

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



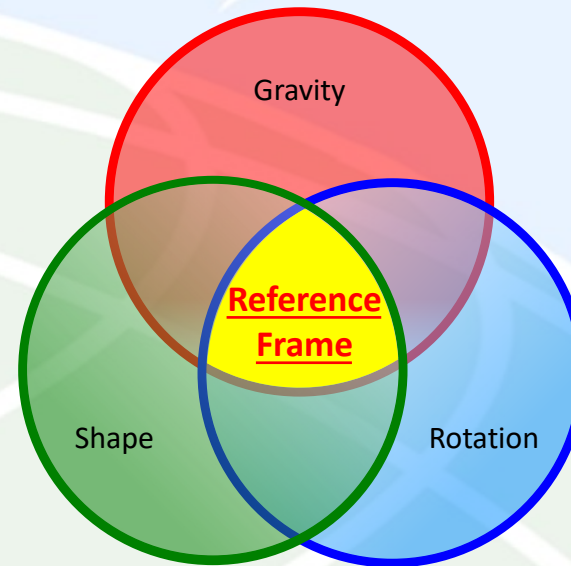
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Geodesy

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

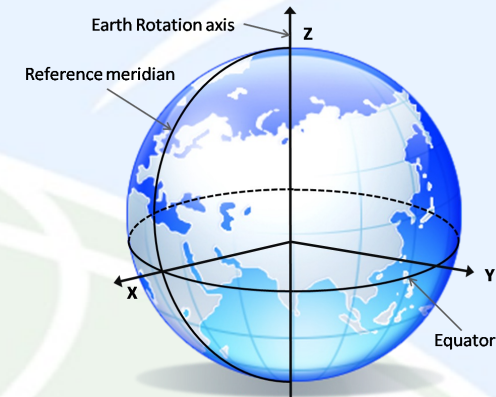


Establishing and disseminating the Terrestrial Reference Frame (TRF) is central to Geodesy

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

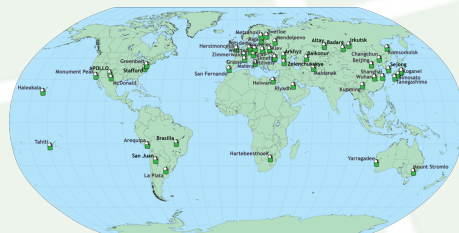
- **Improvement**

- 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



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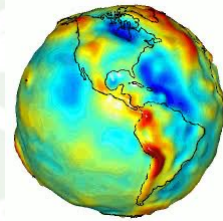
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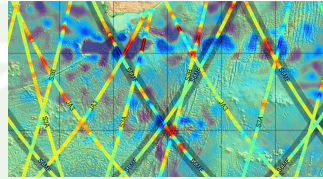
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Geodesy – Impact to Science and Society

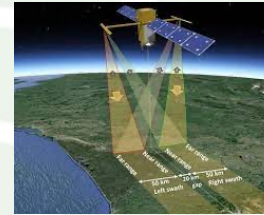
Earth
Observation



Gravity



Sea Level



Oceanography &
Hydrology



Earthquakes



Volcanos

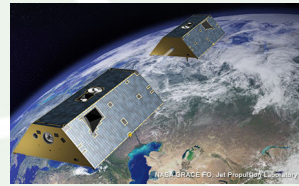


Cryosphere



Tsunamis

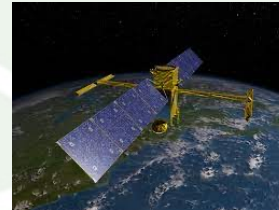
Space Missions



GRACE-FO



Sentinel-6 M-F



SWOT



NISAR

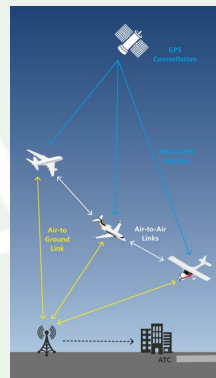


ICESAT-2

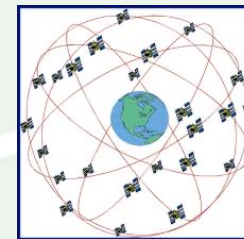
Infrastructure



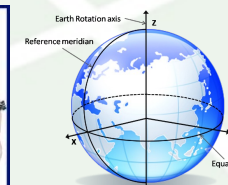
Precision farming



Aviation



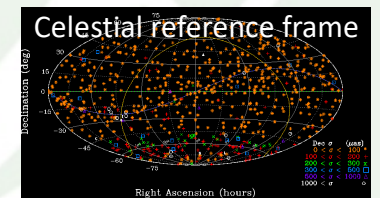
GPS/GNSS



Terrestrial
Reference
Frame



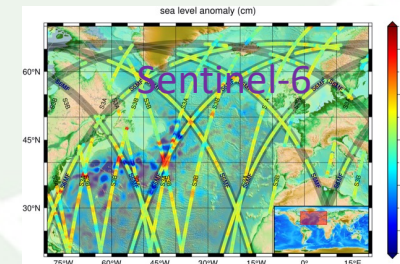
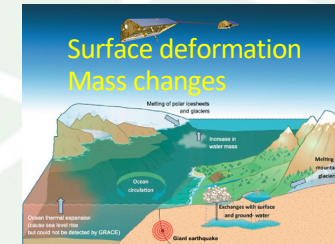
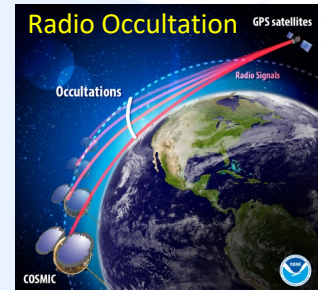
GPS based
Timing for Financial
Transactions



All deep space missions

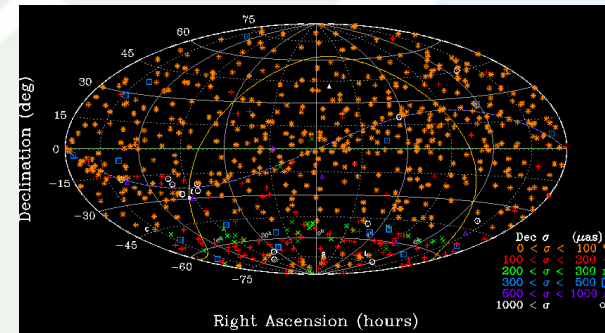
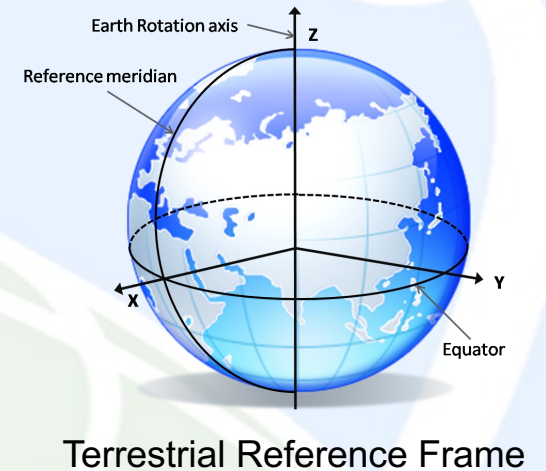
How Geodesy Impacts the Science Community

