The Global Geodesy Supply Chain

Importance to Science and Society

presented by
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Expert Consultation on Strengthening the
Global Geodesy Supply Chain

April 22-23, 2024
Bonn, Germany

Jet Propulsion Laboratory
California Institute of Technology

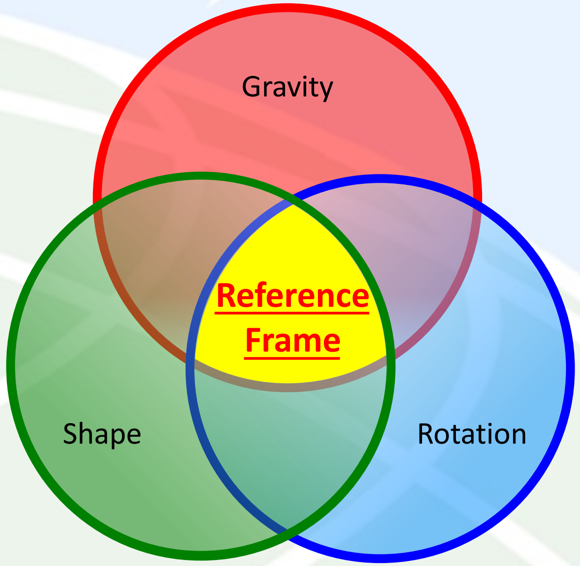
IUGG

IAG AIG
International Association of Geodesy

Geodesy

Geodesy is the science of accurately measuring and understanding three fundamental properties of the Earth and their changes in time

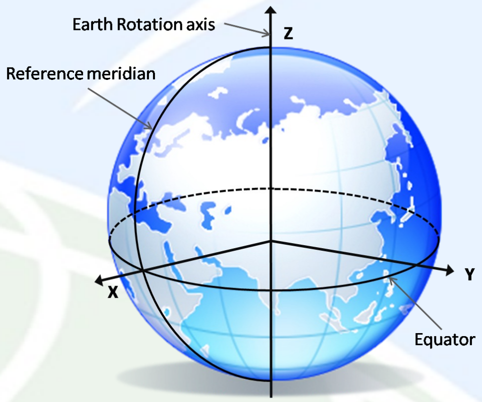
- Geometric shape
- Rotation and orientation in space
- Gravity field



Establishing and disseminating the Terrestrial Reference Frame (TRF) is central to Geodesy

Terrestrial Reference Frame (TRF)

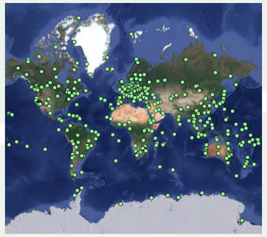
- **Definition**
  - The TRF is an accurate, stable set of positions and velocities of reference points on Earth's surface
  - The TRF provides the stable coordinate system that allows us to link measurements over space and time for numerous scientific and societal applications including critical climate and sea level change studies



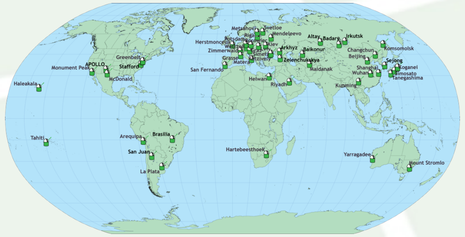
Terrestrial Reference Frame

- **Determination**
  - The GNSS, VLBI, SLR, & DORIS geodetic networks, along with ground surveys of stations at co-located sites to tie the networks together, provide the data for determining the TRF as well as for direct science investigations
- **Improvement**
  - An improved TRF is needed for numerous scientific and societal applications including critical climate and sea level change studies

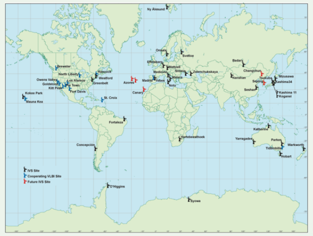
GGOS Goal: TRF accurate to better than 1 mm, stable to better than 0.1 mm/yr over a decade



GNSS



SLR

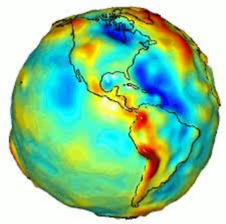


VLBI

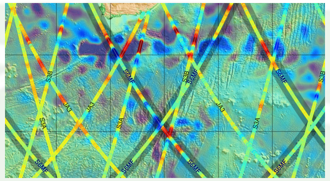
DORIS

Geodesy – Impact to Science and Society

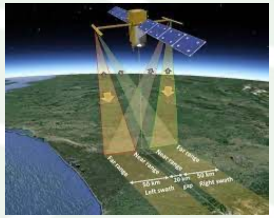
Earth Observation



Gravity



Sea Level



Oceanography & Hydrology

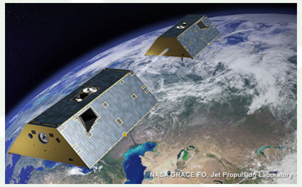
Earthquakes

Volcanos

Cryosphere

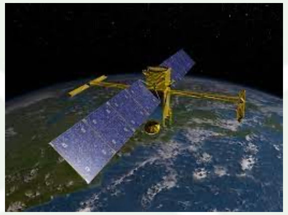
Tsunamis

Space Missions



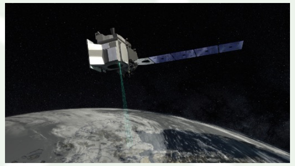
GRACE-FO

Sentinel-6 M-F



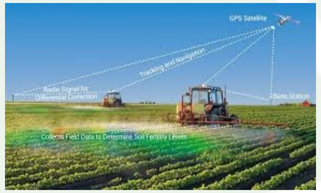
SWOT

NISAR

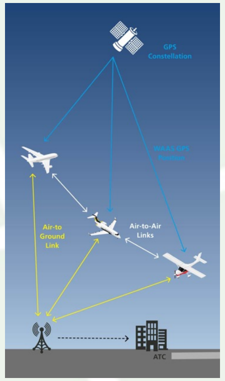


ICESAT-2

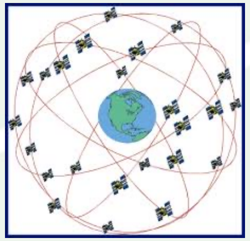
Infrastructure



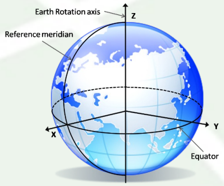
Precision farming



Aviation

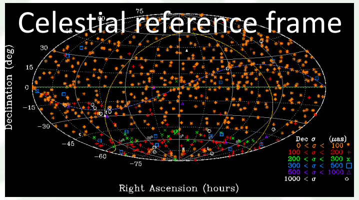


GPS/GNSS



Terrestrial Reference Frame

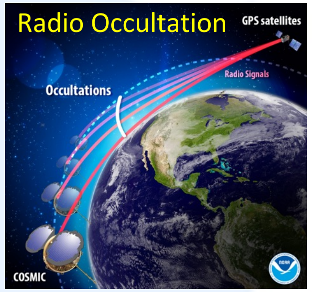
GPS based Timing for Financial Transactions

