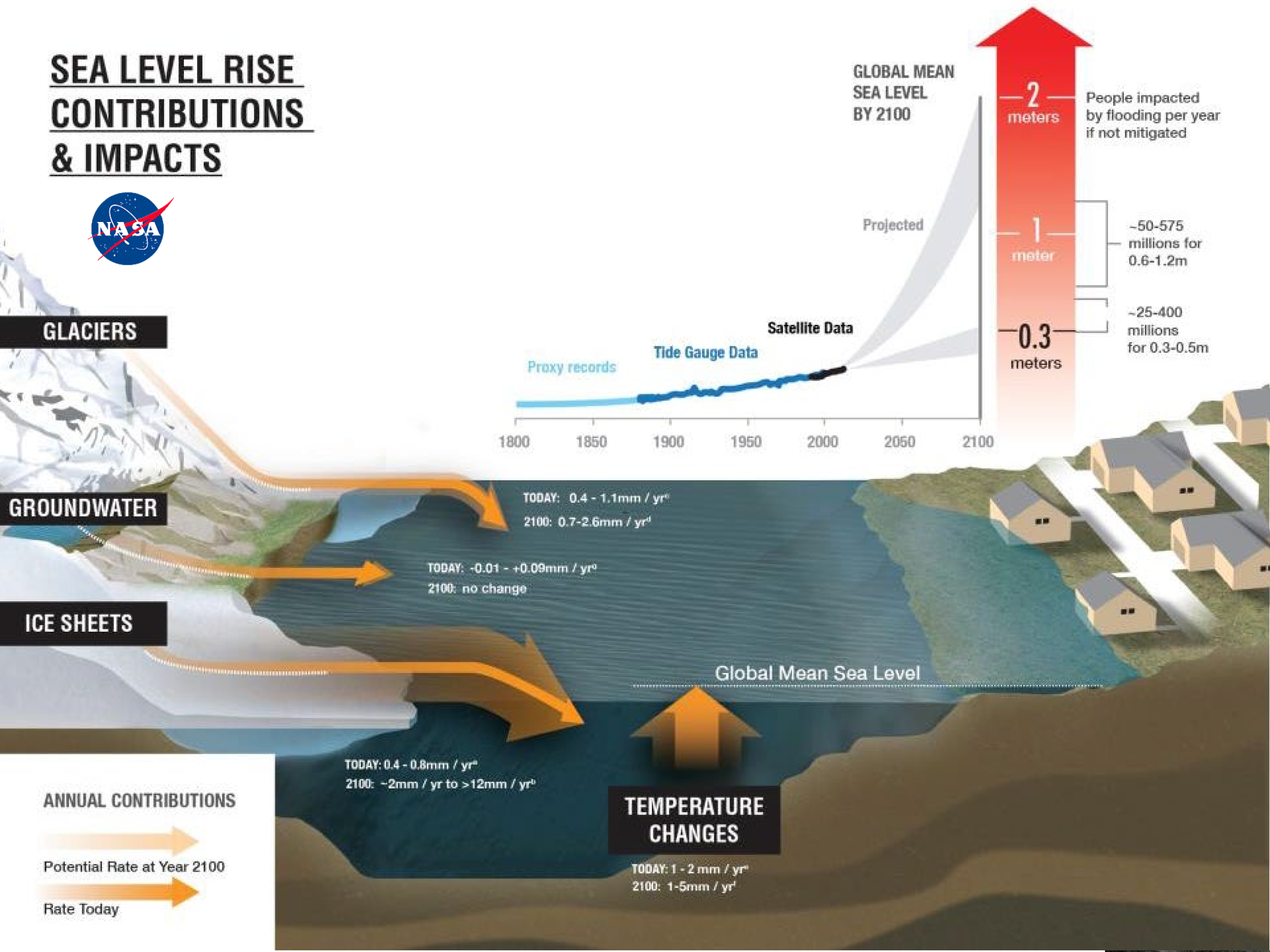
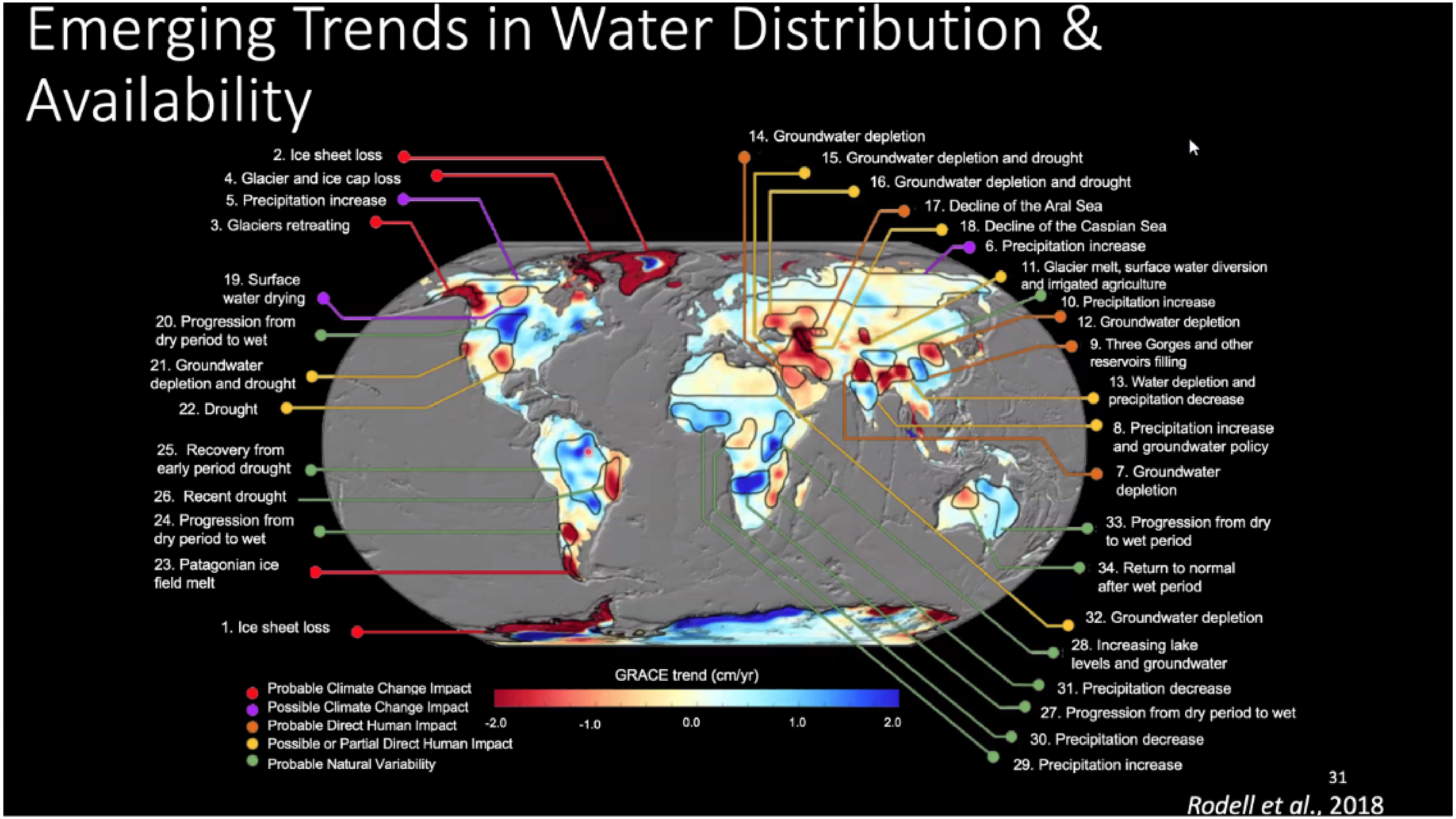
system”

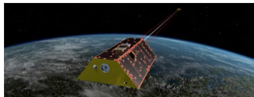




SEA LEVEL RISE CONTRIBUTIONS & IMPACTS
NASA
GLOBAL MEAN SEA LEVEL BY 2100
Projected
Satellite Data
Tide Gauge Data
Proxy records
1800
1850
1900
1950
2000
2050
2100
2 meters
1 meter
0.3 meters
People impacted by flooding per year if not mitigated
~50-575 millions for 0.6-1.2m
~25-400 millions for 0.3-0.5m
GLACIERS
TODAY: 0.4 - 1.1mm / yr
2100: 0.7-2.6mm / yr
GROUNDWATER
TODAY: -0.01 - +0.09mm / yr
2100: no change
ICE SHEETS
TODAY: 0.4 - 0.8mm / yr
2100: ~2mm / yr to >12mm / yr
Global Mean Sea Level
TEMPERATURE CHANGES
TODAY: 1 - 2 mm / yr
2100: 1-5mm / yr
ANNUAL CONTRIBUTIONS
Potential Rate at Year 2100
Rate Today