- 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

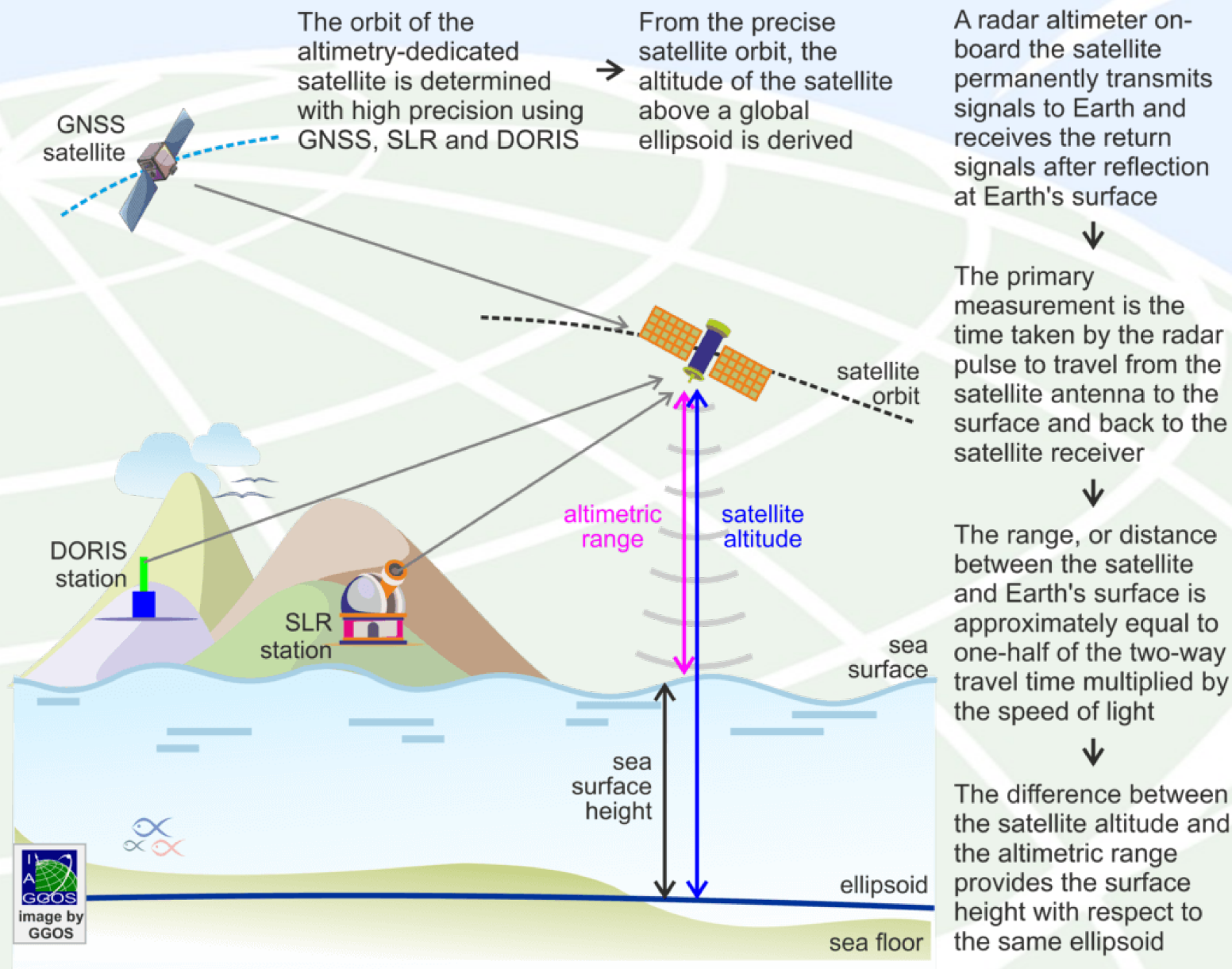
- Positioning
 - GNSS, VLBI and SLR station positions
 - Space Geodesy Program (crustal deformation)
- Navigation
 - Precise orbit determination
 - SWOT, NISAR, Jason-3, Sentinel-6, ICESat/ICESat-2, GRACE/GRACE-FO . . .
 - Interplanetary spacecraft navigation
 - Mars Sample Return, Psyche, Europa Clipper,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

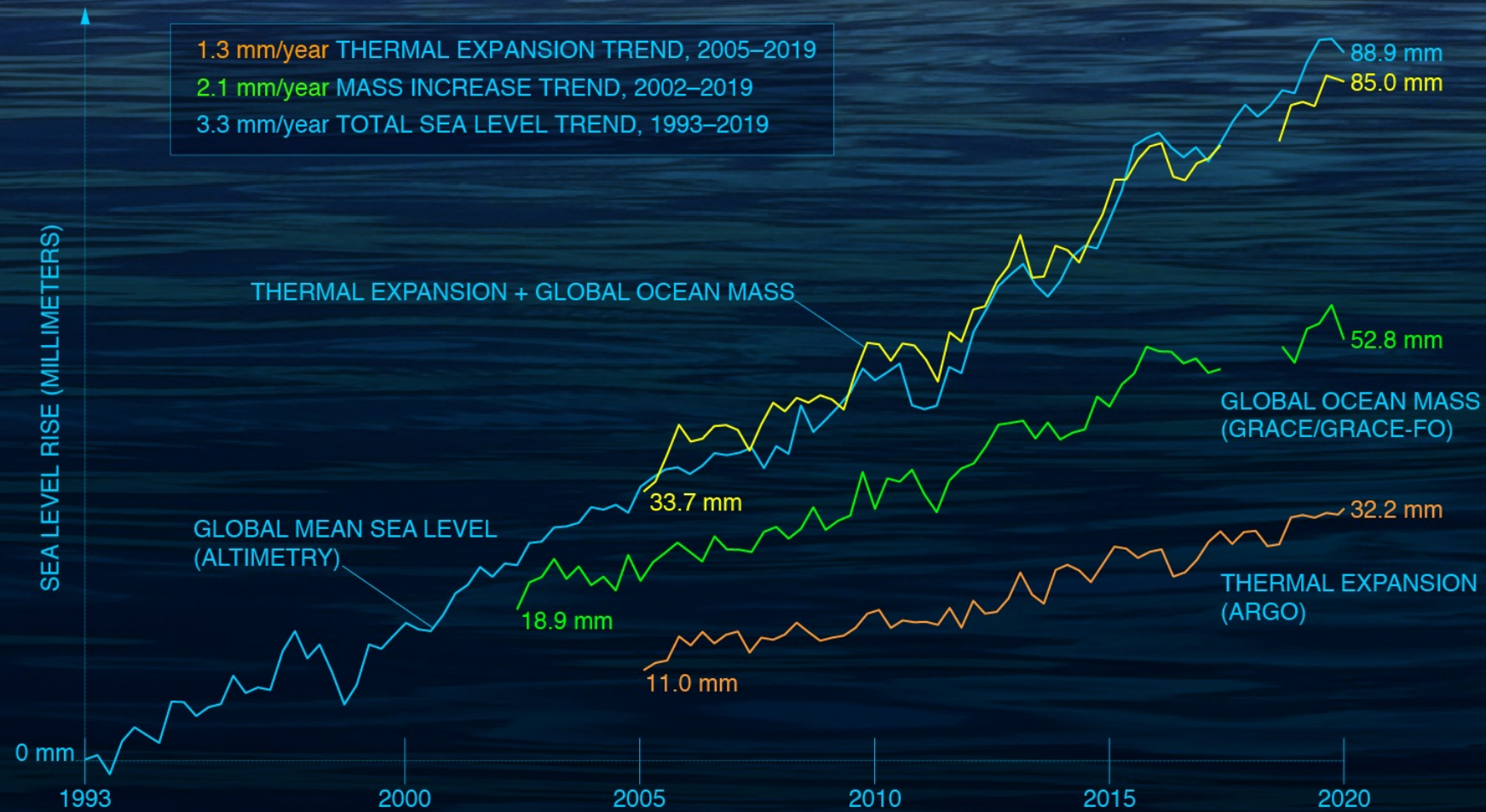


A stylized illustration of a globe with a light green surface and white grid lines representing latitude and longitude. A white arrow points upwards from the top left of the globe. On the right side, a white curved line with a circular end suggests a path or orbit. The background is a solid light blue.