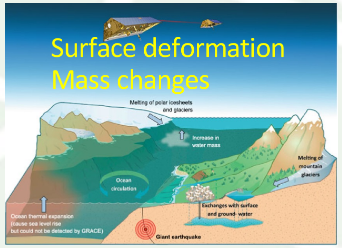


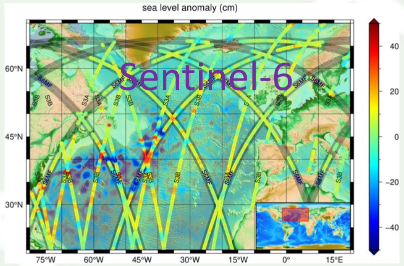
All deep space missions

How Geodesy Impacts the Science Community

- Weather and climate change
  - Numerical weather prediction
    - Assimilation of radio occultation measurements (GNSS)
    - Assimilation of zenith total delay and integrated water vapor measurements (GNSS)
  - Groundwater
    - Surface deformation (GNSS station displacements, InSAR)
    - Mass change (Intersatellite ranging and positioning)
  - Sea level
    - Absolute (GNSS, SLR, & DORIS tracking of radar altimetric satellites)
    - Relative (GNSS measurements of land height change)
  - Ice sheets and glaciers
    - Height change (GNSS & SLR tracking of laser altimetric satellites)
    - Mass change (Intersatellite ranging and positioning)
- Geohazards
  - Earthquakes, volcanoes
    - Crustal deformation (GNSS station displacements, InSAR)
  - Tsunamis
    - Ocean-atmosphere coupling (GNSS ionospheric disturbances)

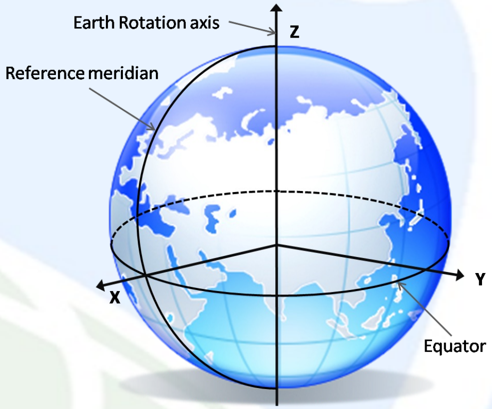




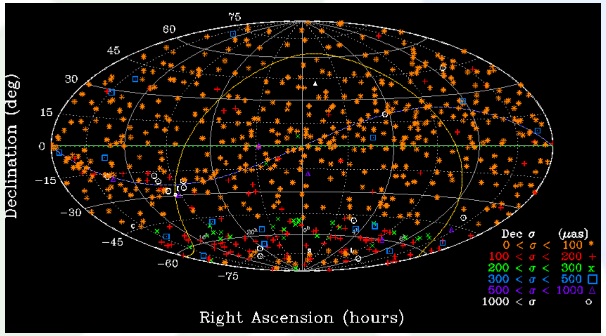


Geodetic Reference Frames – How They Contribute to Space Missions

- Positioning
  - GNSS, VLBI and SLR station positions
    - Space Geodesy Program (crustal deformation)
- Navigation
  - Precise orbit determination
    - SWOT, NISAR, Jason-3, Sentinel-6, ICESat/ICESat-2, GRACE/GRACE-FO . . .
  - Interplanetary spacecraft navigation
    - Mars Sample Return, Psyche, Europa Clipper, . . .
- Image geo-referencing
  - Connects measurements made at the same place at different times



Terrestrial Reference Frame



Celestial Reference Frame

Sea Level Change

Radar Altimetry Measurement Principle

The orbit of the altimetry-dedicated satellite is determined with high precision using GNSS, SLR and DORIS →

From the precise satellite orbit, the altitude of the satellite above a global ellipsoid is derived

A radar altimeter on-board the satellite permanently transmits signals to Earth and receives the return signals after reflection at Earth's surface

↓

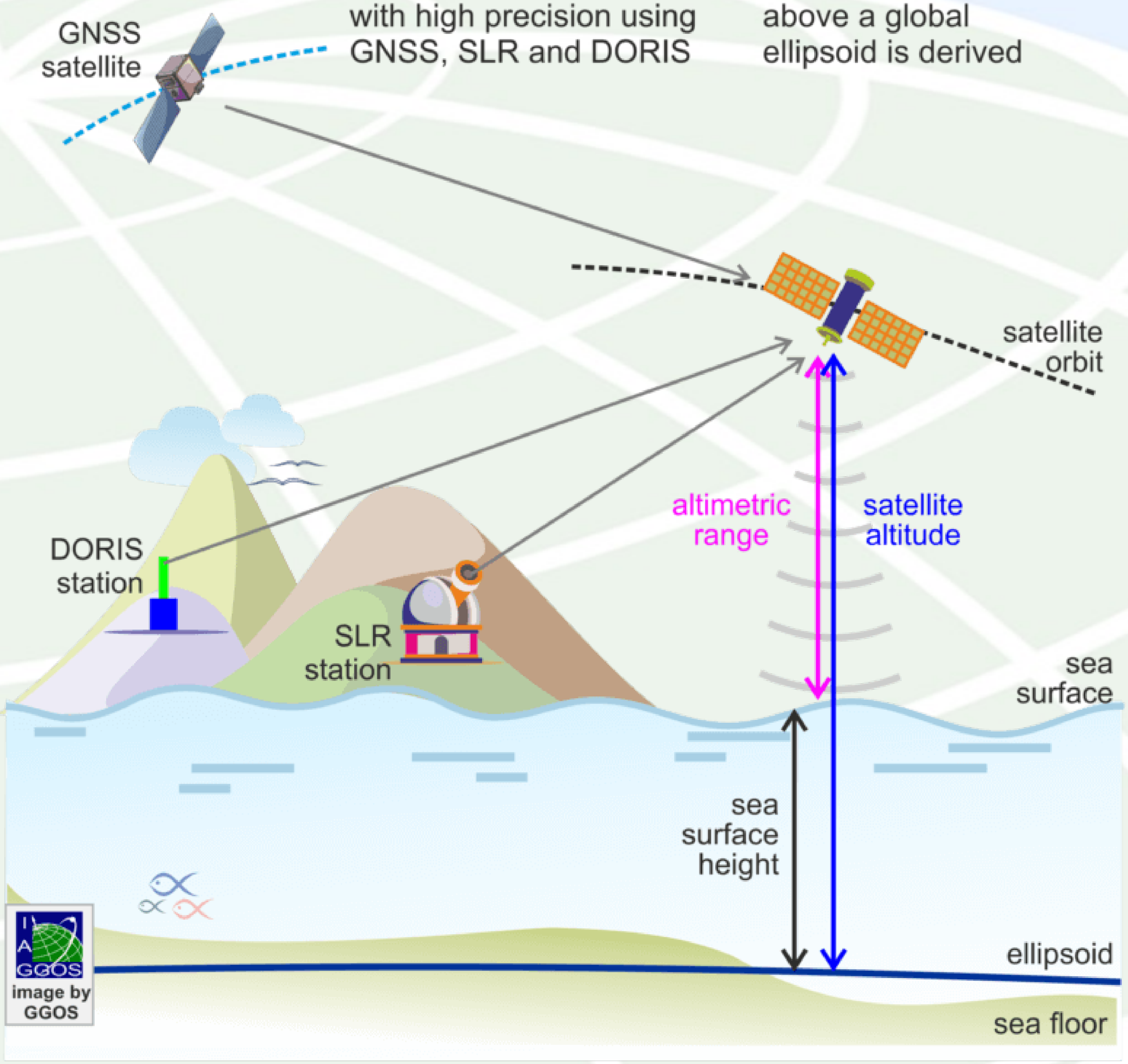
The primary measurement is the time taken by the radar pulse to travel from the satellite antenna to the surface and back to the satellite receiver