Availability of Water





Example: Drought in California

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Nachrichten > Wissenschaft > Natur > Dürre in den USA > Dürre in Kalifornien: Geldstrafen für Wasserverschwender

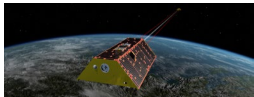
Dürre in Kalifornien: Wasserverschwendern droht hohe Geldstrafe

AFP

Almaden-Stausee (Januar 2014): Wo einst ein breiter Strom floss, ist jetzt nur noch ein Rinnsal übrig

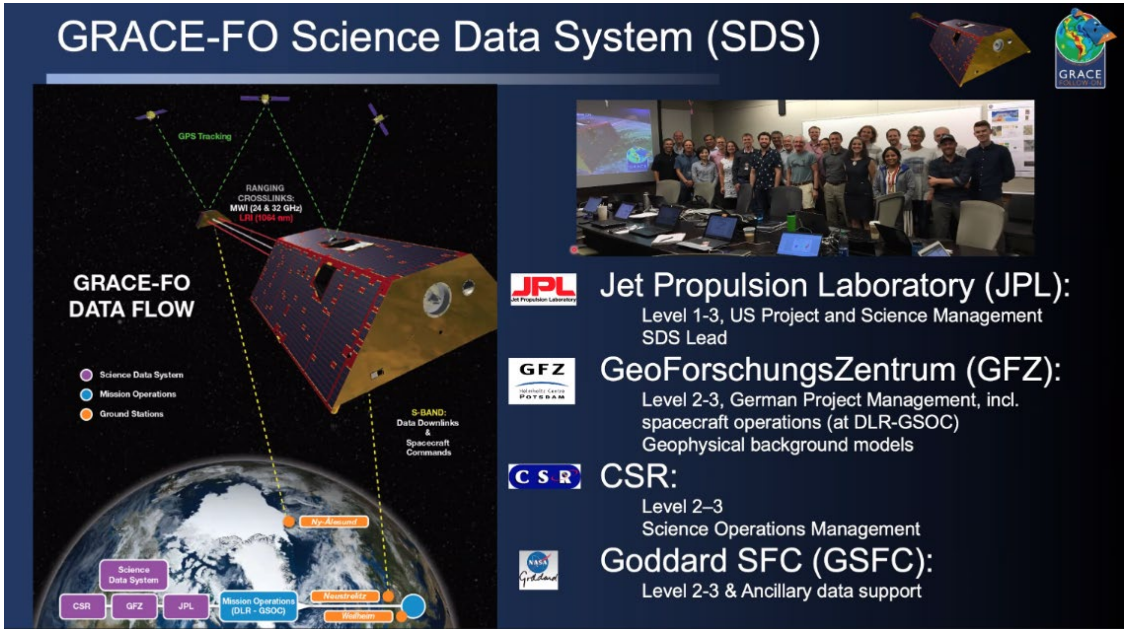
Einwohner Kaliforniens dürfen ab August kein Wasser mehr außerhalb ihres Hauses verbrauchen. So soll während der Dürre Wasser gespart werden. Wer die Regeln missachtet, zahlt bis zu 500 Dollar Strafe - am Tag.

International Collaboration



GRACE-FO Analysis Centers

SDS Analysis Centers



European Analysis Centers

Universität Bern, GFZ Helmholtz Centre Potsdam, TU Graz – Graz University of Technology, cnes, Leibniz Universität Hannover

Chinese Analysis Centers

European Gravity Initiatives

The University of Bern (PI: Adrian Jäggi) coordinated the H2020 project **EGSIEM** (2015-2017). It was explicitly mentioned in NASA's Decadal Survey and paved the way for the current activities.

EGSIEM
European Gravity Service for Improved Emergency Management
http://egsiem.eu/

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Parts of EGSIEM are continued since 2019 as an IAG service activity called **COST-G**, coordinated again by the University of Bern (Founding Chair: Adrian Jäggi).

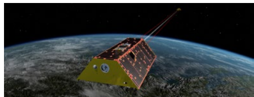
COST-G – Combination Service for Time-variable Gravity Models

http://cost-g.org/

European Gravity Initiatives

The University of Bern initiated to strive for a H2020 follow-up of EGSIEM with the same gravity core-group as in EGSIEM => **Global Gravity-based Groundwater Product (G3P)**, a H2020 project coordinated by GFZ Potsdam (2020-2022, PI: Andreas Güntner).

https://www.g3p.eu/



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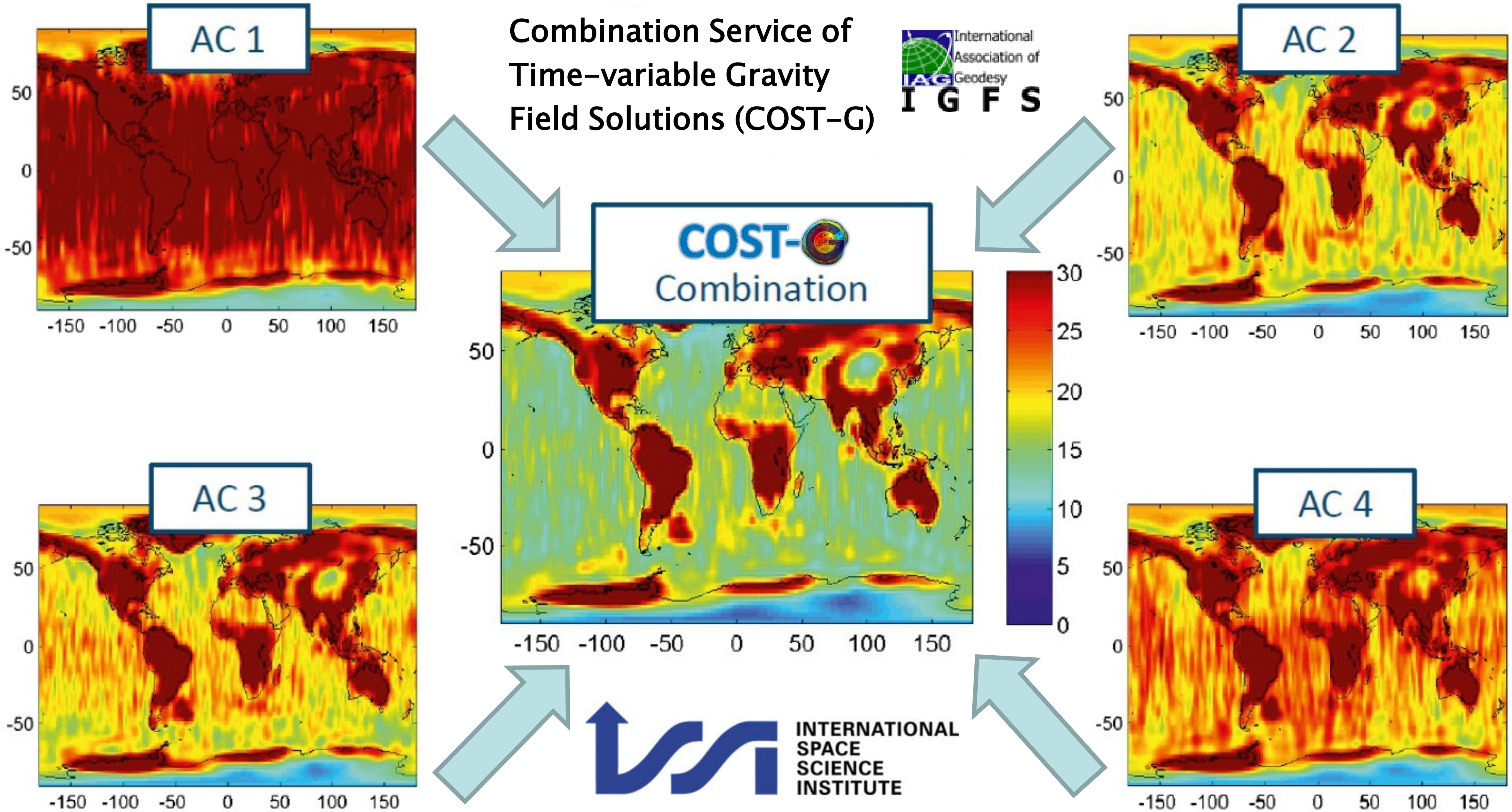
G3P
https://www.g3p.eu/

Combination Service of Time-variable Gravity Field Solutions (COST-G)



Improved and consolidated product integrating the strengths of all ACs

Meyer, U. et al. (2020): International Combination Service for Time-variable Gravity Fields (COST-G) Monthly GRACE-FO Series. V. 01. GFZ Data Services. https://doi.org/10.5880/ICGEM.COST-G.002

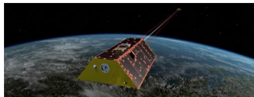
Permanent Components of COST-G

COST-G accomplishes its objectives through the following permanent components and roles:

- **Central Bureau (CB) & Analysis Center Coordinator (ACC)**
  - AIUB
- **Analysis Centers (ACs)**
  - AIUB, CNES, GFZ, TUG, LUH
- **Candidate ACs:** Chinese ACs
- **Level-3 Center (L3C)**
  - GFZ
- **Validation Centers (VCs)**
  - GRGS, GFZ
- **Product Evaluation Group (PEG)**
  - A. Eicker, T. Döhne, A.Blazquez

GRACE/GRACE-FO SDS (CSR, JPL) contribute as partner ACs to COST-G combinations.

