Geodesy and Geodetic Reference Frames

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Applications for Disasters

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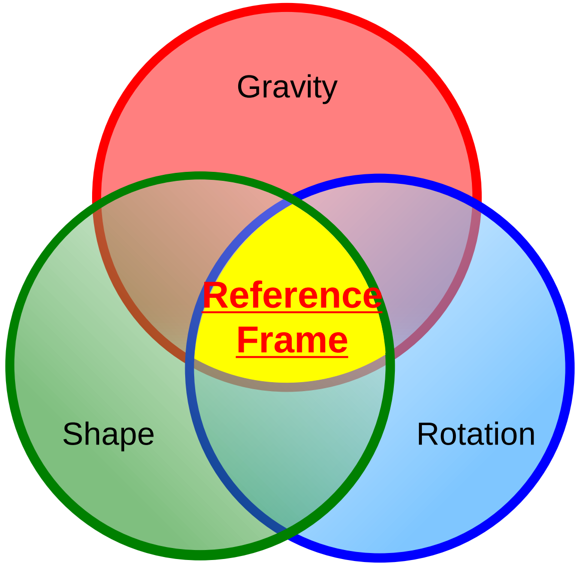
Jet Propulsion Laboratory
California Institute of Technology

Geodesy

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

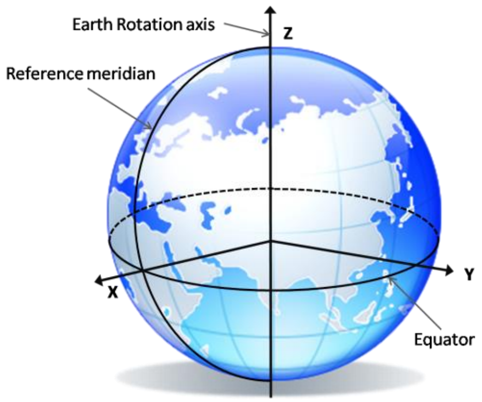
- Geometric shape
- Rotation and orientation in space
- Gravity field