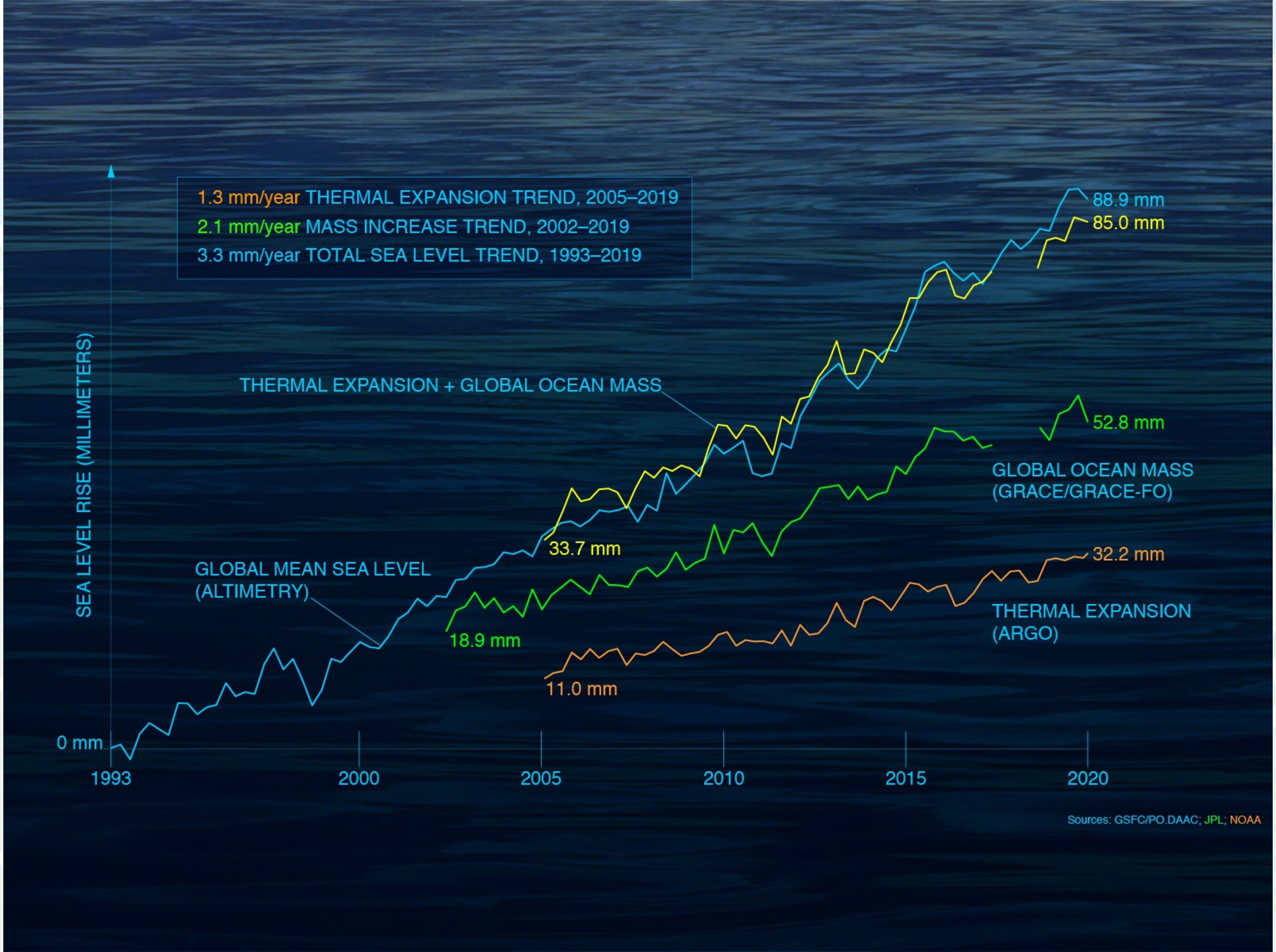
↓

The range, or distance between the satellite and Earth's surface is approximately equal to one-half of the two-way travel time multiplied by the speed of light

↓

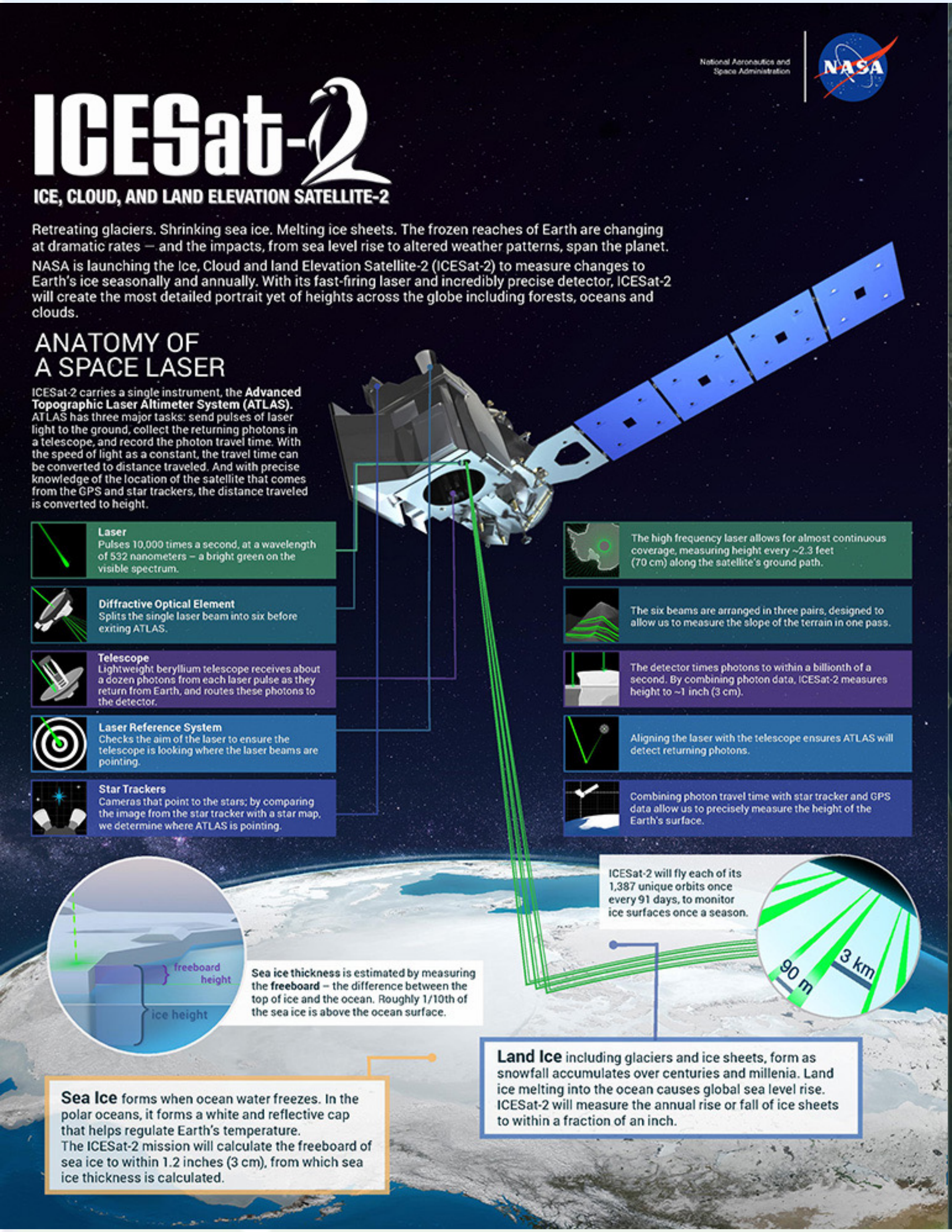
The difference between the satellite altitude and the altimetric range provides the surface height with respect to the same ellipsoid