Jäggi, A. et al. (2020): International Combination Service for Time-Variable Gravity Fields (COST-G) - Start of Operational Phase and Future Perspectives. https://doi.org/10.1007/1345_2020_109



COST-G

Combination Service for Time-variable Gravity Fields

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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 H2020 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!

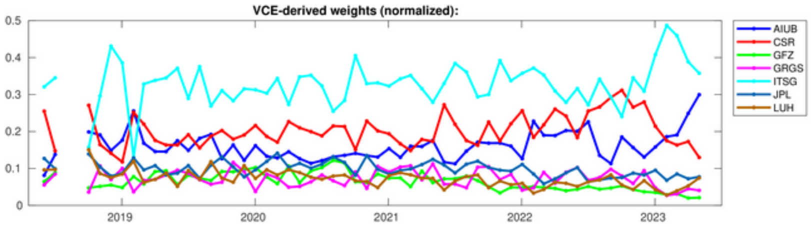
Best regards,
Your COST-G Team.

Project flyer

Download our new project flyer!

Latest GRACE-FO combination results

Weights (RL02)



Latest News

July 20th 2023

Starting on 18th July, the Copernicus POD Service deployed a new version of the system (3.3.0) which uses the COST-G FSM for gravity field modeling in all the operational chains.

July 10th 2023

COST-G has a new flyer! Check it here!

June 26th 2023

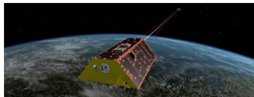
COST-G is kicking off its annual meeting in Bern this week!

April 18th 2023

COST-G GRACE-FO RL02 is now available at ICGEM.

New input time-series of RL02 are: GFZ-, JPL-, CSR-RL06.1, which apply the new JPL accelerometer transplant product, and AIUB-GRACE-FO-RL03, which makes use of empirical noise modelling strategies.

https://cost-g.org/



https://plot.cost-g.org/
http://gravis.gfz-potsdam.de/
http://icgem.gfz-potsdam.de/

COST-G Plotter

GravIS

Easy accessibility

The COST-G plotter is an easy and convenient way to look at and evaluate the data products of the ACs and other partner centres as well as the combined solutions generated at the University of Bern (AIUB).

GravIS, the Gravity Information Service of GFZ in collaboration with AWI and TUD, enables the usage of satellite gravimetry data for a broader community. **User-friendly and ready-to-use products ('Level-3') are generated and visualized based on the most recent GRACE and GRACE-FO data releases from GFZ and COST-G.** The products presented at GravIS are available for download at GFZ's Information System and Data Center (ISDC).

Partners

- GFZ German Research Centre for Geosciences, Germany (GFZ)
- Centre National d'Études Spatiales, France (CNES)
- University of Bern, Switzerland (AIUB)
- Graz University of Technology, Austria (TUG)
- Leibniz Universität Hannover, Germany (LUH)
- Alfred-Wegener-Institut, Germany (AWI)
- Technical University Dresden, Germany (TUD)
- Stellar Space Studies

International Association of Geodesy

IAG

I G F S

Contact point

Prof. Dr. Adrian Jäggi
Astronomical Institute
University of Bern
Sidlerstrasse 5
3012 Bern, CH
adrian.jaeggi@unibe.ch

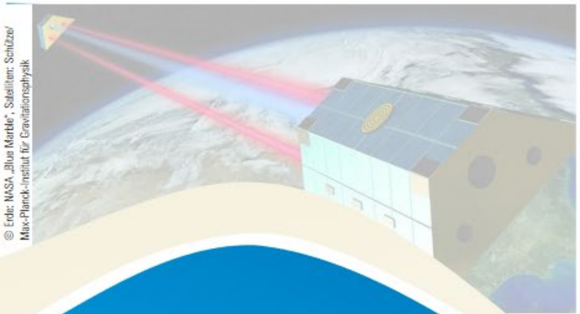
Prof. Dr. Frank Flechtner
Helmholtz Centre Potsdam
GFZ German Research Centre for Geosciences
Claude-Dornier-Straße 1
82234 Weßling, Germany
frank.flechtner@gfz-potsdam.de

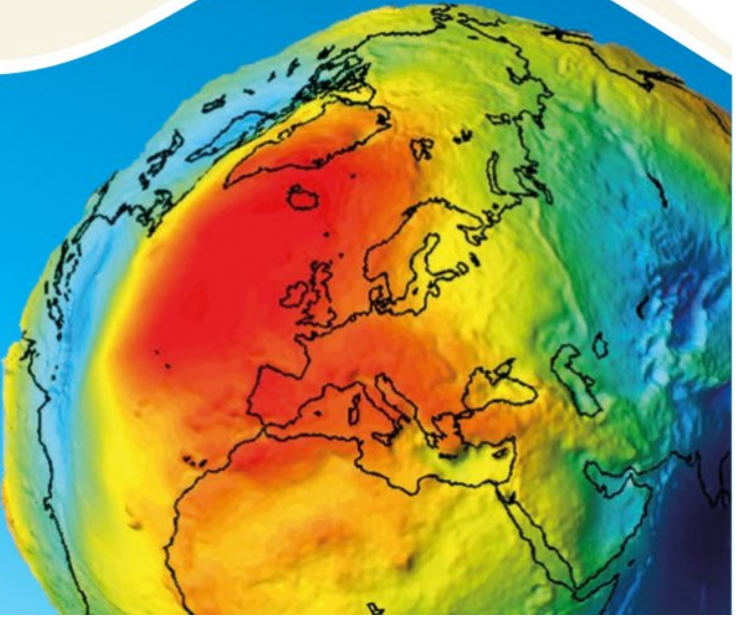
COST-G is supported by the Cluster of Excellence 2123 QuantumFrontiers

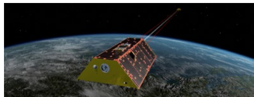
Enhance your research

COST-G

Combination Service for Time-variable Gravity Fields





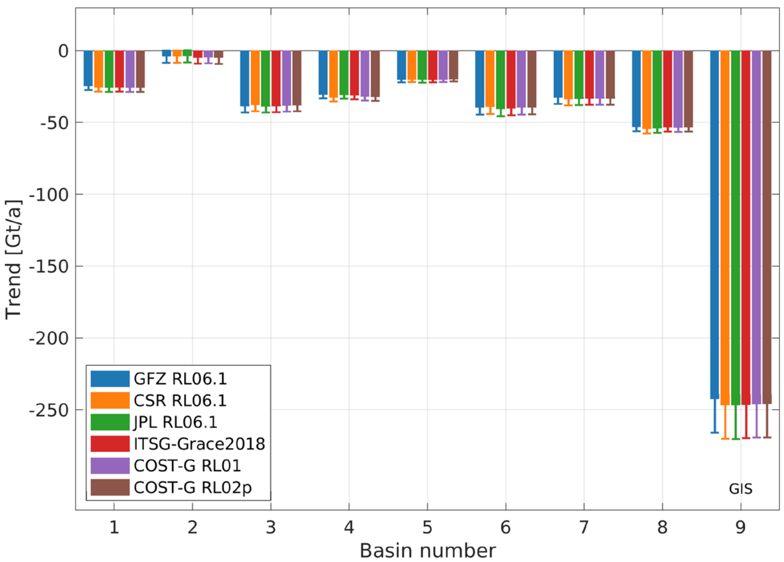


Consistency of Input Products

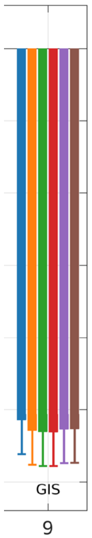
Basin-integrated Greenland/Antarctic Ice Sheet (GIS/AIS) mass changes based on the sensitivity kernel approach by TU Dresden.