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



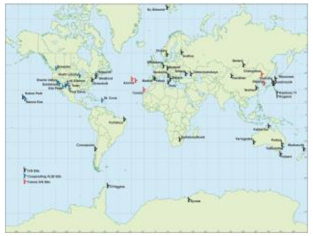
Terrestrial Reference Frame

- **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

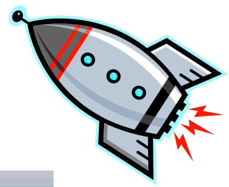

SLR


VLBI


DORIS

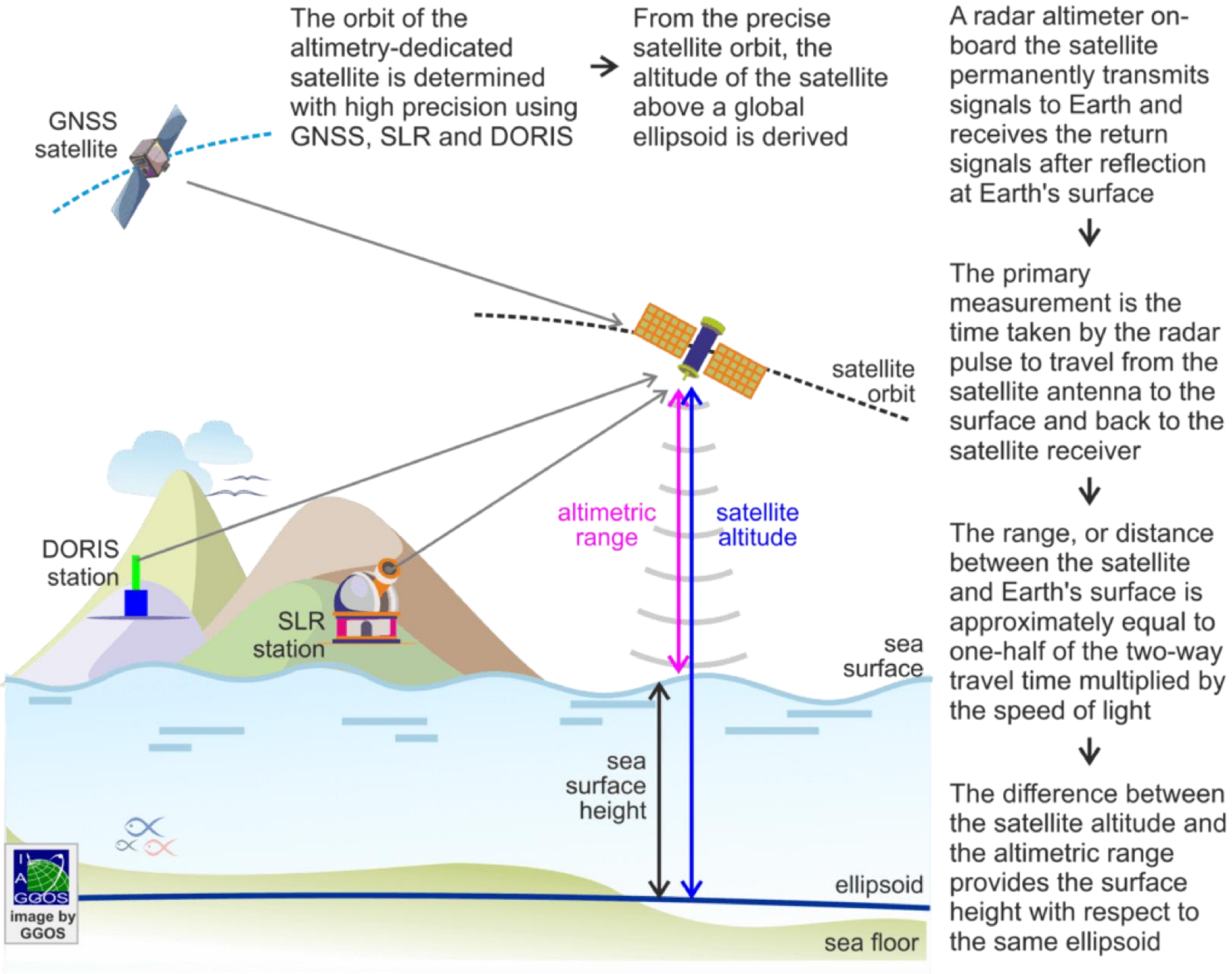
Benefits of an accurate TRF

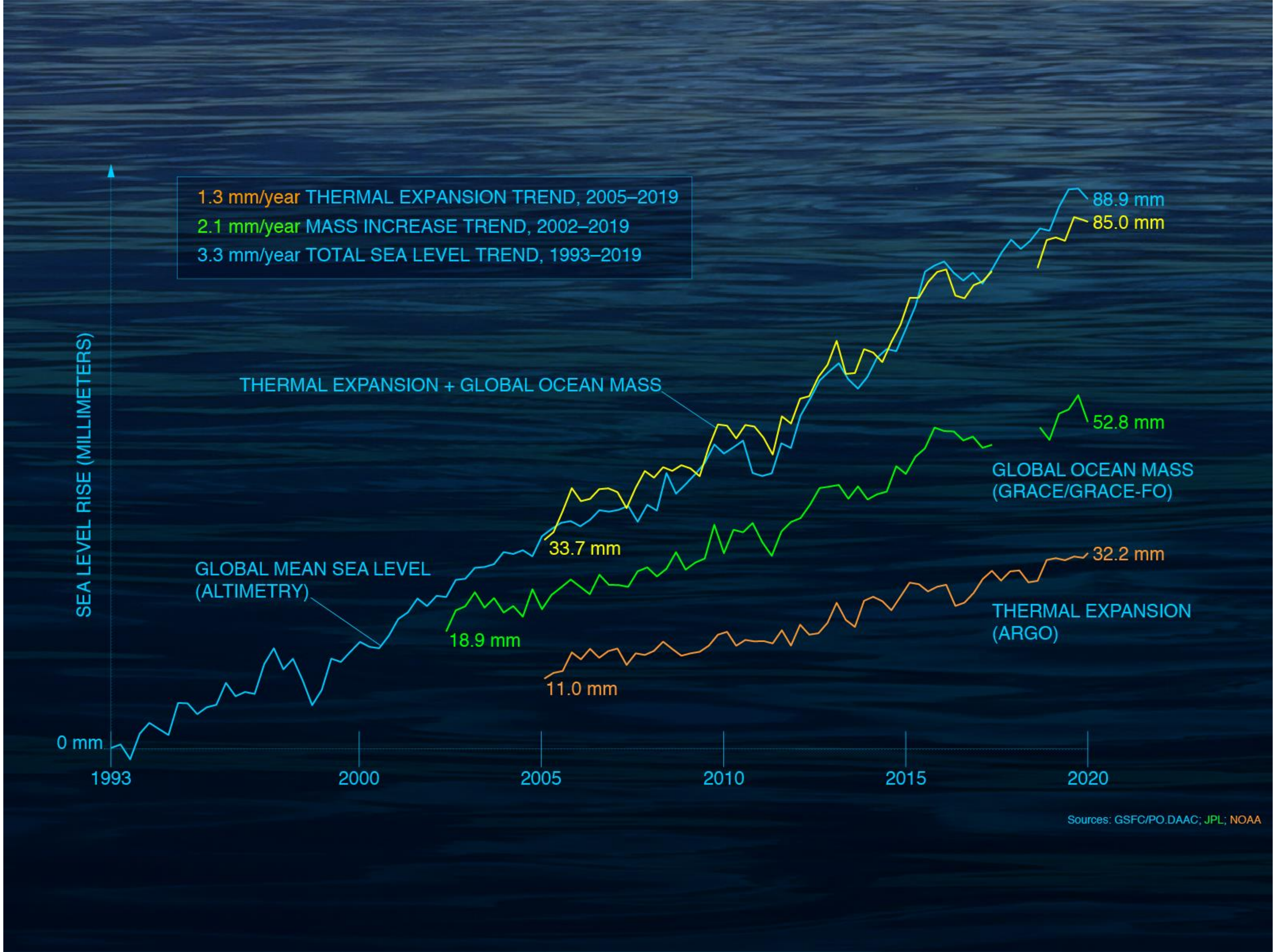
Credit: Norwegian Mapping Authority



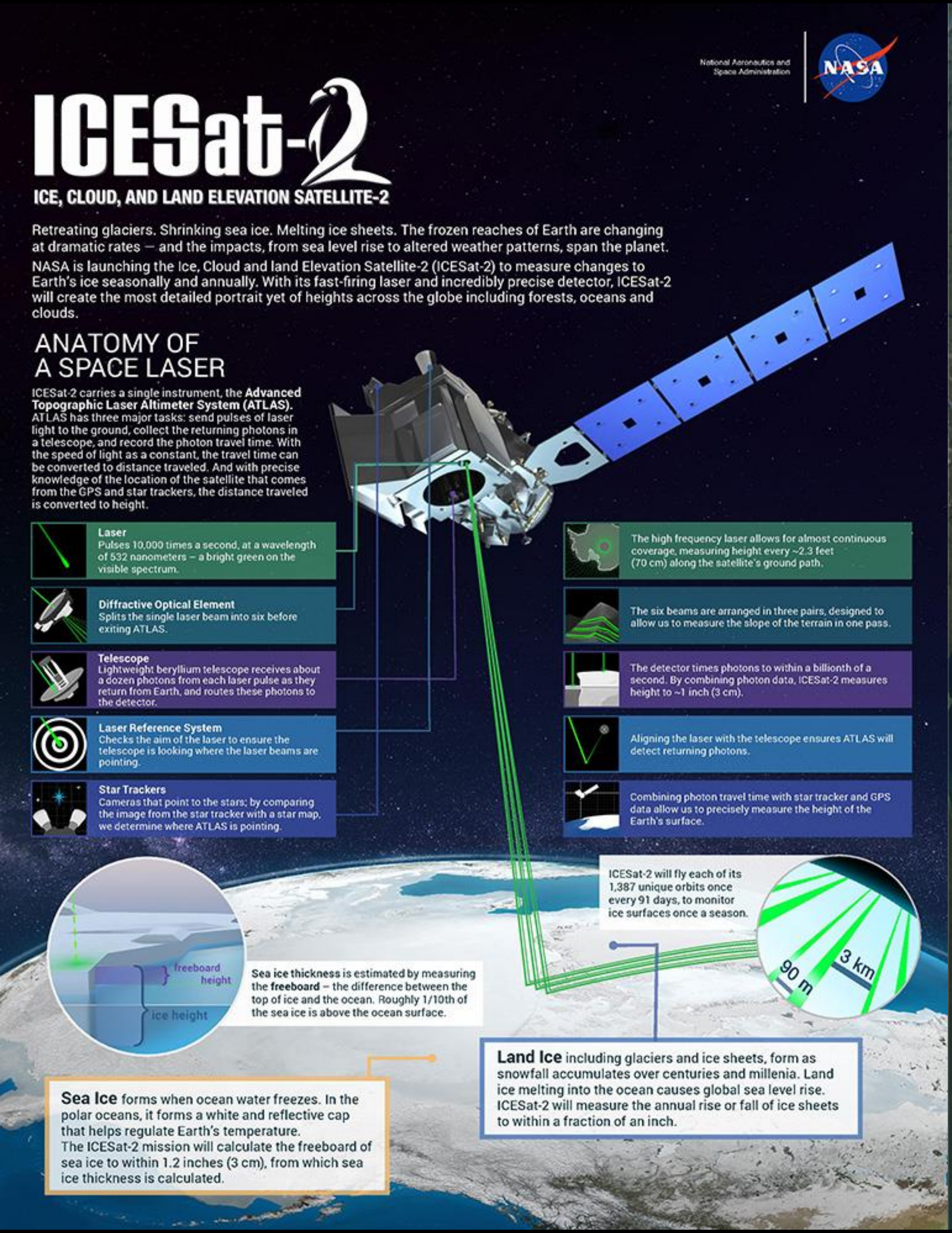