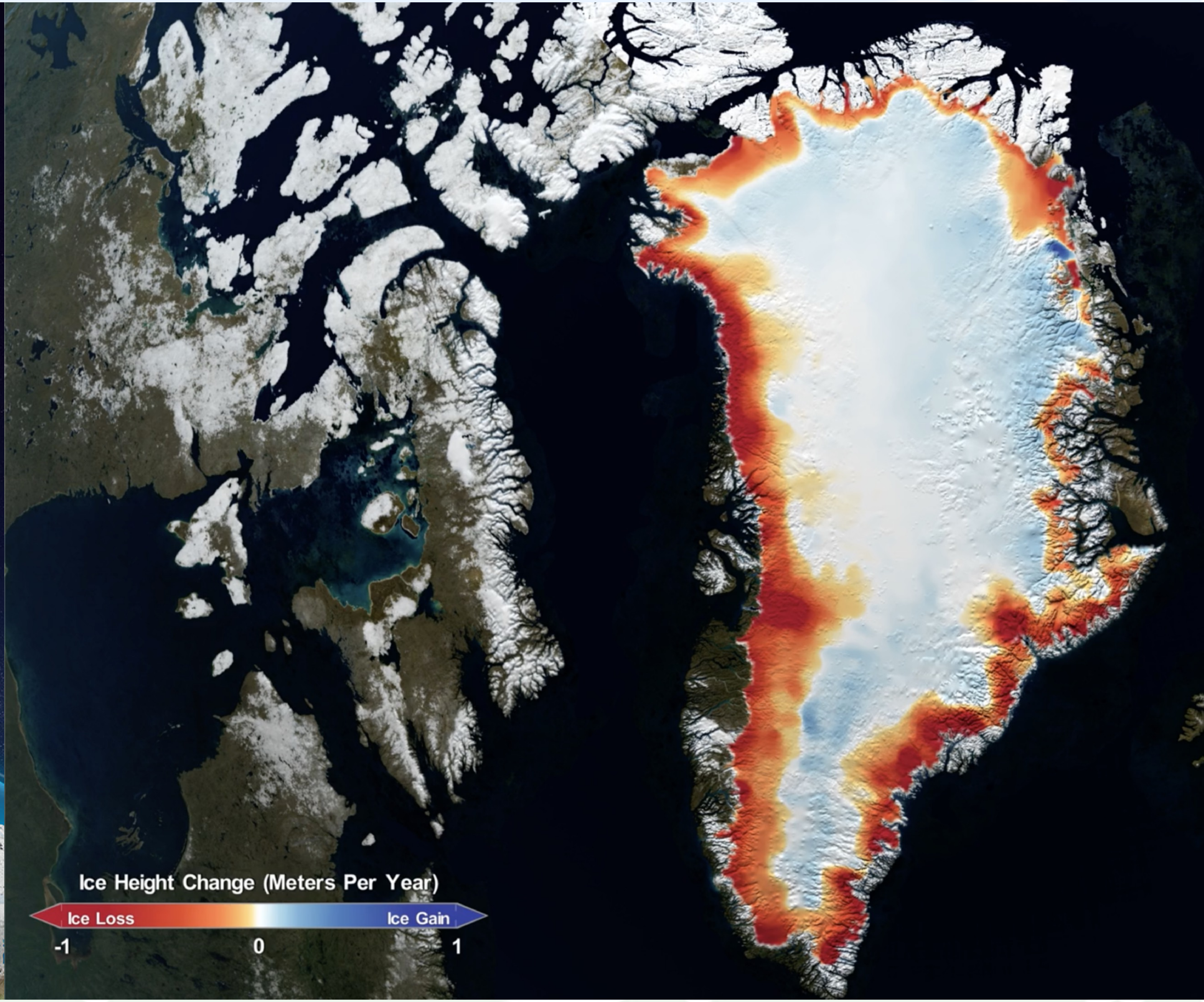




1.3 mm/year THERMAL EXPANSION TREND, 2005–2019
2.1 mm/year MASS INCREASE TREND, 2002–2019
3.3 mm/year TOTAL SEA LEVEL TREND, 1993–2019
SEA LEVEL RISE (MILLIMETERS)
88.9 mm
85.0 mm
THERMAL EXPANSION + GLOBAL OCEAN MASS
52.8 mm
GLOBAL OCEAN MASS
(GRACE/GRACE-FO)
33.7 mm
GLOBAL MEAN SEA LEVEL
(ALTIMETRY)
32.2 mm
THERMAL EXPANSION
(ARGO)
18.9 mm
11.0 mm
0 mm
1993
2000
2005
2010
2015
2020
Sources: GSFC/PO.DAAC; JPL; NOAA