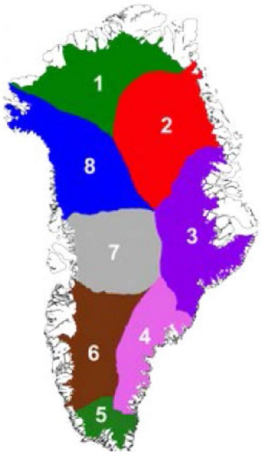
Trends are calculated from GRACE and GRACE-FO results (from a fitted linear, quadratic and seasonal model).

GRACE/GRACE-FO



GRACE





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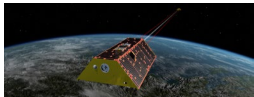
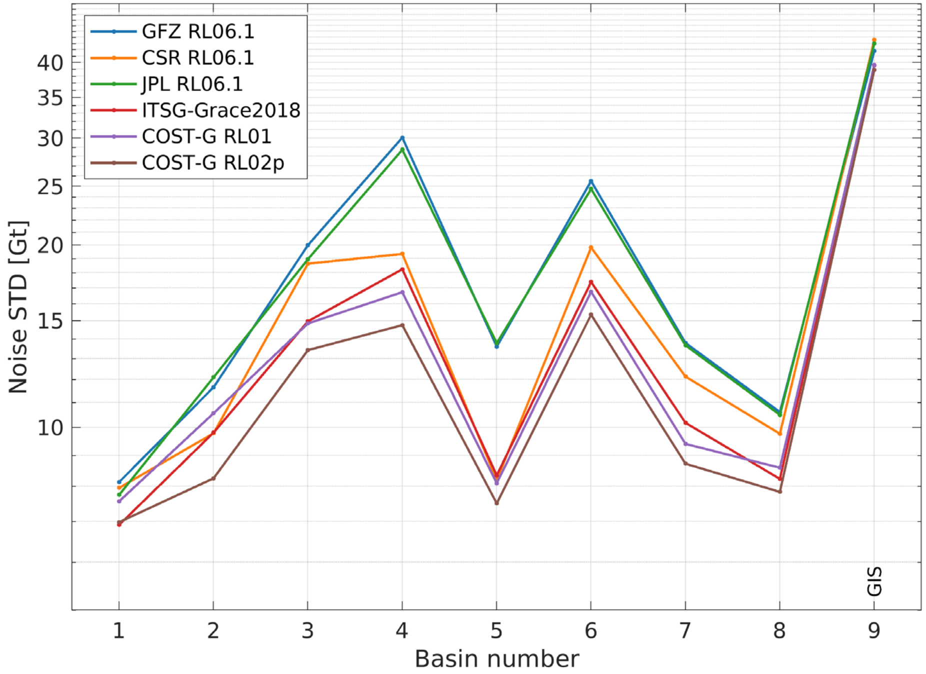
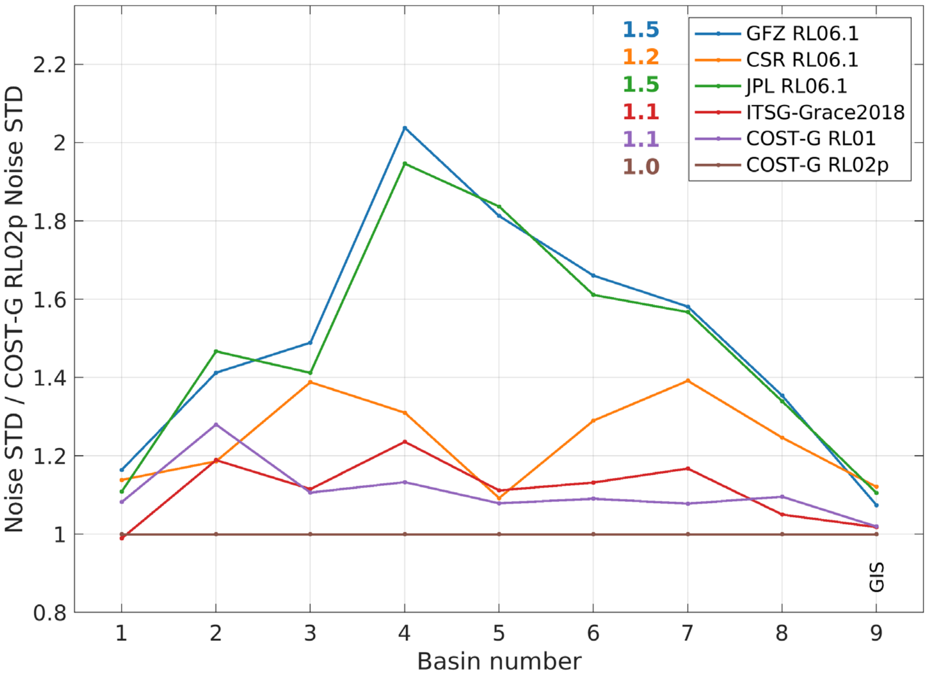


Noise Reduction GIS





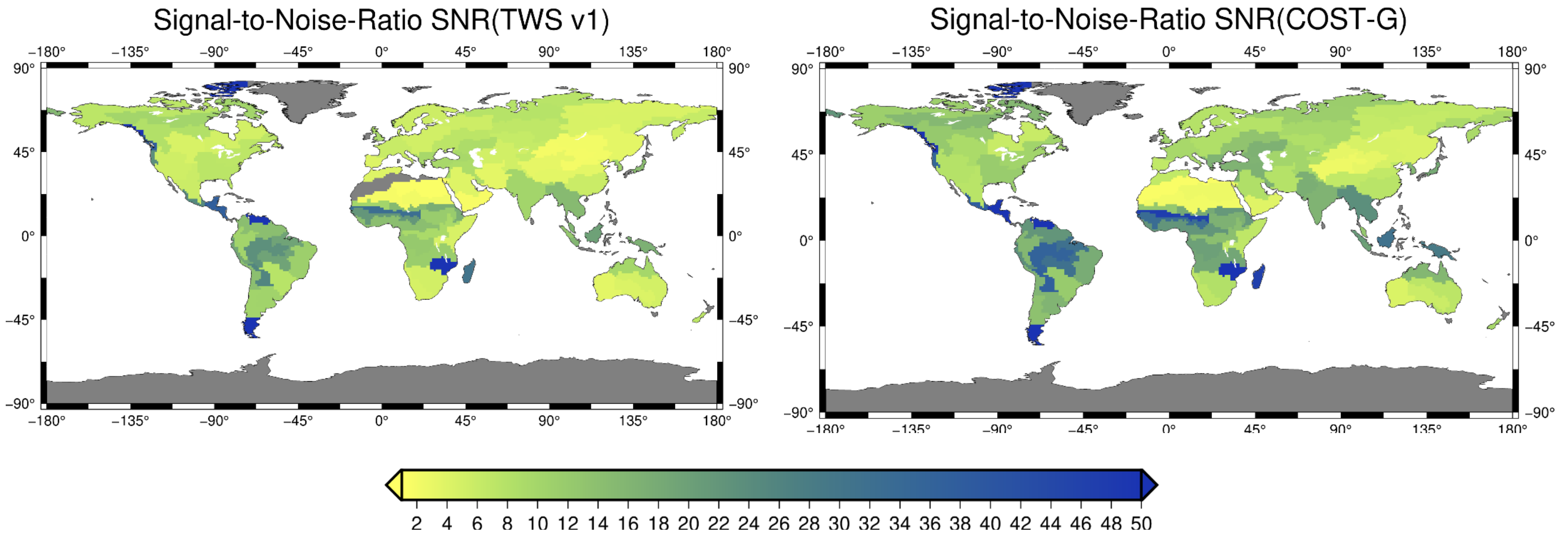
Noise measure for each basin time series for individual solutions and the 1st and 2nd releases of COST-G combined solutions.

Ratio w.r.t. noise measure of the latest COST-G combined time series (numbers indicate the median of all basin ratios).