Sea Level Change

Radar Altimetry Measurement Principle





Sources: GSFC/PO.DAAC; JPL; NOAA

A stylized illustration of a globe with a light green surface and white grid lines representing latitude and longitude. A white satellite orbit with a circular node is shown on the right side, and a white arrow points upwards from the top left. The background is a solid light blue.

Ice Sheet Height Change

ICESat-2

ICE, CLOUD, AND LAND ELEVATION SATELLITE-2

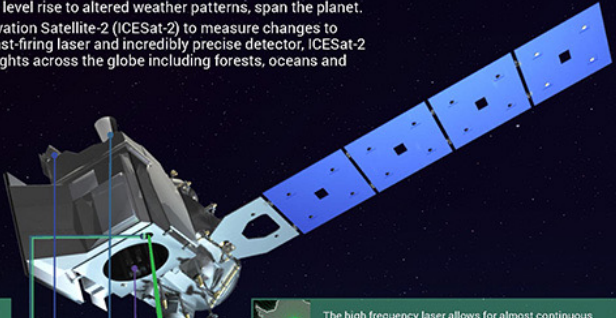
National Aeronautics and Space Administration



Retreating glaciers. Shrinking sea ice. Melting ice sheets. The frozen reaches of Earth are changing at dramatic rates — and the impacts, from sea level rise to altered weather patterns, span the planet. NASA is launching the Ice, Cloud and land Elevation Satellite-2 (ICESat-2) to measure changes to Earth's ice seasonally and annually. With its fast-firing laser and incredibly precise detector, ICESat-2 will create the most detailed portrait yet of heights across the globe including forests, oceans and clouds.

ANATOMY OF A SPACE LASER

ICESat-2 carries a single instrument, the **Advanced Topographic Laser Altimeter System (ATLAS)**. ATLAS has three major tasks: send pulses of laser light to the ground, collect the returning photons in a telescope, and record the photon travel time. With the speed of light as a constant, the travel time can be converted to distance traveled. And with precise knowledge of the location of the satellite that comes from the GPS and star trackers, the distance traveled is converted to height.



Laser
Pulses 10,000 times a second, at a wavelength of 532 nanometers — a bright green on the visible spectrum.

Diffractive Optical Element
Splits the single laser beam into six before exiting ATLAS.

Telescope
Lightweight beryllium telescope receives about a dozen photons from each laser pulse as they return from Earth, and routes these photons to the detector.

Laser Reference System
Checks the aim of the laser to ensure the telescope is looking where the laser beams are pointing.

Star Trackers
Cameras that point to the stars; by comparing the image from the star tracker with a star map, we determine where ATLAS is pointing.

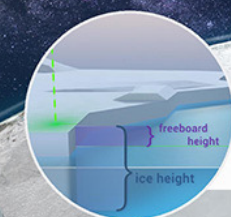
The high frequency laser allows for almost continuous coverage, measuring height every ~2.3 feet (70 cm) along the satellite's ground path.

The six beams are arranged in three pairs, designed to allow us to measure the slope of the terrain in one pass.

The detector times photons to within a billionth of a second. By combining photon data, ICESat-2 measures height to ~1 inch (3 cm).

Aligning the laser with the telescope ensures ATLAS will detect returning photons.

Combining photon travel time with star tracker and GPS data allow us to precisely measure the height of the Earth's surface.

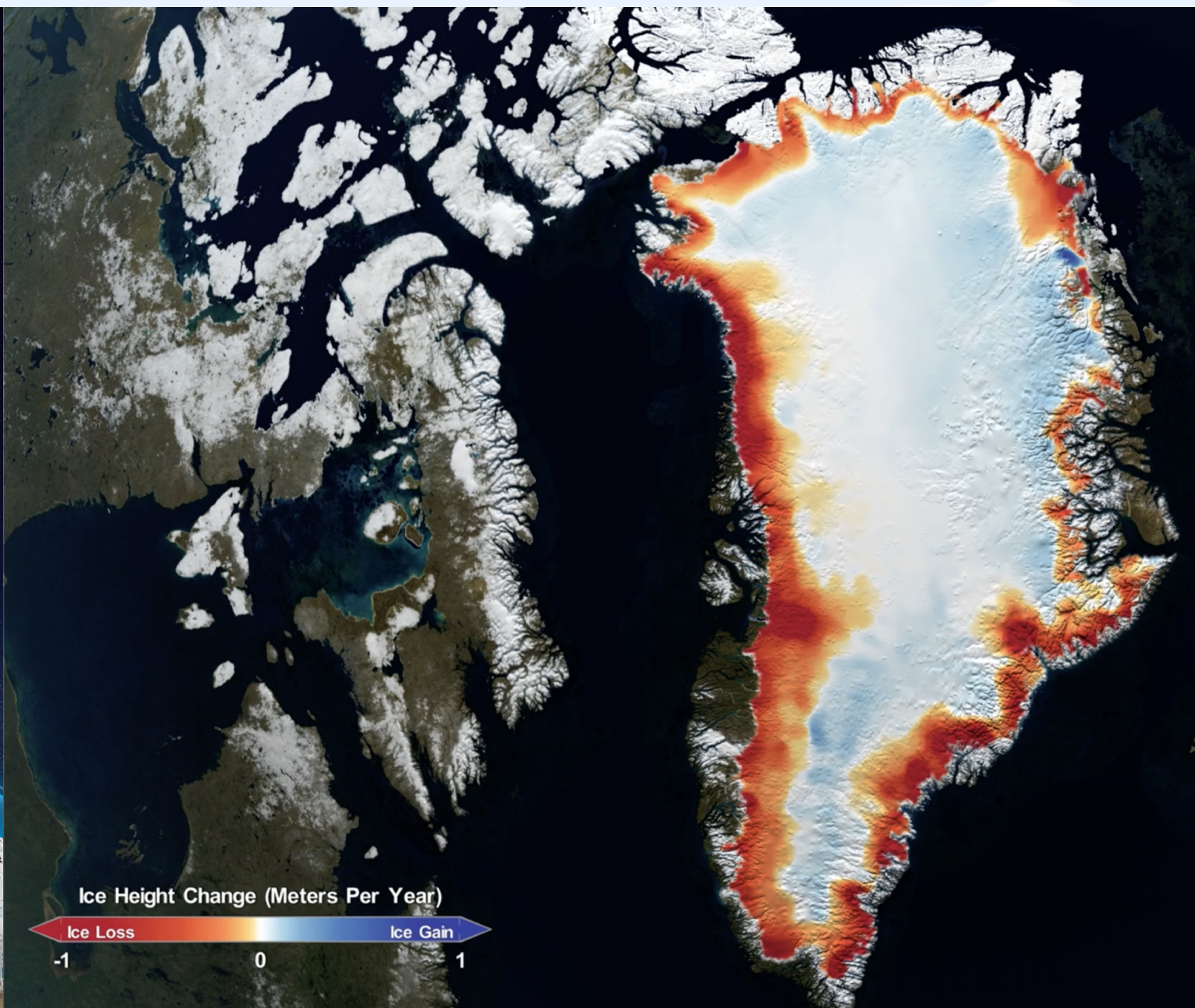
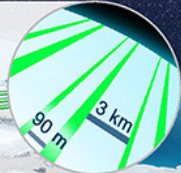


Sea ice thickness is estimated by measuring the freeboard — the difference between the top of ice and the ocean. Roughly 1/10th of the sea ice is above the ocean surface.

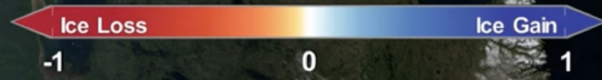
Sea Ice forms when ocean water freezes. In the polar oceans, it forms a white and reflective cap that helps regulate Earth's temperature. The ICESat-2 mission will calculate the freeboard of sea ice to within 1.2 inches (3 cm), from which sea ice thickness is calculated.