Ice Sheet Height Change

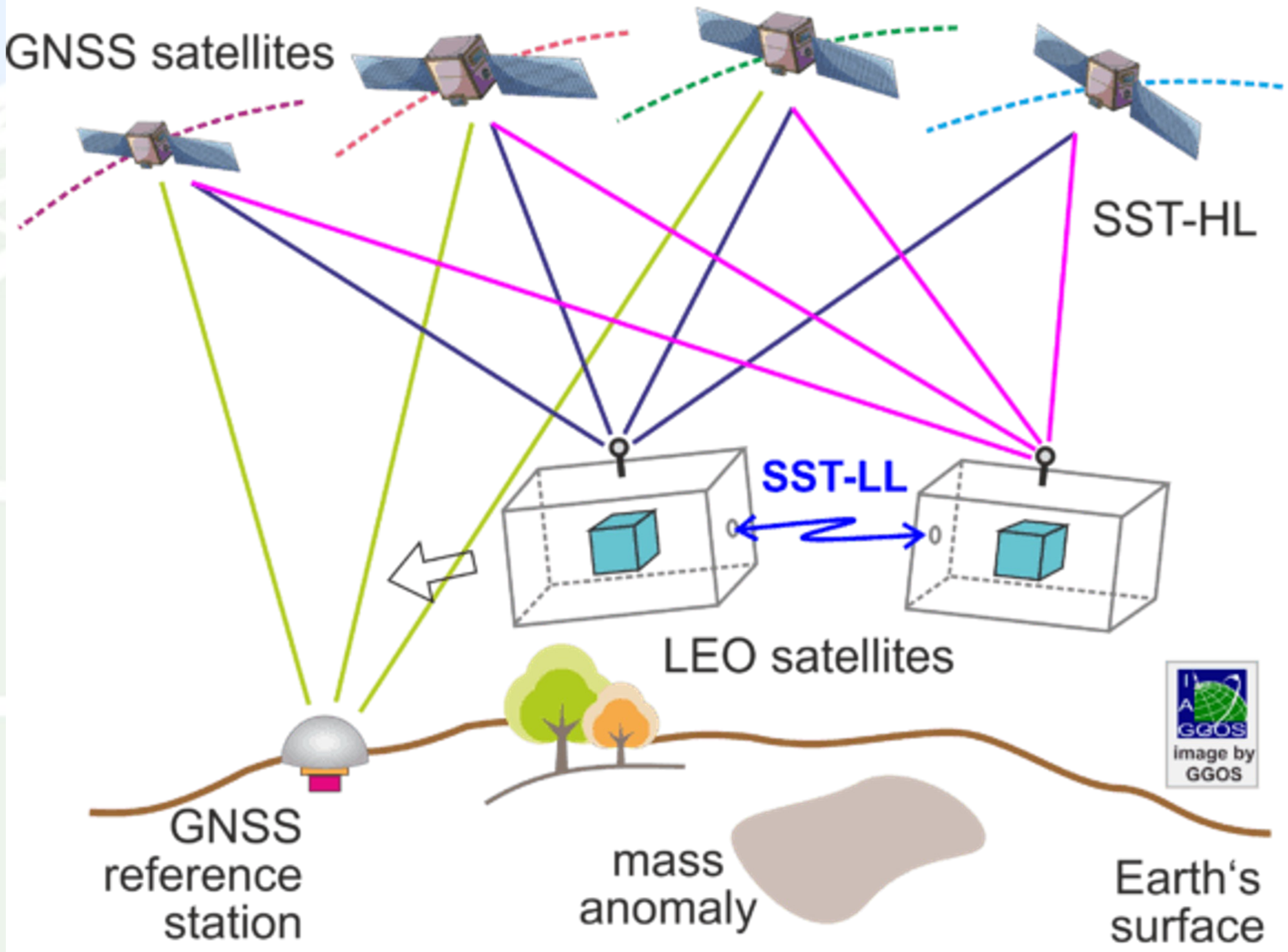




Source: NASA Scientific Visualization Studio

Mass Change

GRACE Measurement Principle

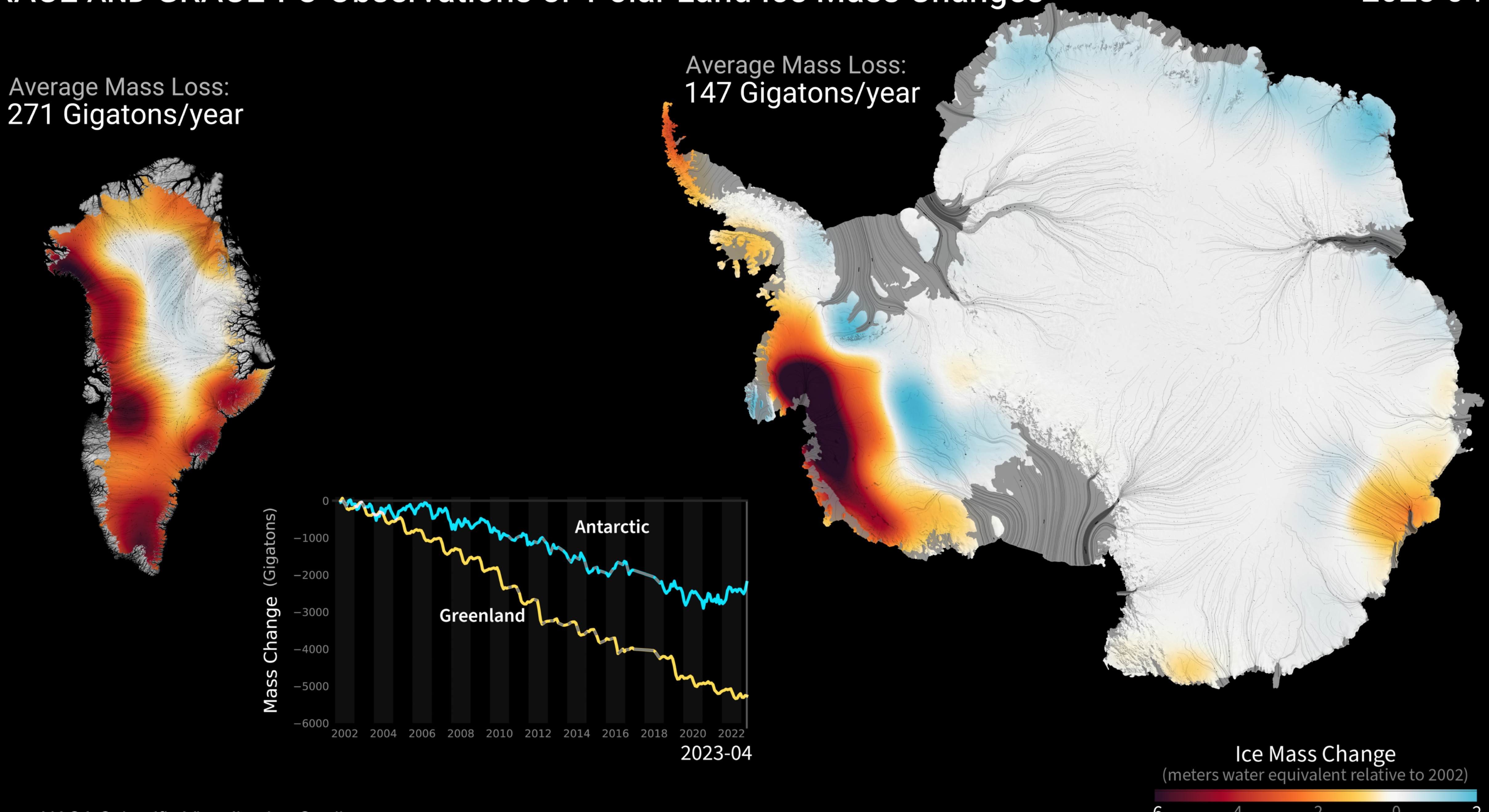


Satellite-to-satellite tracking in the low-low (SST-LL) mode: measurement of acceleration differences between two low Earth orbiting (LEO) satellites.

The orbits of the two satellites are determined using GNSS. The distance between the two satellites is measured with the highest possible accuracy. The acceleration differences between the two satellites allow the determination of the gravity field with a spatial resolution of about 170 km for the static component and about 300 km for monthly solutions.

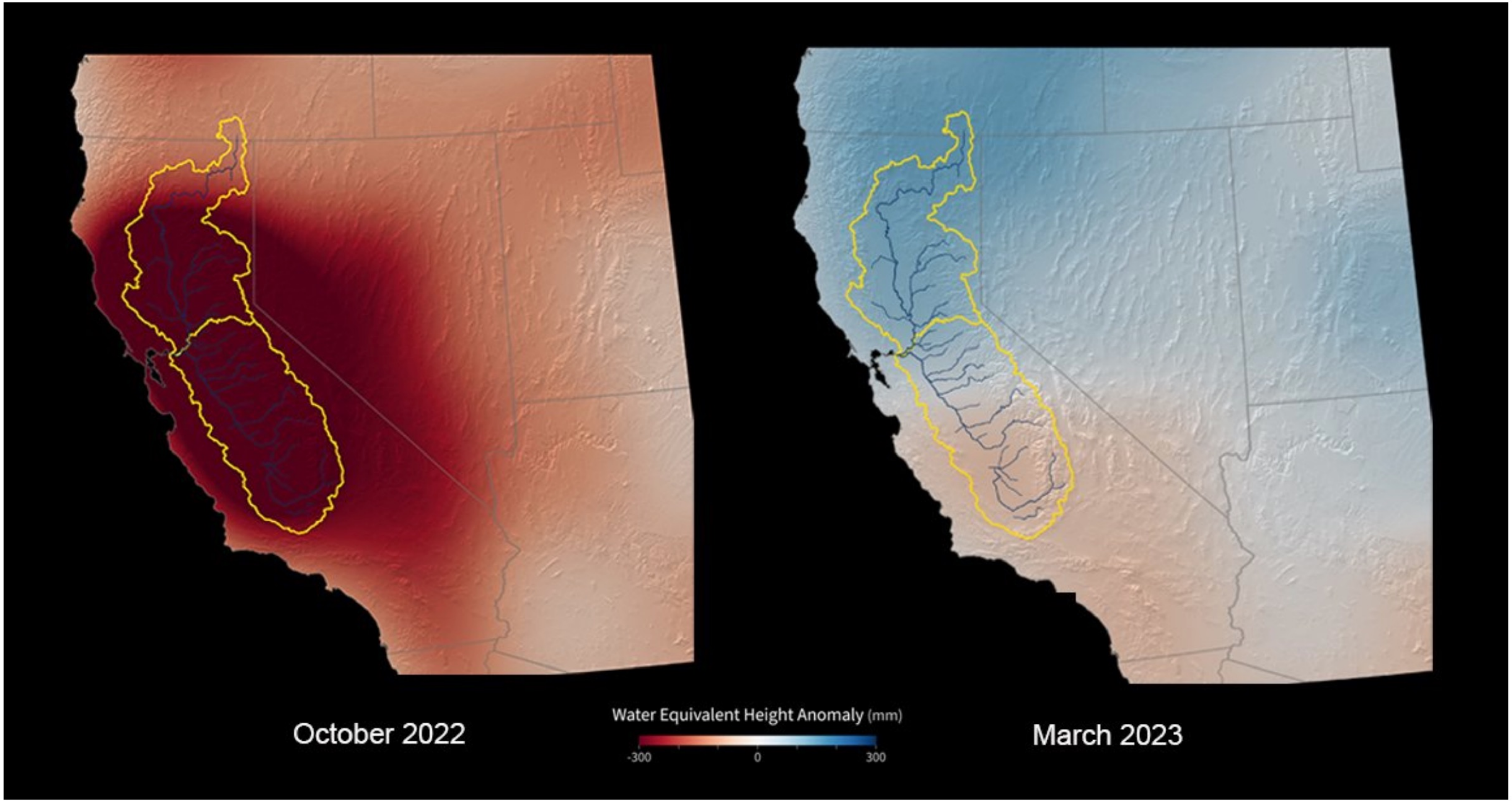
GRACE AND GRACE-FO Observations OF Polar Land Ice Mass Changes