COST-G
Combination Service for Time-variable Gravity Models

Noise Reduction for Major River Basins

GFZ v1 | **COST-G G3P**

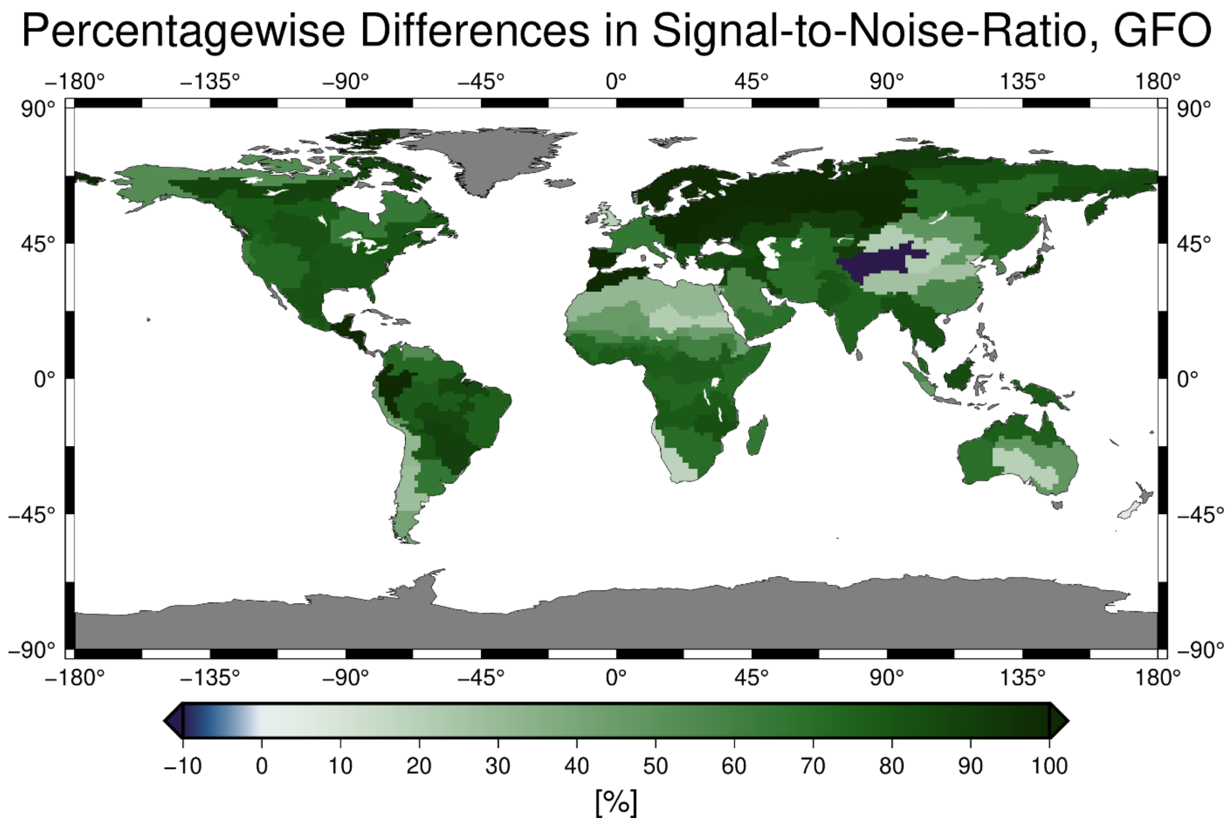


Boergens, E. et al. (2020): COST-G GravIS RL01 Continental Water Storage Anomalies. V. 0005. GFZ Data Services. https://doi.org/10.5880/COST-G.GRAVIS_01_L3_TWS

COST-G Combination Service for Time-variable Gravity Models

G3P

Noise Reduction for Major River Basins



Boergens, E. et al. (2020): COST-G GravIS RL01 Continental Water Storage Anomalies. V. 0005. GFZ Data Services.
https://doi.org/10.5880/COST-G.GRAVIS_01_L3_TWS

COST-G
Combination Service for Time-variable Gravity Models
G3P

Product Uptake in Operational Activities

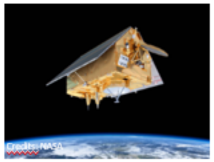
ESA
EUMETSAT
Copernicus Europe's eyes on Earth
Copernicus POD Service

Copernicus Sentinel-1

Copernicus Sentinel-2

Copernicus Sentinel-3

Copernicus Sentinel-6 Michael Freilich



- Sentinel satellites are equipped with various Earth observation instruments
- Mission requirements demand high levels of orbital accuracy (**GPS**, DORIS+SLR only S-3 + S-6 (+GAL)) → **Copernicus POD Service**

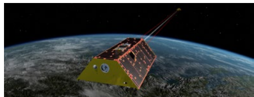
Copernicus POD Service

- Consortium led by **GMV**, Tres Cantos, Spain
- **magicGNSS**, external GPS orbit and clock provider (NRT, STC)
- **PosiTim**, QWG management, quality control, improvements, scientific outreach …
- **DLR, TUM, TUD, GFZ** quality control, QWG members

Copernicus POD QWG

- Additional members: **AIUB, CNES, GRGS, GSFC, JPL, ESOC, TUG**

Starting on 18 July 2023, the Copernicus POD Service deployed a new version of the system (3.3.0) which uses the **COST-G Fitted Signal Models** for gravity field modeling in all the operational chains.



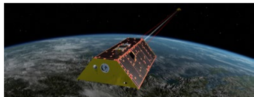
Institutional Support

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

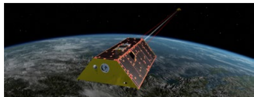
- **ESA / Swarm DISC:**
  - Funded from 2020 to today (PI: João Teixeira da Encarnação): Operational provision of Swarm release

- **International Space Science Institute Beijing (ISSI-Beijing):**
  - Funded from 2021 to today (PI: Wei Feng): Extension with Chinese Analysis Centers

- **H2020:**
  - Funded from 2020 to 2022 (PI: Andreas Güntner): Use of COST-G products as an essential input for the development of a global gravity-based groundwater product.



Example: Groundwater

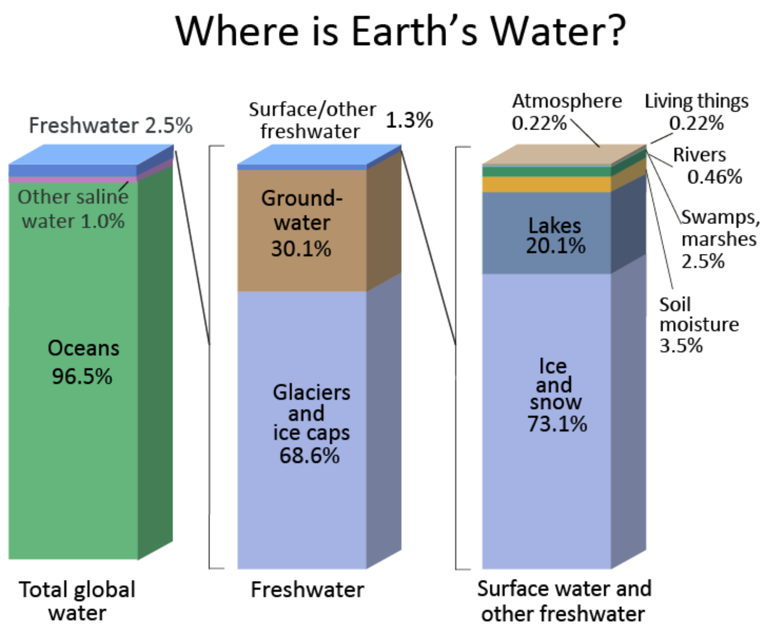


Groundwater on a Global Setting

Groundwater represents **30%** of the global freshwater and accounts **33%** of the global water withdrawals. It ensures ecosystem stability, energy and food security.

Despites its importance, groundwater is often not included in sustainable water management actions and plans.

Poor in-situ monitoring capabilities in many regions, with sparse and un-representative groundwater monitoring networks, largely unknown storage capacities and accessibility of data.



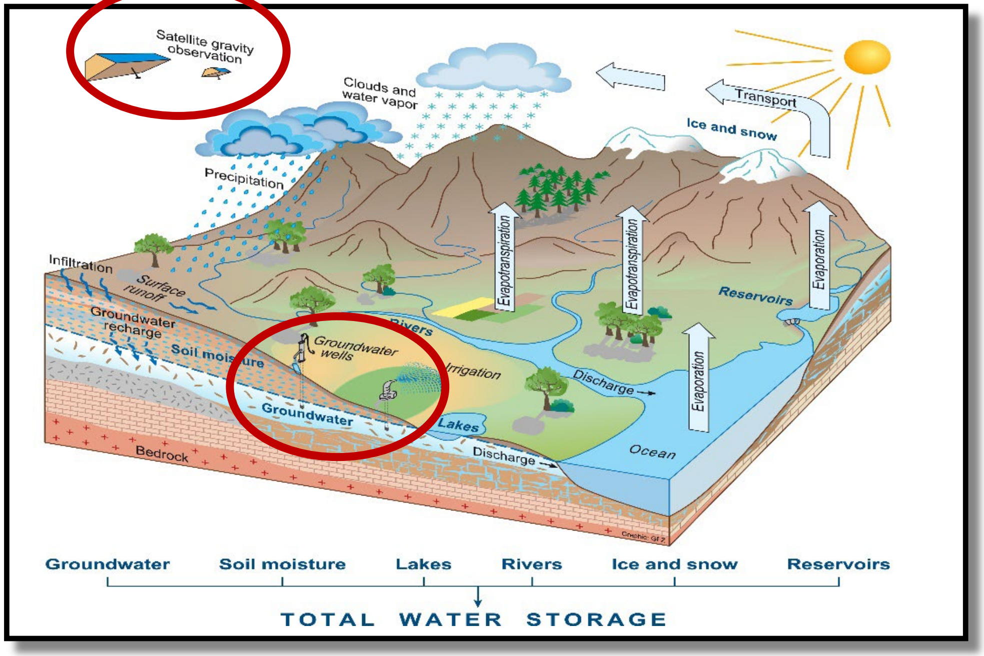
Courtesy: U.S. Geological Survey's

Spatially quantification of groundwater storage changes may contribute to fill the monitoring gap. This can be achieved through satellite technologies