Land Ice including glaciers and ice sheets, form as snowfall accumulates over centuries and millennia. Land ice melting into the ocean causes global sea level rise. ICESat-2 will measure the annual rise or fall of ice sheets to within a fraction of an inch.

ICESat-2 will fly each of its 1,387 unique orbits once every 91 days, to monitor ice surfaces once a season.



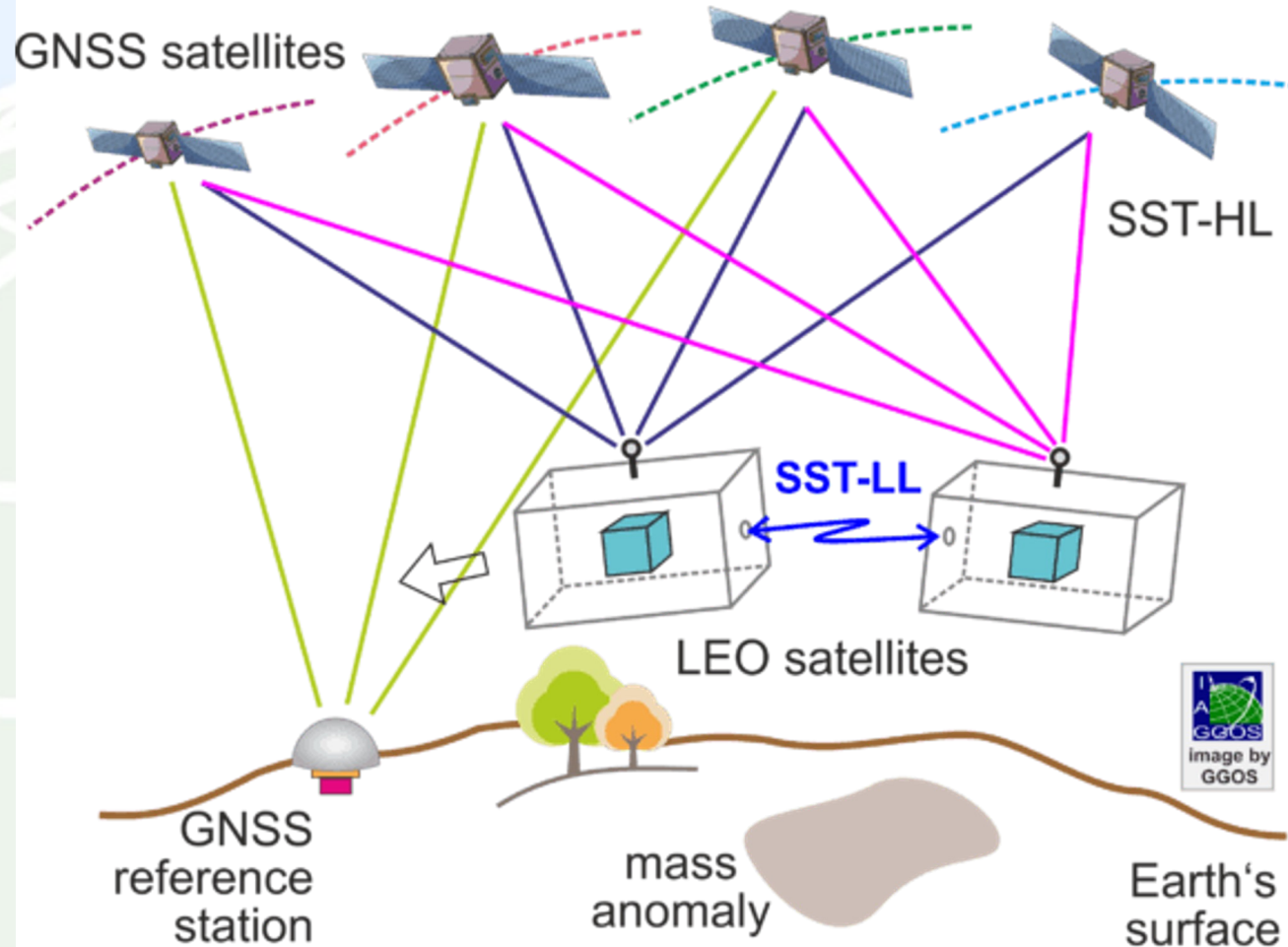
Ice Height Change (Meters Per Year)



A stylized illustration of a globe with a light green surface and white grid lines representing latitude and longitude. A white satellite orbit with a circular node is shown on the right side of the globe. A white arrow points upwards from the top left of the globe. The background is a solid light blue color.

Mass Change

GRACE Measurement Principle



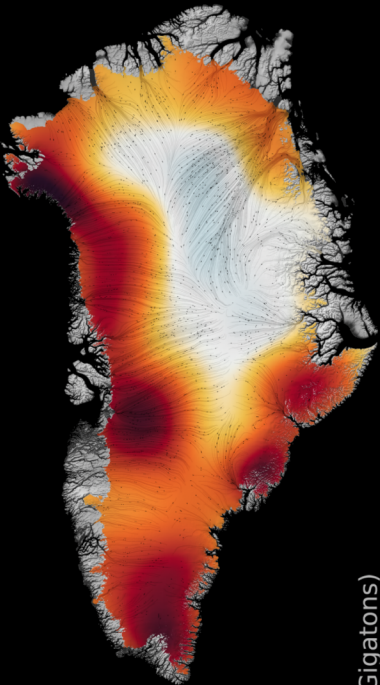
Satellite-to-satellite tracking in the low-low (SST-LL) mode: measurement of acceleration differences between two low Earth orbiting (LEO) satellites.

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.