2023-04



Source: NASA Scientific Visualization Studio

Terrestrial Water Storage Change

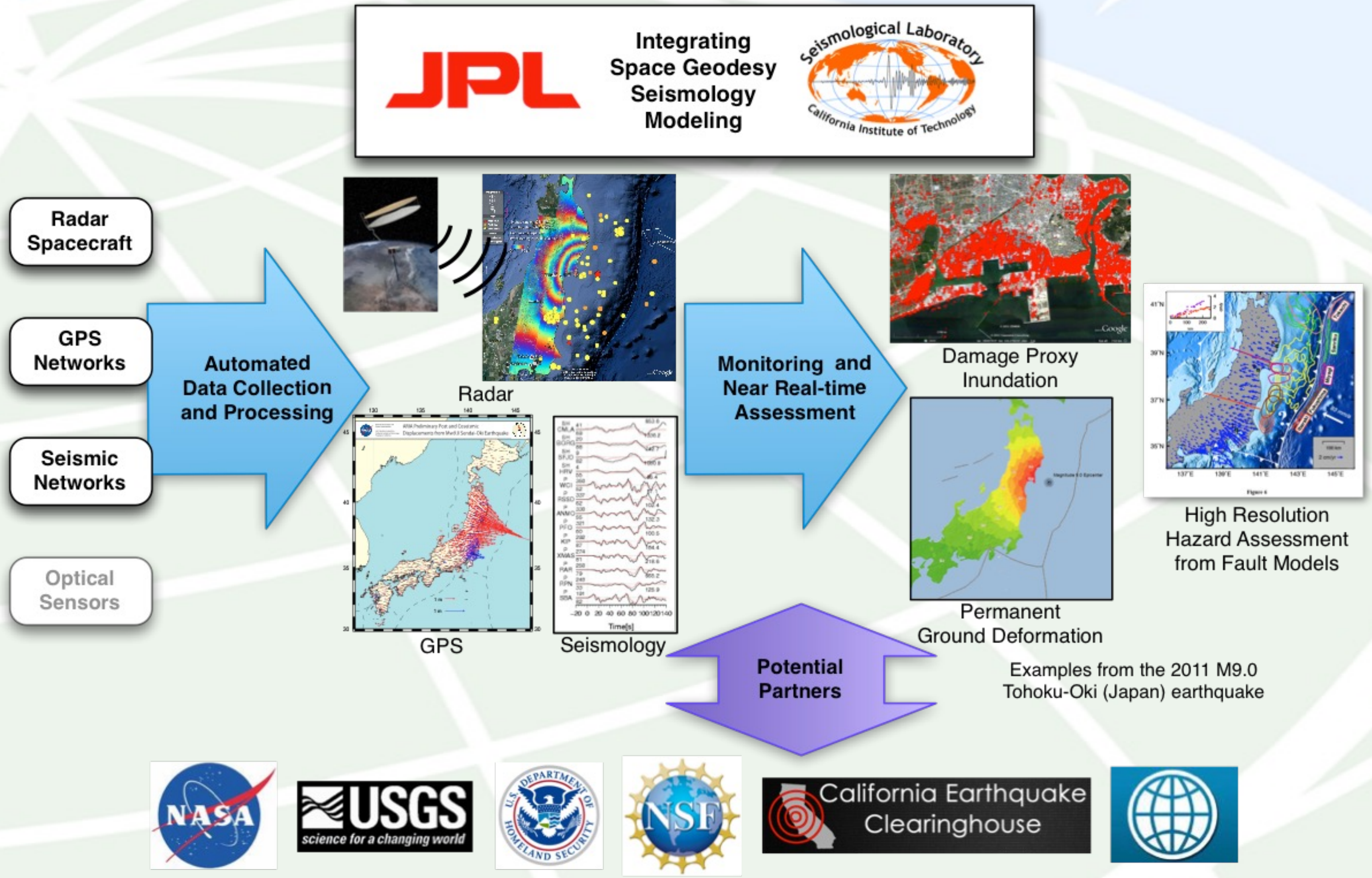


Thanks to a wet winter, California saw tremendous gains in the amount of water in the San Joaquin, Sacramento, and Tulare river basins (outlined in yellow) from October 2022 to March 2023, GRACE-FO data shows. The measurement includes water in lakes, rivers, reservoirs, snowpack, and groundwater aquifers.