Sea Level Change

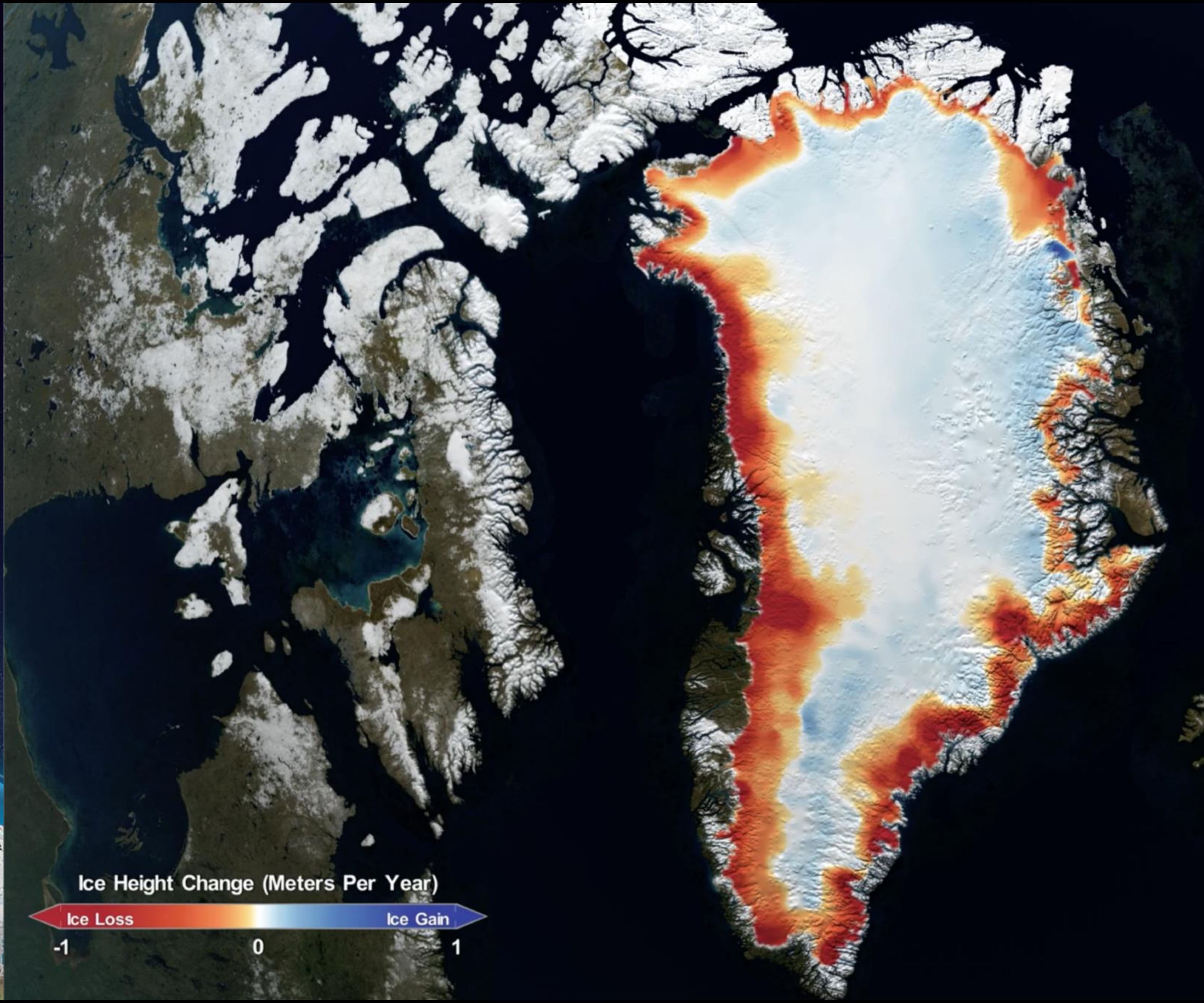
Radar Altimetry Measurement Principle




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)
THERMAL EXPANSION + GLOBAL OCEAN MASS
GLOBAL MEAN SEA LEVEL
(ALTIMETRY)
GLOBAL OCEAN MASS
(GRACE/GRACE-FO)
THERMAL EXPANSION
(ARGO)
88.9 mm
85.0 mm
52.8 mm
33.7 mm
32.2 mm
18.9 mm
11.0 mm
0 mm
1993
2000
2005
2010
2015
2020
Sources: GSFC/PO.DAAC; JPL; NOAA