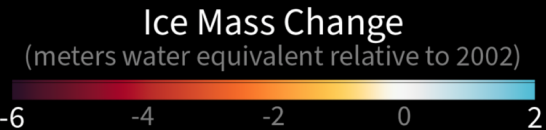
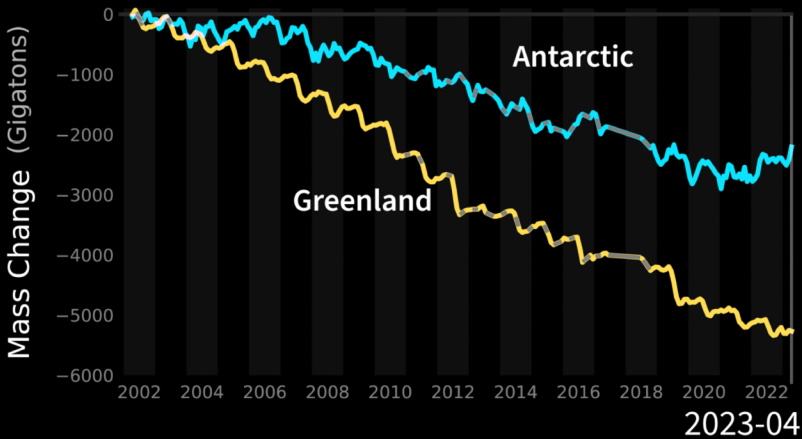
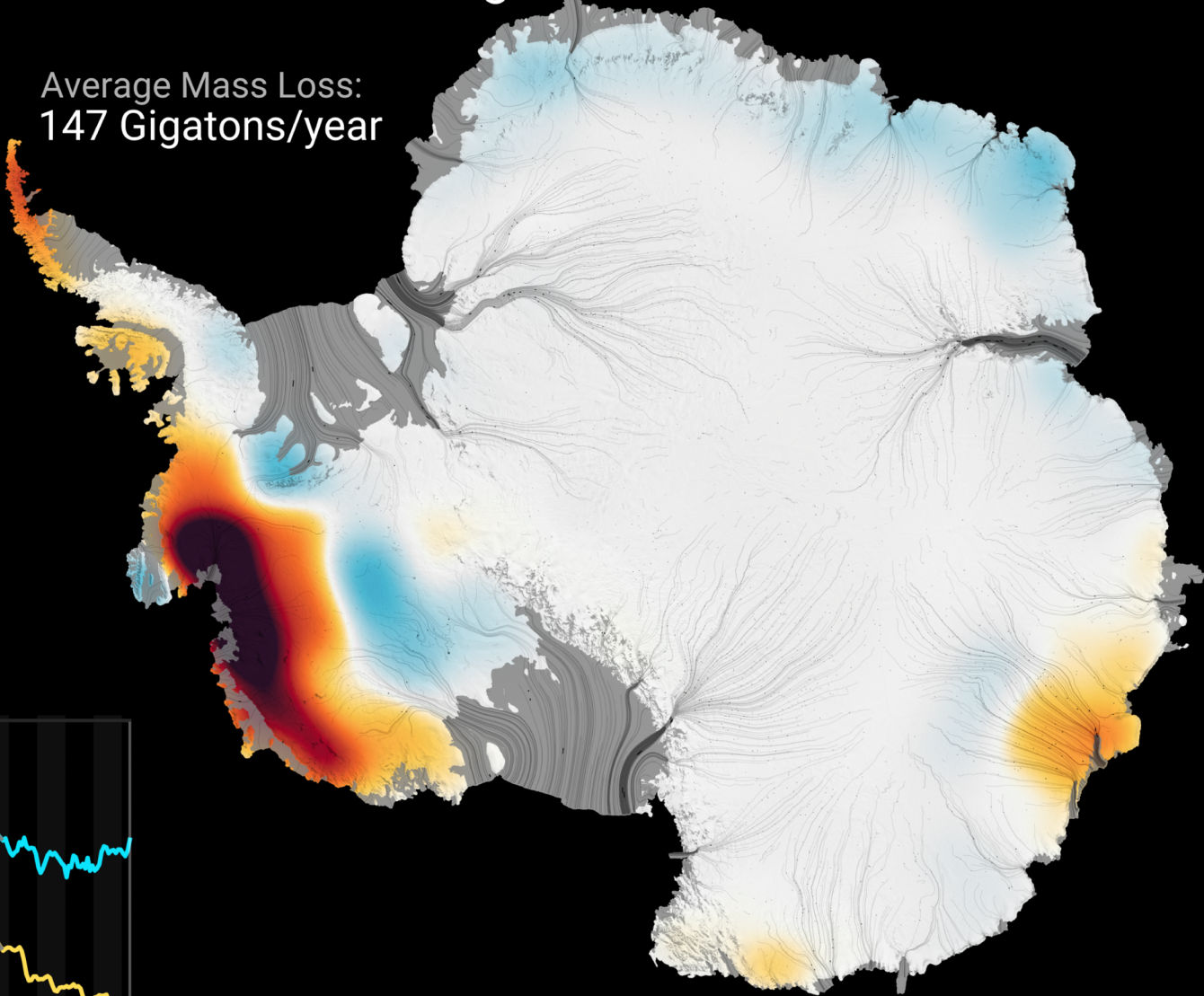
GRACE AND GRACE-FO Observations of Polar Land Ice Mass Changes