Source: NASA Scientific Visualization Studio

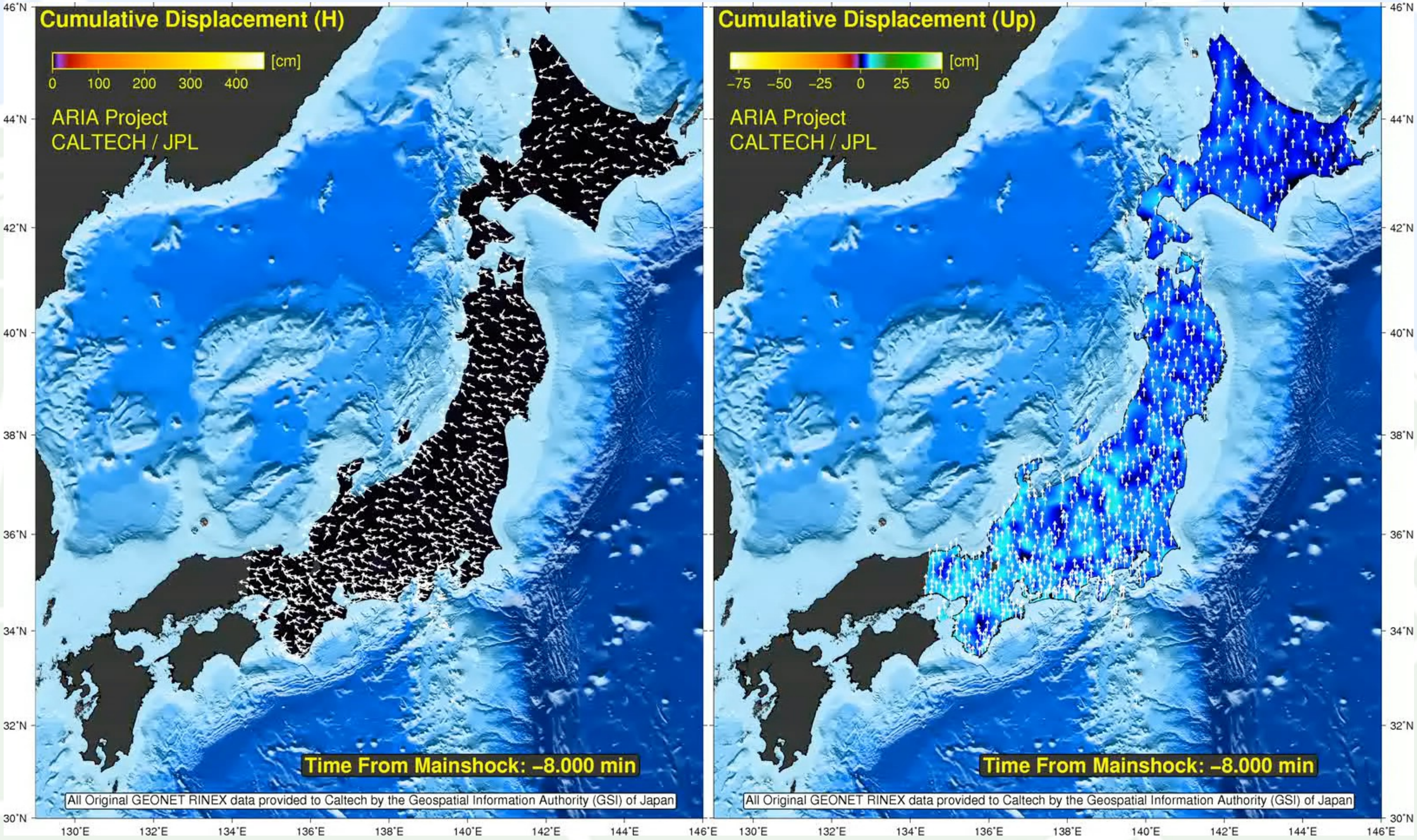
Crustal Deformation

Advanced Rapid Imaging and Analysis (ARIA)