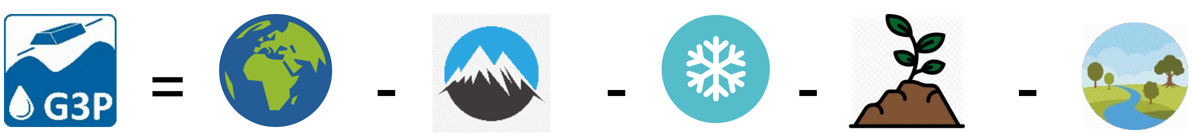
Groundwater and the Earth's Gravity Field

G3P concept

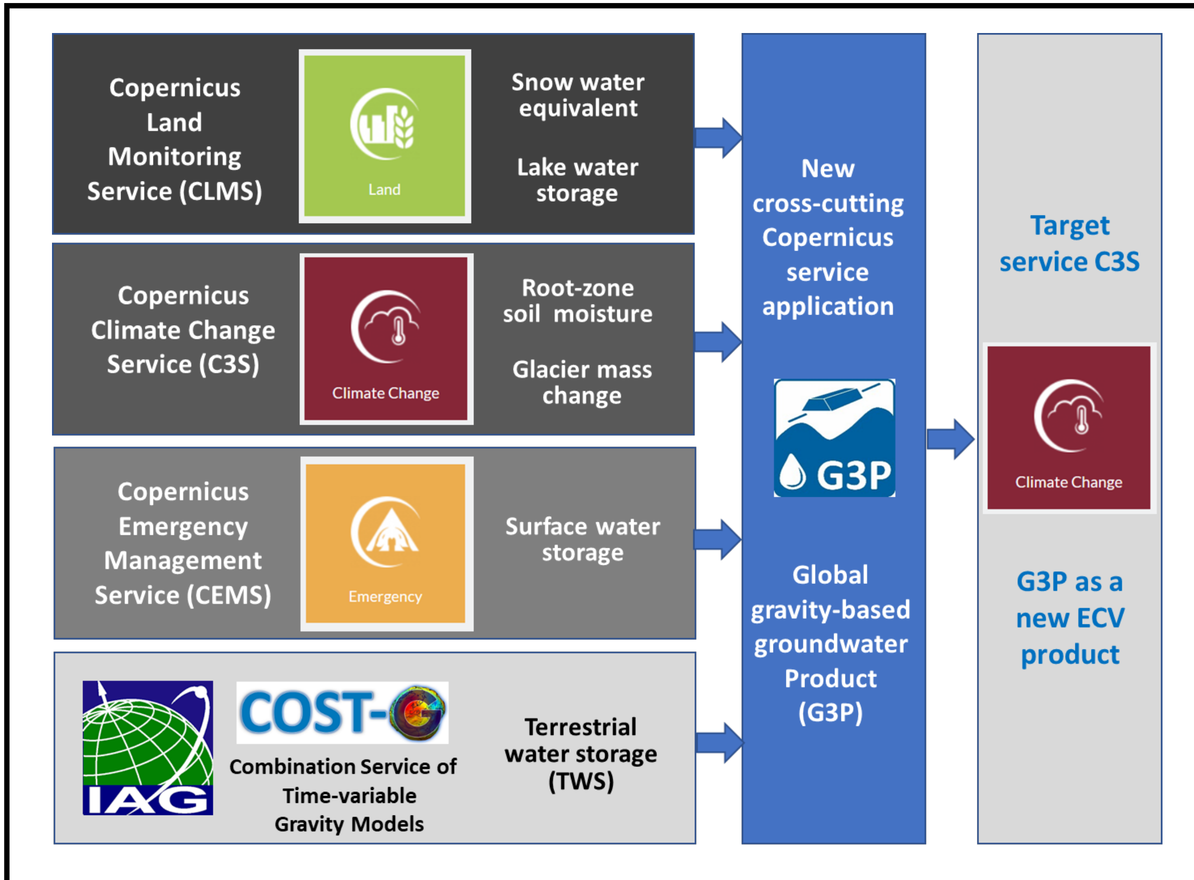
- Satellite gravimetry observes Terrestrial Water Storage (TWS) variations
- Resolving for groundwater storage variations follows a subtraction approach:



Groundwater = TWS - glaciers - snow - soil moisture - storage in surface water bodies



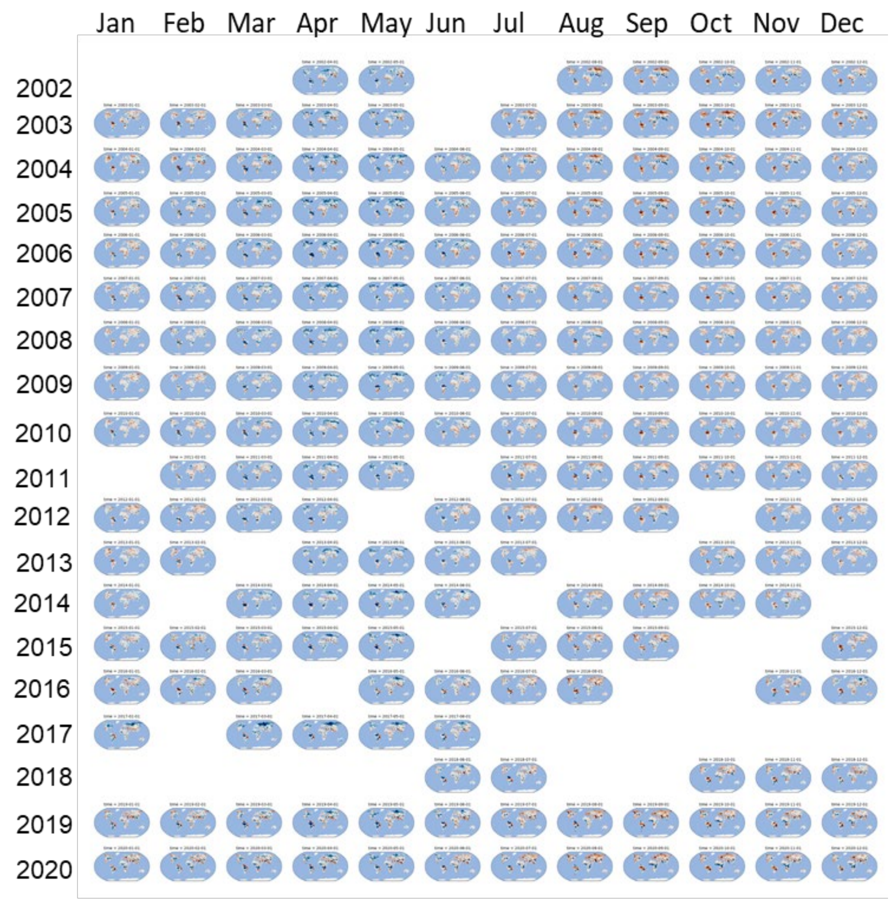
G3P – Cross-cutting Service Combination



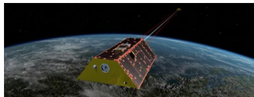
Groundwater storage anomalies (GWSA)

G3P status

- Global data set of monthly groundwater storage anomalies on a 0.5-degree grid
- Full uncertainty information on a 0.5-degree grid
- For the GRACE/GRACE-FO time period of April 2002 to December 2020