2023-04

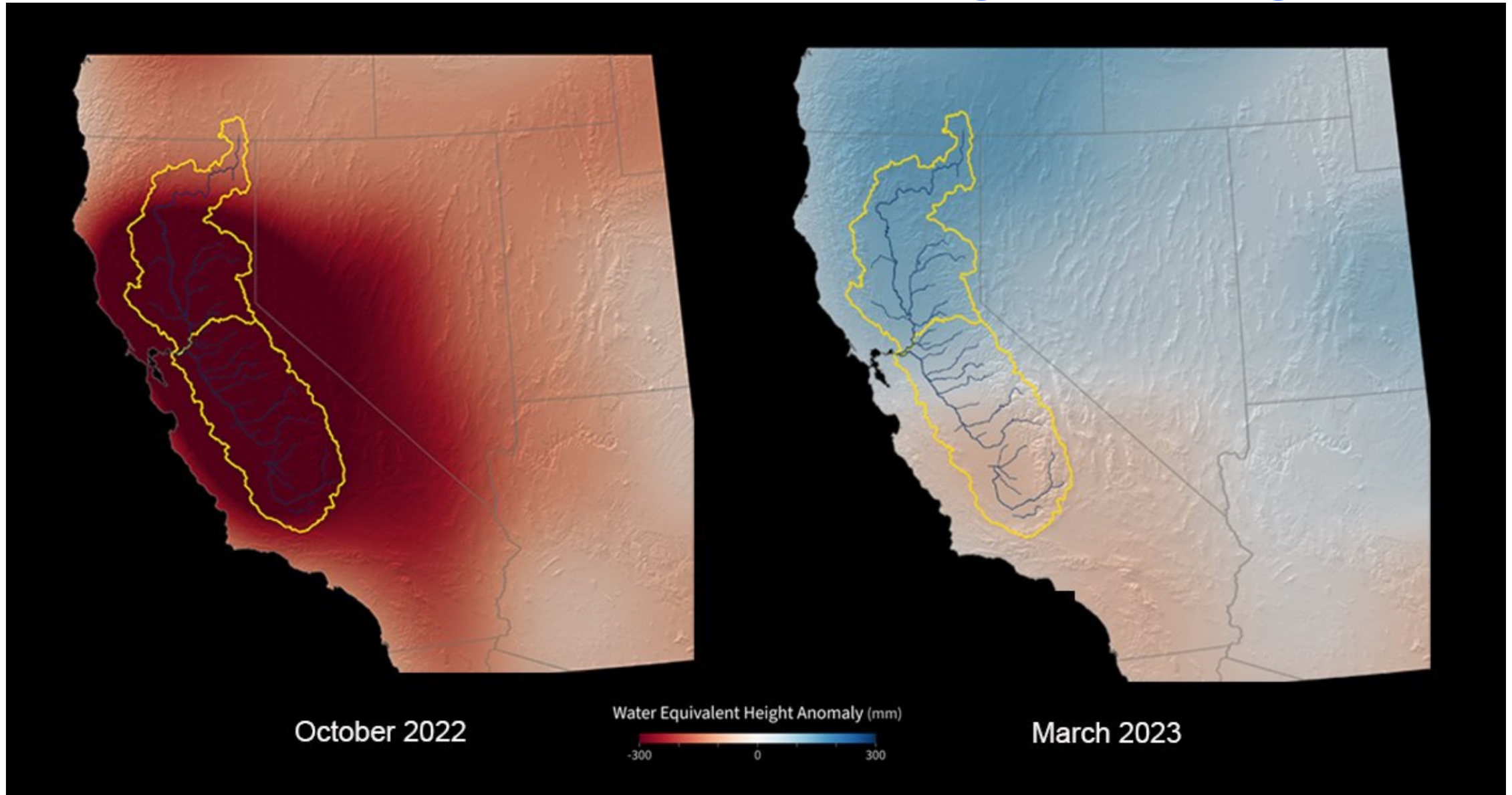
Average Mass Loss:
271 Gigatons/year



Average Mass Loss:
147 Gigatons/year



Terrestrial Water Storage Change



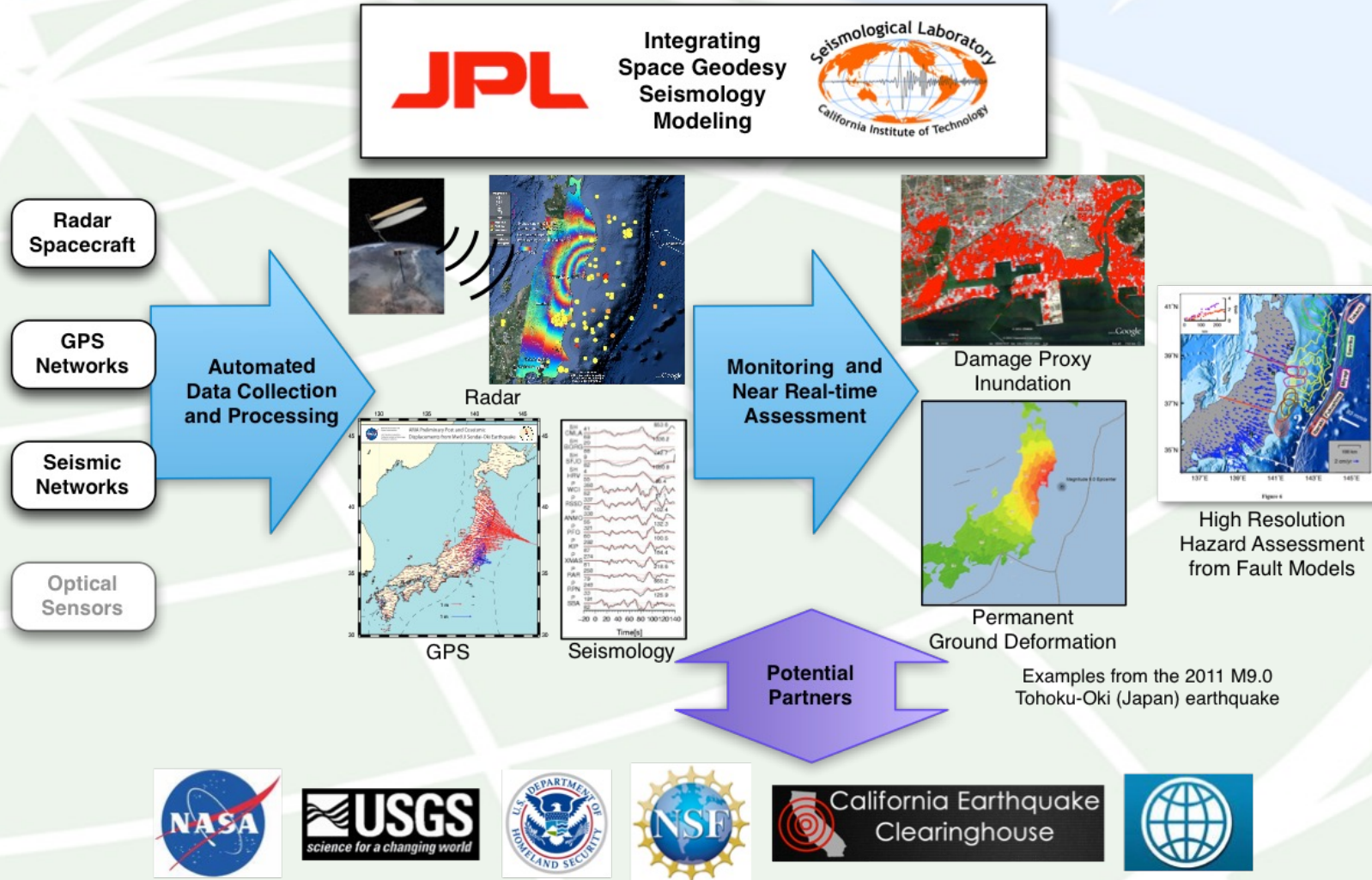
Thanks to a wet winter, California saw tremendous gains in the amount of water in the San Joaquin, Sacramento, and Tulare river basins (outlined in yellow) from October 2022 to March 2023, GRACE-FO data shows. The measurement includes water in lakes, rivers, reservoirs, snowpack, and groundwater aquifers.

Source: NASA Scientific Visualization Studio

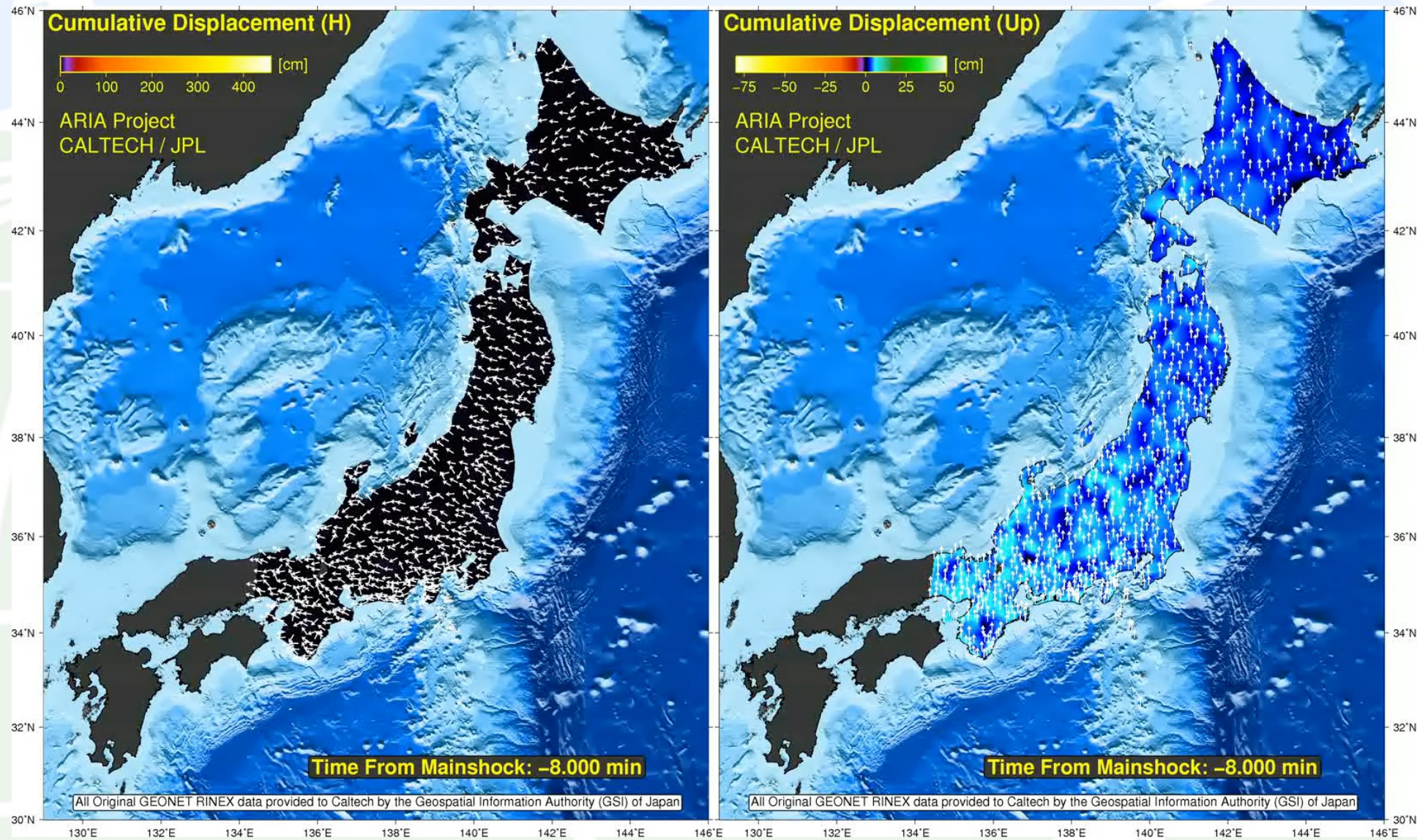


Crustal Deformation

Advanced Rapid Imaging and Analysis (ARIA)