Source: aria.jpl.nasa.gov

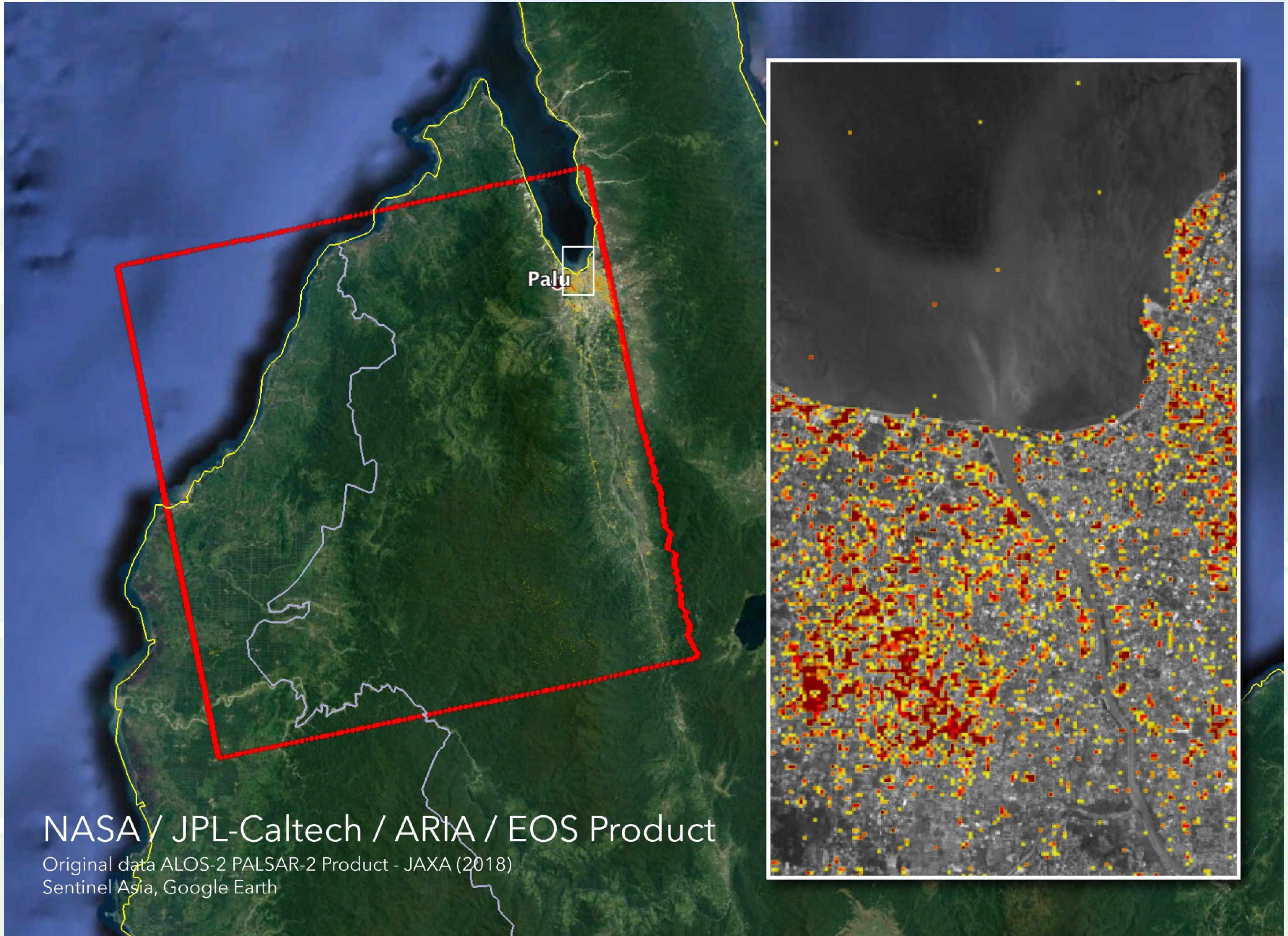
2011 Tohoku-Oki



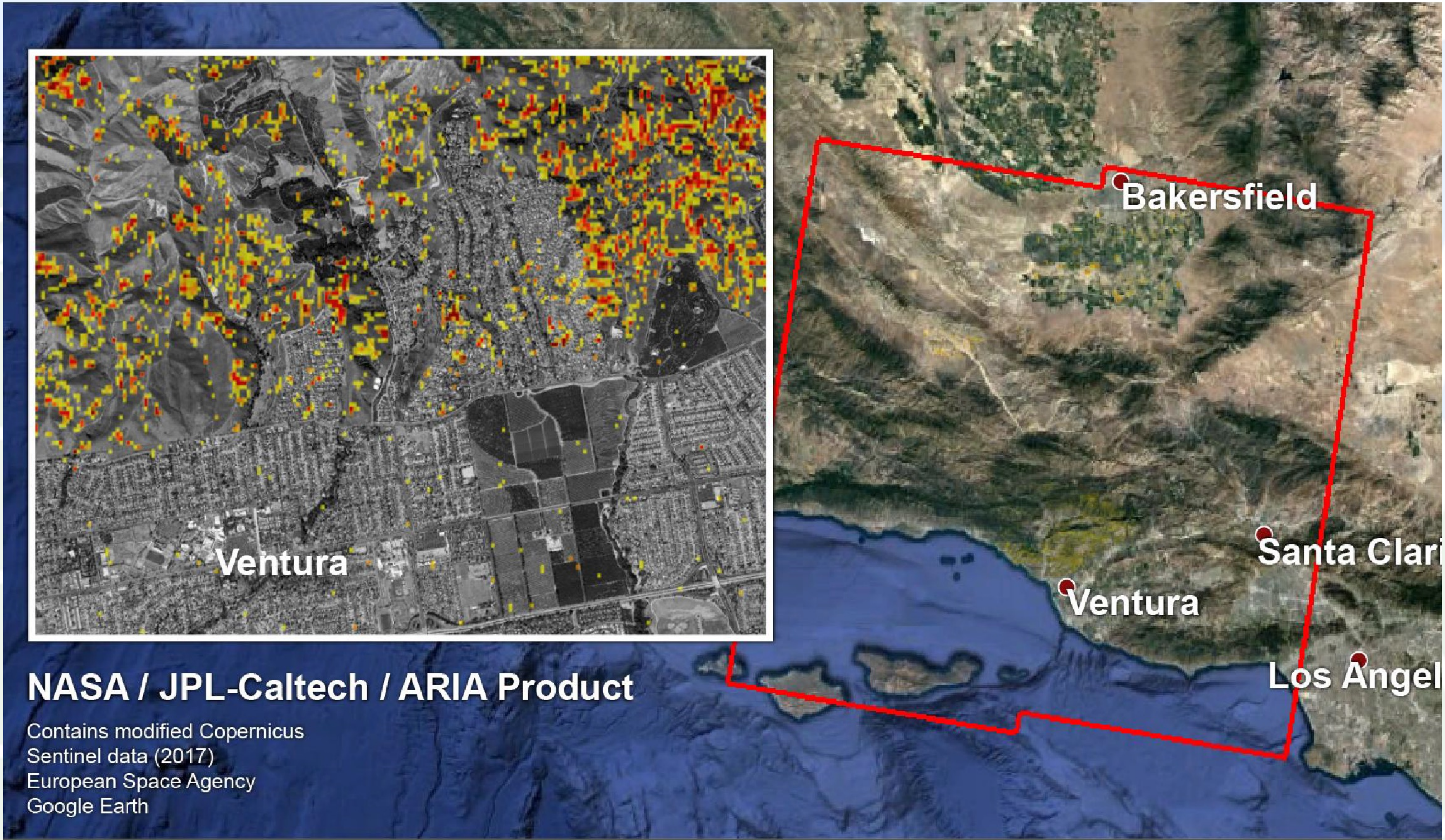
http://tectonics.caltech.edu/slip_history/2011_taiheiyo-oki/Displacement/

Damage Proxy Maps

Damage Proxy Map (Earthquake & Tsunami)

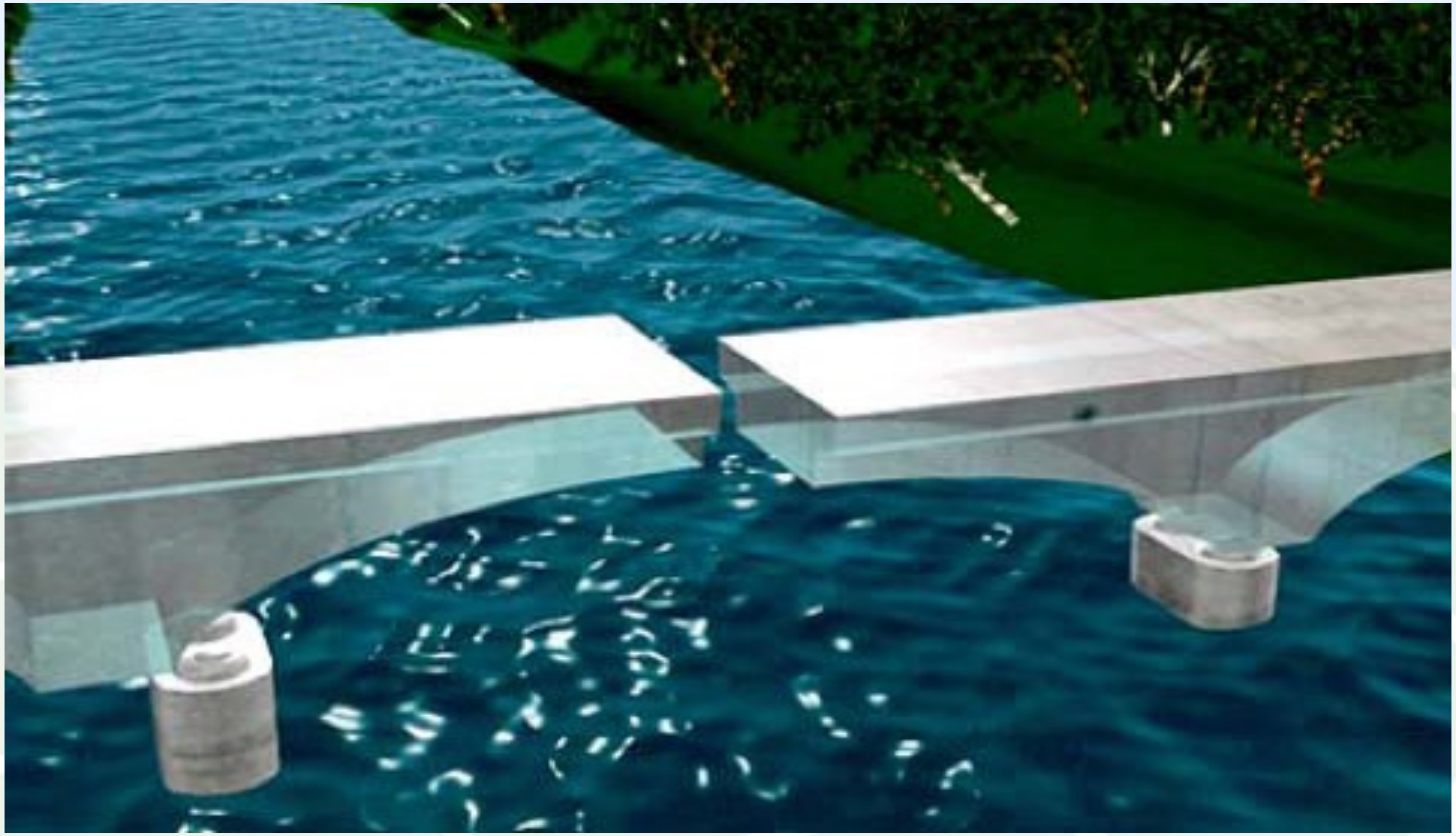


Damage Proxy Map (Wildfire)



Engineering Geodesy

An Inaccurate Reference Frame Can Be Very Expensive



Design error at bridge construction in Laufenburg (2003): During the construction of the bridge across the Rhine river in Laufenburg, a control showed that a height difference of 54 centimeters exists between the bridge built from the Swiss side and the roadway of the German side. Reason of the error is the fact that the horizons of the German and Swiss side are based on different reference frames. Germany refers to the sea level of the North Sea, Switzerland to the Mediterranean.

Interplanetary Spacecraft Navigation

Interplanetary Spacecraft Navigation

- Accurate navigation of interplanetary spacecraft requires accurate knowledge of Earth's orientation
  - Must know Earth's orientation in space to know spacecraft's position in space from Earth-based tracking measurements
    - Uncertainty in Earth's orientation can be a major, if not the dominant, source of error in spacecraft navigation and tracking (Estefan and Folkner, 1995)
    - Error in UT1 of 0.1 ms (4.6 cm) produces an error of 7 nrad in spacecraft right ascension, corresponding to a position error at Mars of 1.6 km
- Earth's orientation in space given by 5 parameters:
  - 2 precession-nutation parameters (dX, dY)
    - Specifies location of spin axis in *celestial* reference frame
  - 2 polar motion parameters (PMX, PMY)
    - Specifies location of spin axis in *terrestrial* reference frame
  - 1 spin parameter (UT1)
    - Specifies angle through which Earth has rotated about spin axis