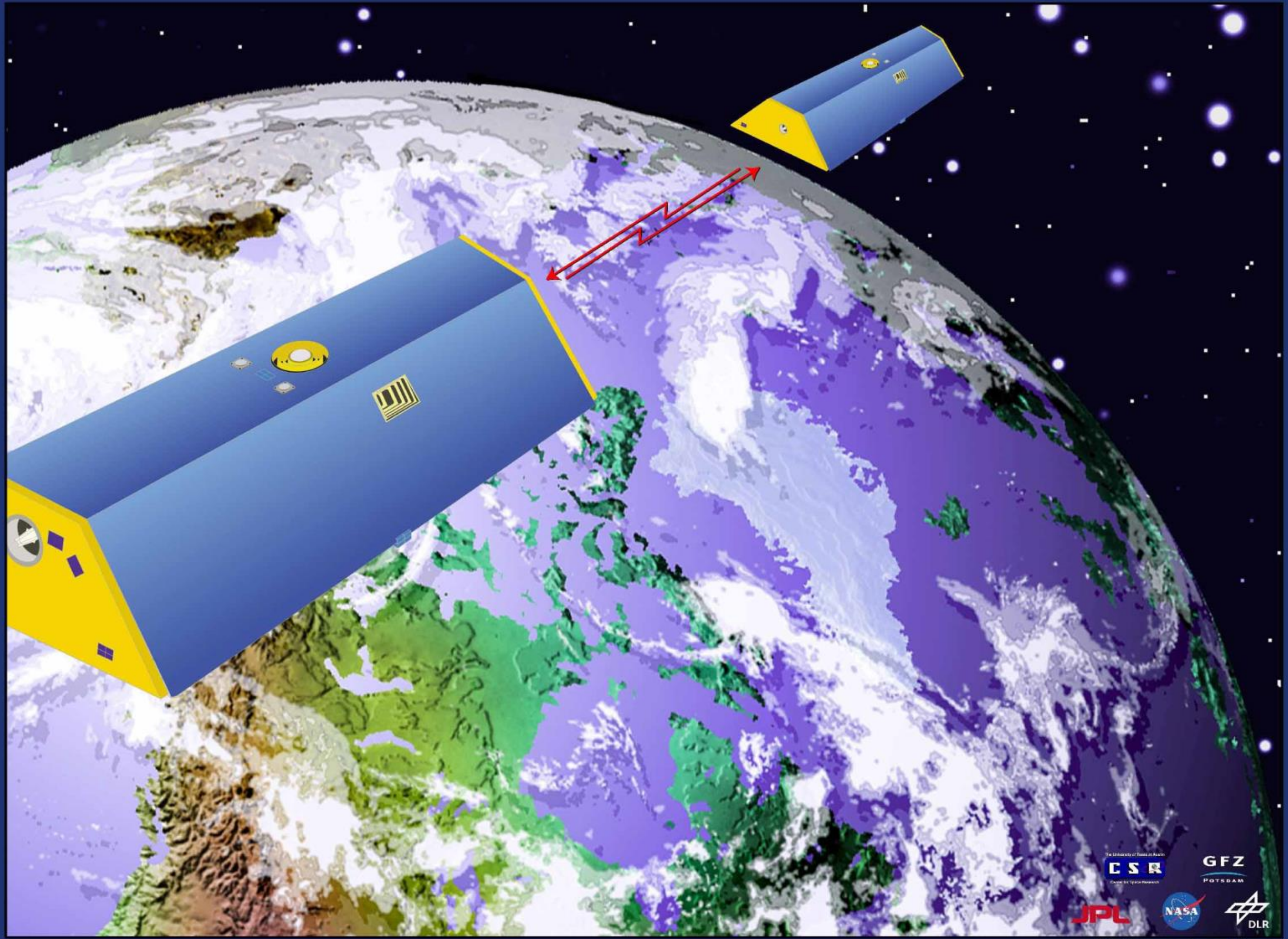
Ice Sheet Height Change





Source: NASA Scientific Visualization Studio

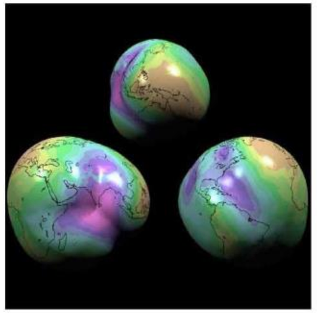
Mass Change



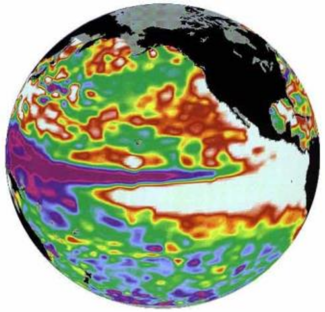
http://www.csr.utexas.edu/grace/

G R A C E

Gravity Recovery And Climate Experiment



Due to an uneven distribution of mass inside the Earth, the Earth's gravity field is not uniform - that is, it has "lumps". By far the biggest is a flattening at the poles (called the Earth's oblateness), but in these three views, we've exaggerated the scale so that many more lumps can be seen. The GRACE Mission will map out the precise location and sizes of these lumps, enabling us to learn more about the structure of the Earth.



The oceans undergo continual small changes in circulation. Occasionally, however, more significant changes, like the El Niño shown above, occur. The picture shows the changes in sea level during an El Niño measured by the TOPEX/Poseidon mission. GRACE will also measure changes in ocean circulation by "weighing" parts of the ocean to see how water has moved.