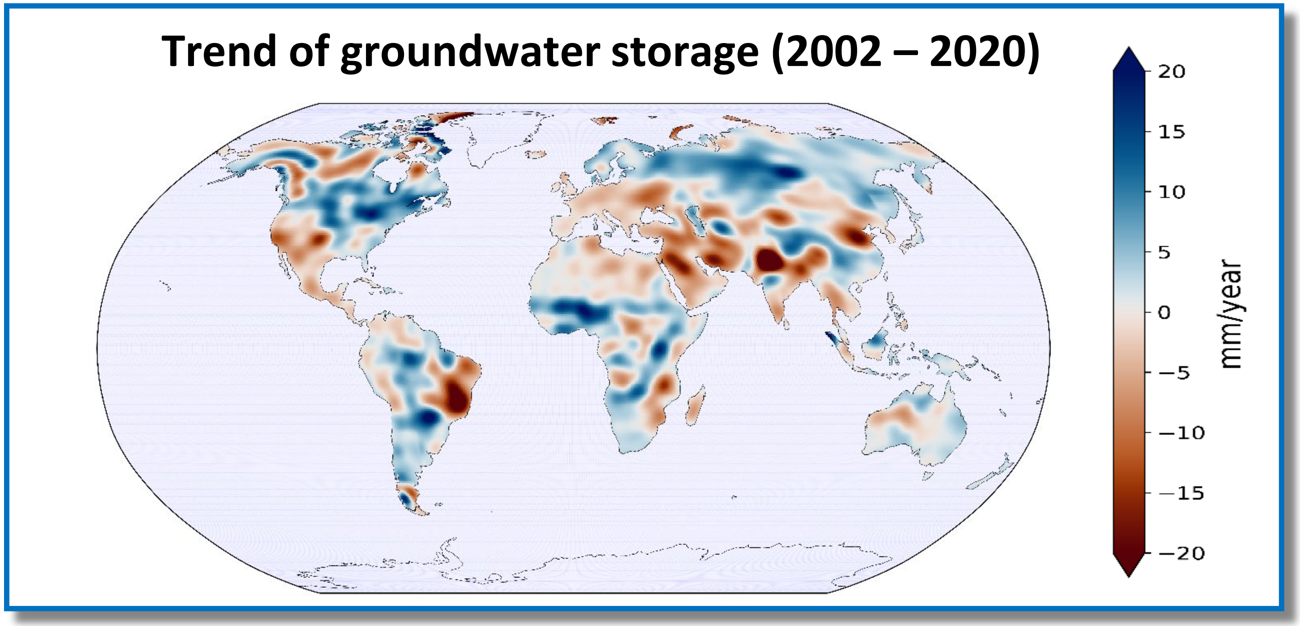


Güntner, A. et al. (2023): Global Gravity-based Groundwater Product (G3P). V. 1.11. GFZ Data Services. https://doi.org/10.5880/G3P.2023.001



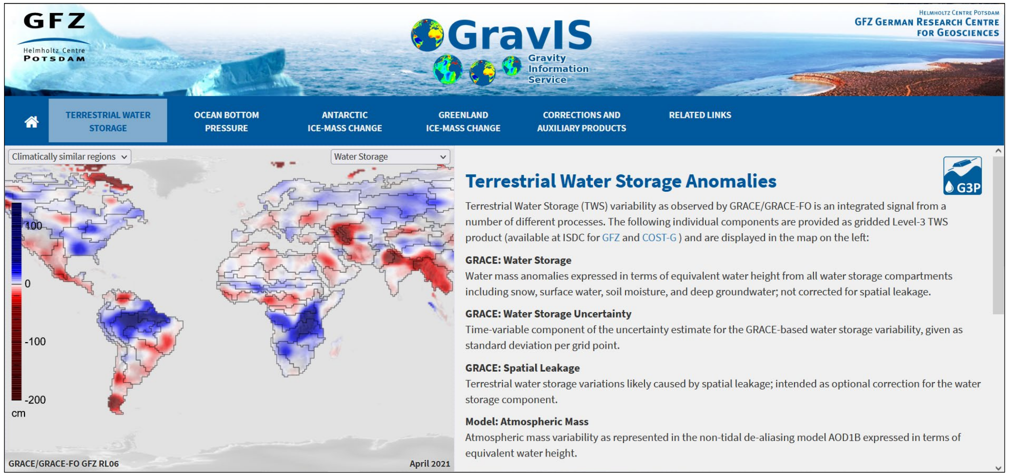
Groundwater storage anomalies (GWSA)

- Prototype development of G3P service (2002-2020)
- 0.5° nominal; ~200 km real spatial resolution
- monthly
- uncertainties included
- Globally consistently processed



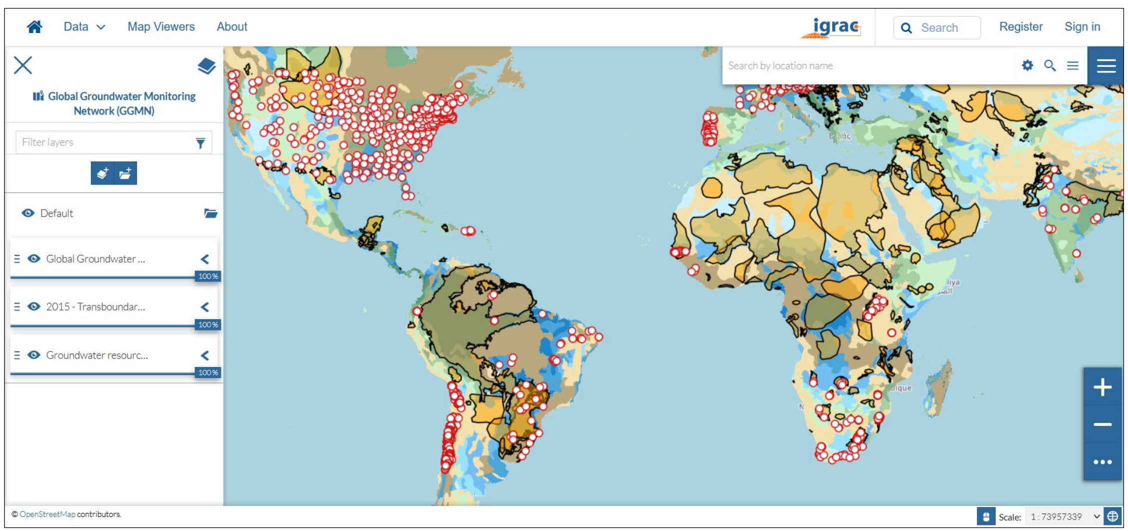
The global pattern of GWSA trends for the period 2002 to 2020 is shown in the map. The magnitude of the long-term trends for the GWSA is mostly within ±20 mm/year. Some of the well-known features of groundwater are visible in this trend map, for example over-exploitation in several regions worldwide (e.g., north-western India, north-eastern China, Middle East, California).

Data Dissemination



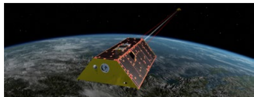
TWS and Groundwater Anomalies available at Gravity Information Service of the German Research Centre for Geosciences (GFZ) (GravIS):

http://gravis.gfz-potsdam.de/land

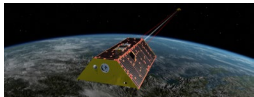


Groundwater Anomalies available at Global Groundwater Monitoring Network (GGMN):