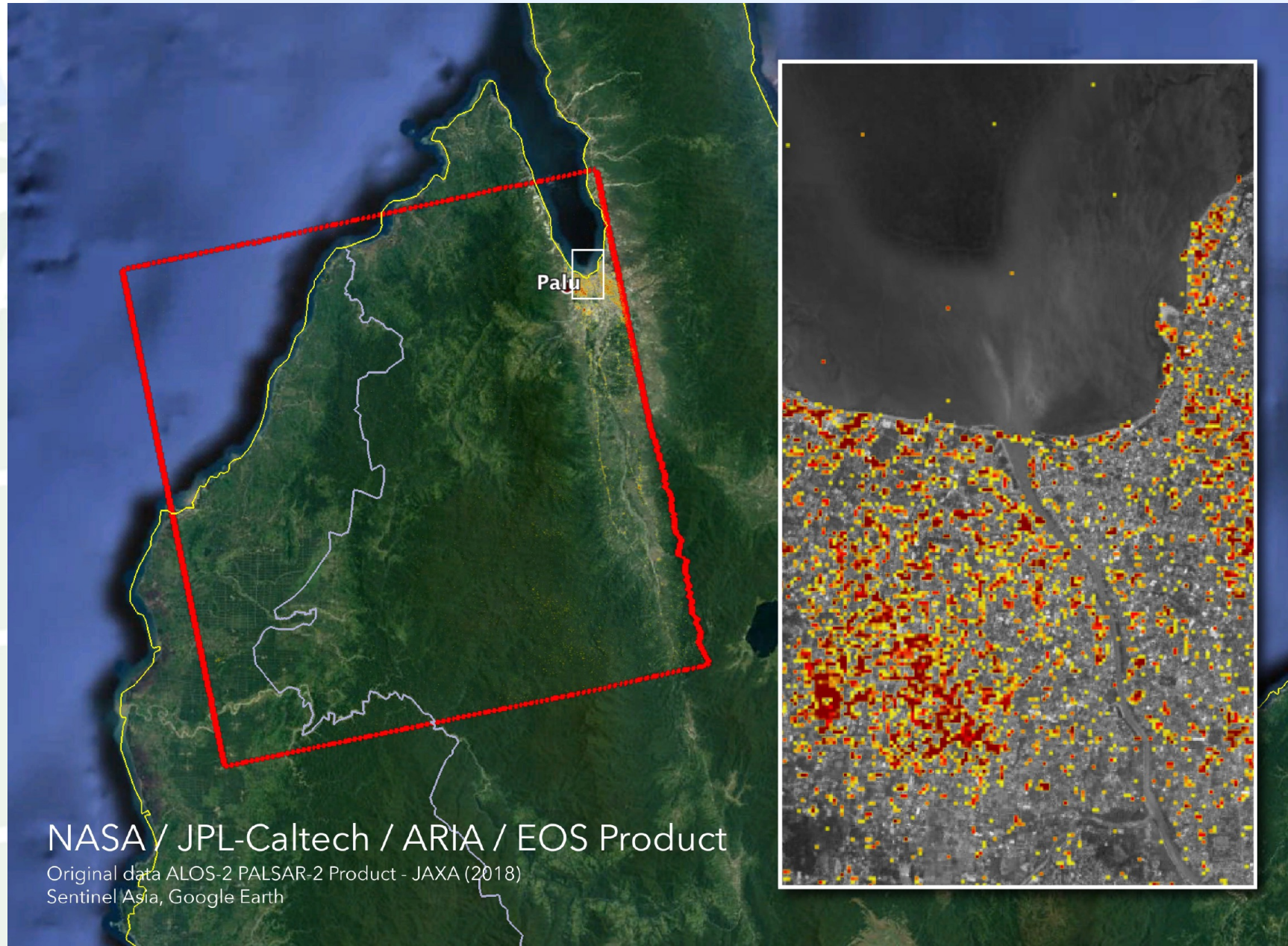
2011 Tohoku-Oki



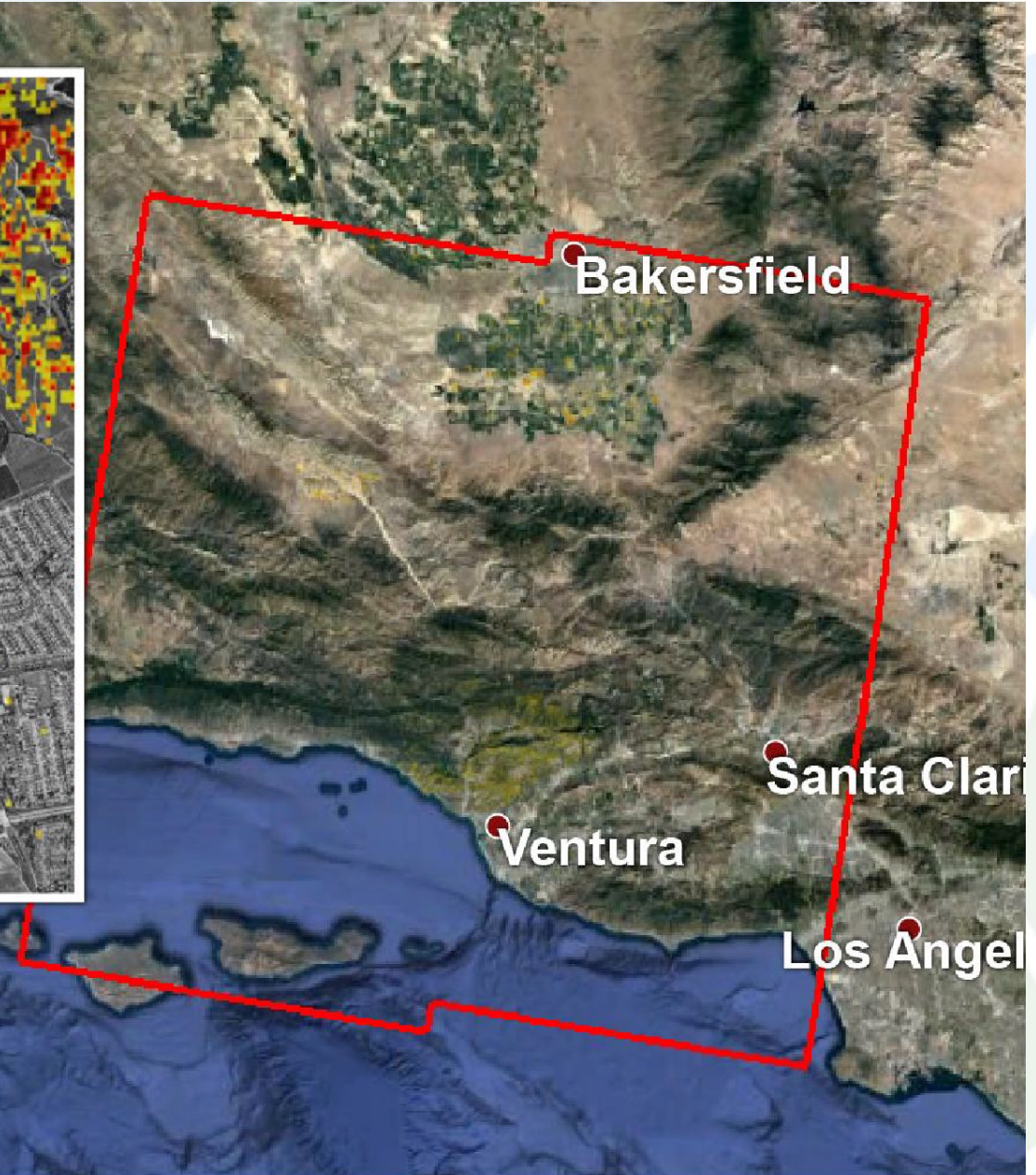
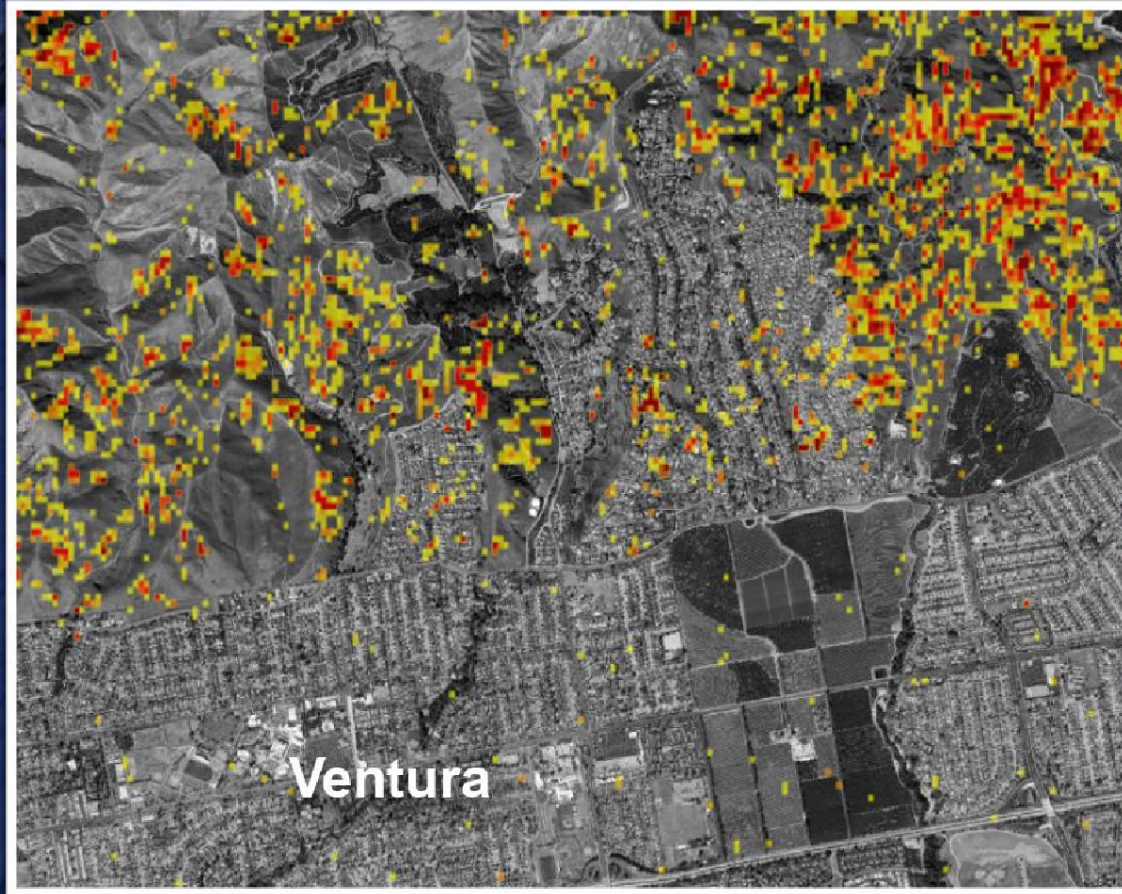
A stylized illustration of a globe with a light green surface and white grid lines representing latitude and longitude. A white satellite orbit with a circular node is shown on the right side of the globe. A white arrow points upwards from the top left of the globe. The background is a solid light blue color.