https://ggmn.un-igrac.org/



Future Perspectives



Perspectives in Terms of Missions

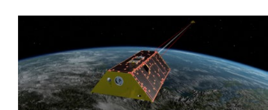
Courtesy: ESA

Europe's Earth Observation Programme

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

Copernicus
Europe's eyes on Earth

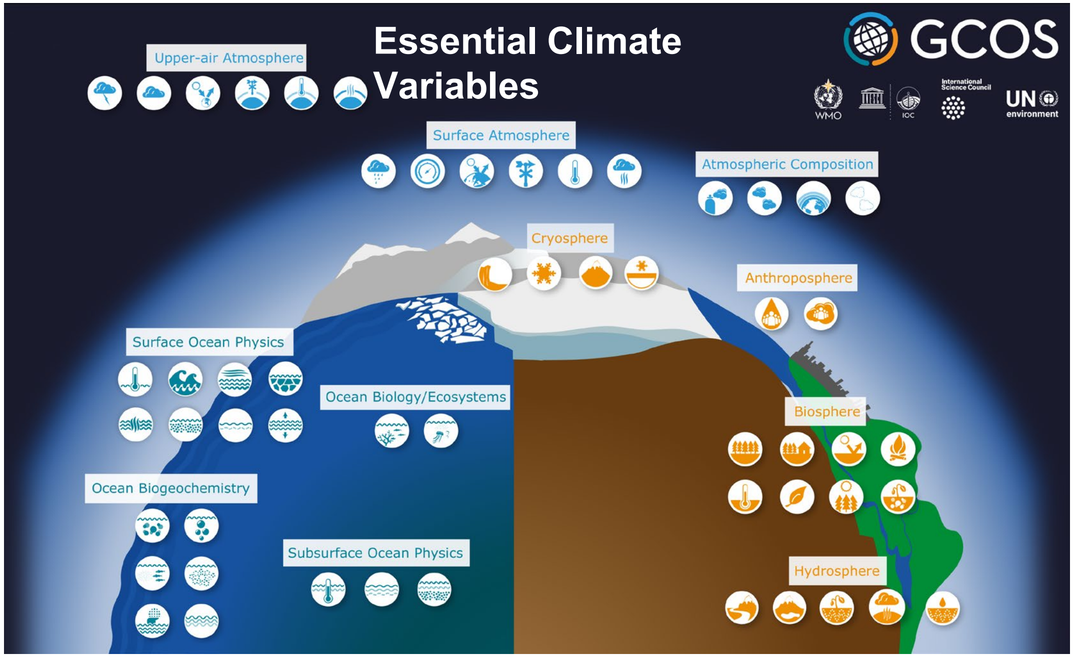
https://www.copernicus.eu/



Essential Climate Variables

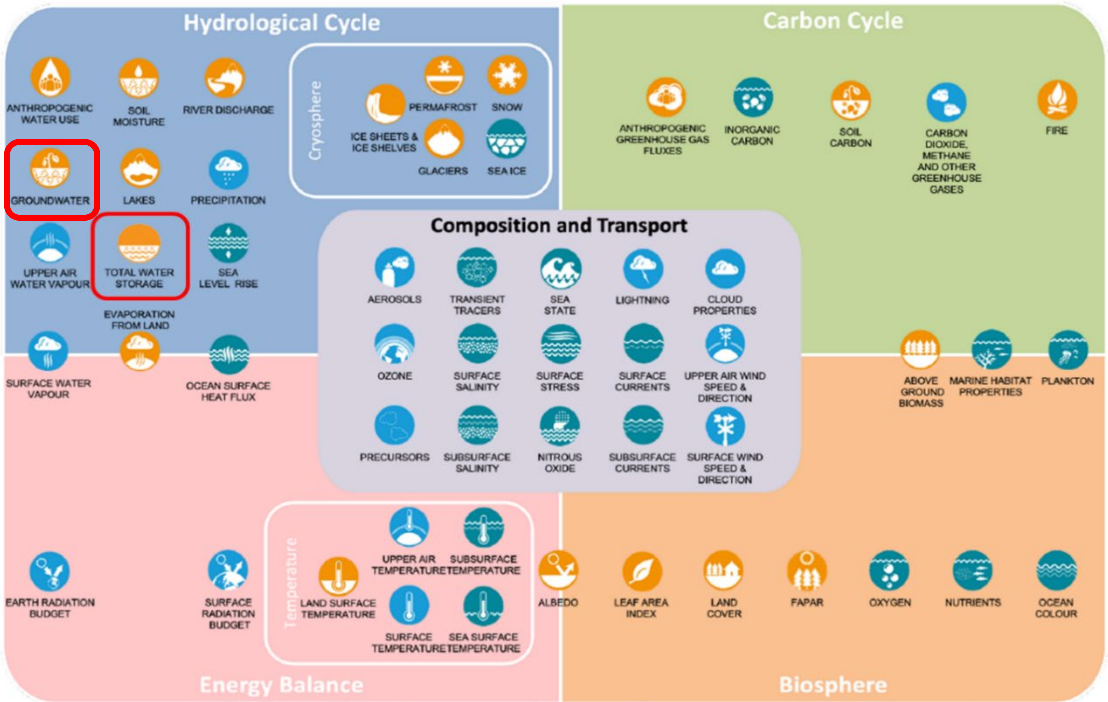
The Global Climate Observing System (GCOS) defines several **Essential Climate Variables** (ECVs):

- 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, …



https://gcos.wmo.int

Towards new ECV products for C3S



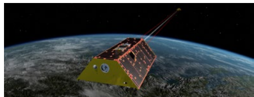
ECV Groundwater

no Copernicus product available so far

Terrestrial Water Storage

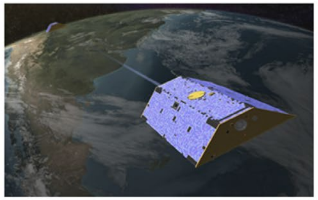
- new ECV in GCOS implementation plan 2022
- no Copernicus product available so far

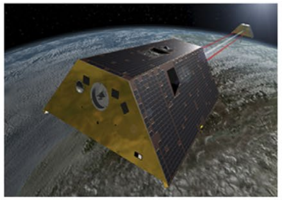
Terrestrial Water Storage (TWS) variations comprise all the water storage on the Earth’s continental areas in frozen and liquid state, including ice caps, glaciers, snow cover, soil moisture, groundwater and the storage in surface water bodies and the interaction with ocean mass and sea level.

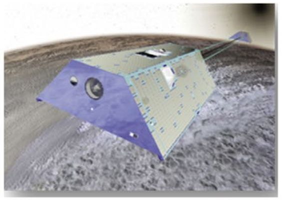


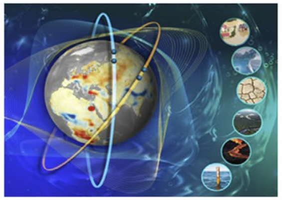
Future Gravity Missions

Grounds are prepared for perpetuating COST-G/G3P data products by approved **future satellite gravimetry missions**
for providing
long-term ECV climate data records of
- TWS
- groundwater storage









GRACE
2002 2017

First time enabling of mass change monitoring from space based on two-way micro-wave ranging.

GRACE-FO GFZ
2018 2028

Continued times series of mass change. Additionally operates a Laser Ranging Interferometer (LRI) as technology demonstrator for future missions.

GRACE-I/MC
2028 2033

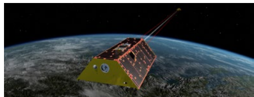
Data continuity based on LRI measurements.

NGGM/MAGIC esa
2032 2037

Improved spatial/temporal resolution based on combination of GRACE-I/MC with ESA´s NGGM to realize MAGIC.

NASA-DLR Implementation Arrangement signed in 10/2023

Mass-change And Geoscience International Constellation (MAGIC): **ESA Member States Ministerial Meeting approved funding in 11/2022**



IUGG Resolution 2023

IUGG Resolution 2: Sustained Terrestrial Water Storage (TWS) Monitoring by Dedicated Gravity Satellite Constellations

The International Union of Geodesy and Geophysics,

Considering

- the interest of the IUGG scientific community to understand the processes of changes in global Terrestrial Water Storage (TWS), comprising all the water storage on the Earth's continental areas in frozen and liquid state, including ice caps, glaciers, snow cover, soil moisture, groundwater and the storage in surface water bodies and the interaction with ocean mass and sea level,
- that satellite gravimetry missions are a unique observing system to directly measure TWS on a regional to global scale,
- the ongoing efforts of national and international institutions and space agencies to extend the GRACE/GRACE-FO program of record that runs already for more than two decades and enhance it with improved satellite gravimetry products, and
- the significant efforts of the International Association of Geodesy (IAG) in developing and maintaining fundamental geodetic products, in particular snapshots of the Earth's time-variable gravity field providing TWS maps for scientific and societal benefits,

Acknowledging

the adoption by the IUGG of Resolution 2 in Prague 2015 on Future Satellite Gravity and Magnetic Mission Constellations, and the adoption of TWS as a new Essential Climate Variable (ECV) in the implementation plan 2022 of the Global Climate Observing System (GCOS),

IUGG Resolution 2023

IUGG

IAG AIG International Association of Geodesy

Noting

- that satellite gravimetry missions such as GRACE and GRACE-FO successfully demonstrated the ability to globally observe the spatial and temporal variations of TWS from time-variable gravity on all continental areas,
- that improved temporal and spatial resolution and significantly increased accuracy are urgently needed by the user community and by operational services for, e.g., flood and drought monitoring and forecasting and water resources management, and
- that new technologies have been developed (such as laser ranging interferometry) or are currently being investigated (such as quantum gravimetry),

Urges

national and international space agencies and decision makers to

- implement and maintain long-term sustained observing systems of the Earth's time-variable gravity field realized by dedicated gravity satellite constellations with improved measurement technology to enable new science and applications of enormous societal benefit; and
- evolve them into sustainable operational services in the longer term.

Sustainable Satellites are serving Society

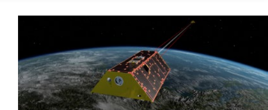
Data processing
and dissemination

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



Acknowledgments

The **EGSIEM** project has received funding from the European Union's Horizon 2020 research and innovation program under the grant agreement no. 637010 and from the Swiss State Secretariat for Education, Research and Innovation.

The **G3P** project has received funding from the European Union's Horizon 2020 research and innovation program under grand agreement no 870353.

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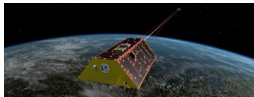
The **COST-G** international team is receiving support from the International Space Science Institute in Bejing (ISSI-Beijing).

All contributions from the **EGSIEM**, **COST-G**, **G3P** teams and from the corresponding **ISSI** and **ISSI-Beijing** teams shown in this presentation are kindly acknowledged.



Thanks a lot for your attention !