Damage Proxy Maps

Damage Proxy Map (Earthquake & Tsunami)



Damage Proxy Map (Wildfire)



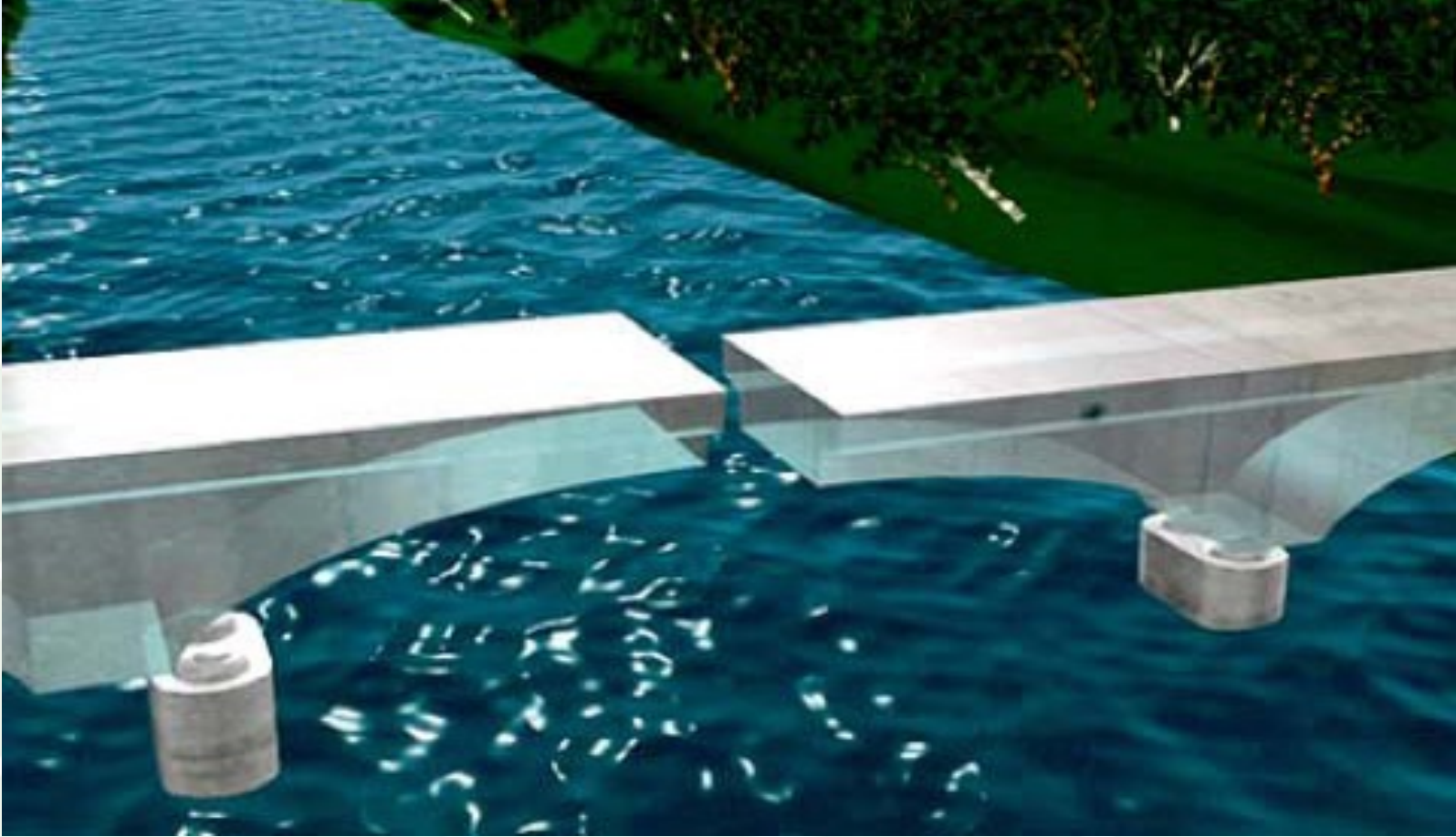
NASA / JPL-Caltech / ARIA Product

Contains modified Copernicus
Sentinel data (2017)
European Space Agency
Google Earth

A stylized graphic of a globe with a light green surface and white grid lines representing latitude and longitude. A white satellite orbit with a circular station is shown on the right side of the globe. A white arrow points upwards from the top left of the globe. The background is a solid light blue color.

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.

A stylized illustration of a globe with a light green grid of latitude and longitude lines. A white arrow points upwards from the top left, and a white orbital path with a small circular spacecraft is shown on the right side of the globe. The background is a light blue gradient.

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