Greenland Ice Sheet

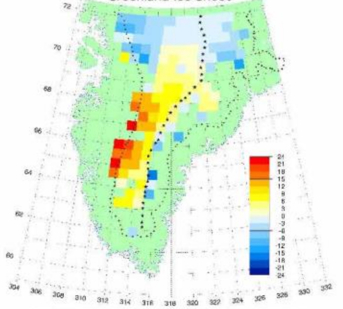
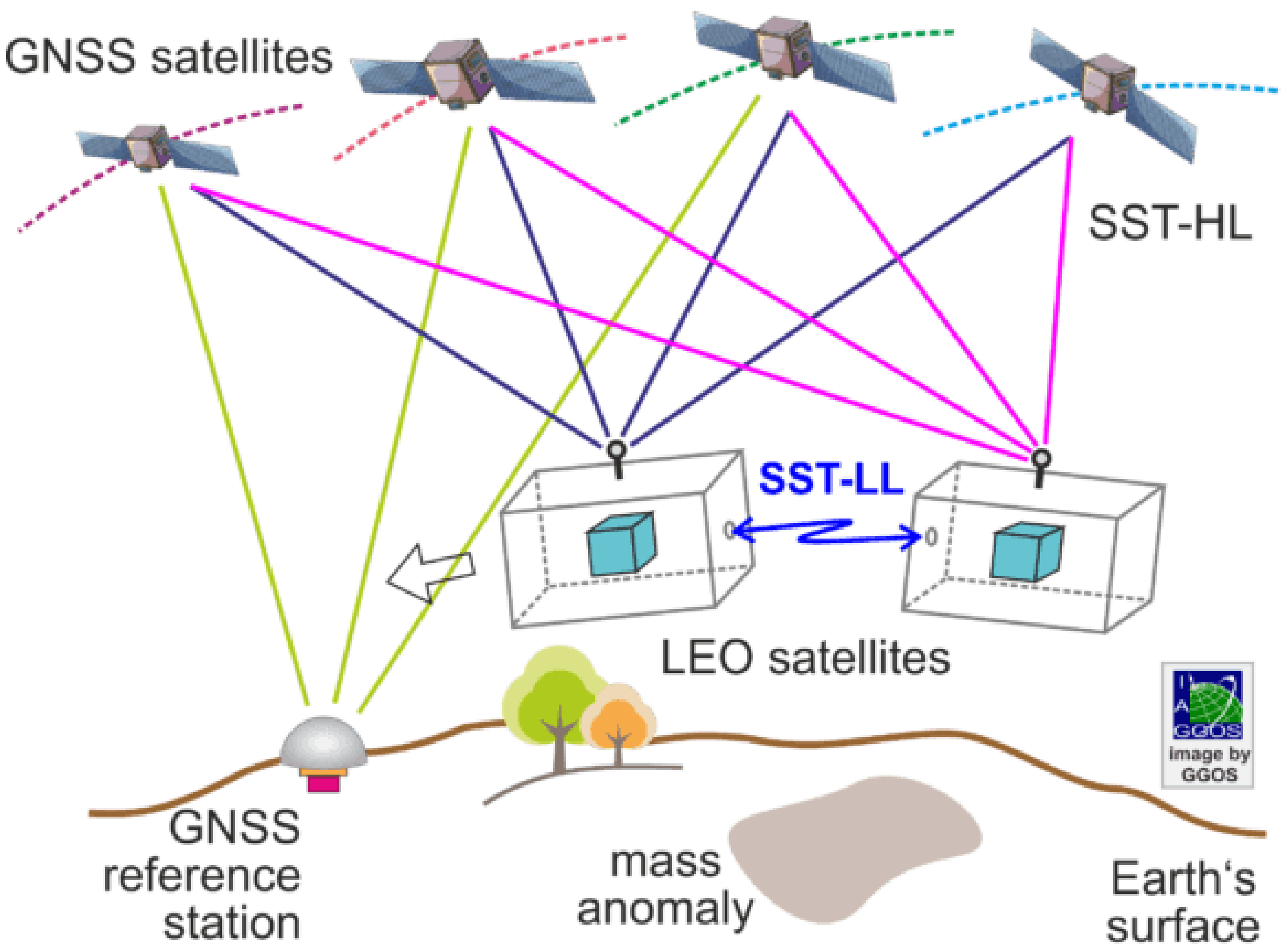


Illustration courtesy of C.H. Davis, C.A. Kluever, B.J. Haines, Science 279, 2086 (1998).

The polar ice sheets (such as the Greenland ice sheet shown above) change in size each year, although precise measurements of this change are very difficult to make. GRACE will "weigh" the ice sheets in Greenland and Antarctica by measuring their gravitational attraction to better understand their growth and/or retreat.

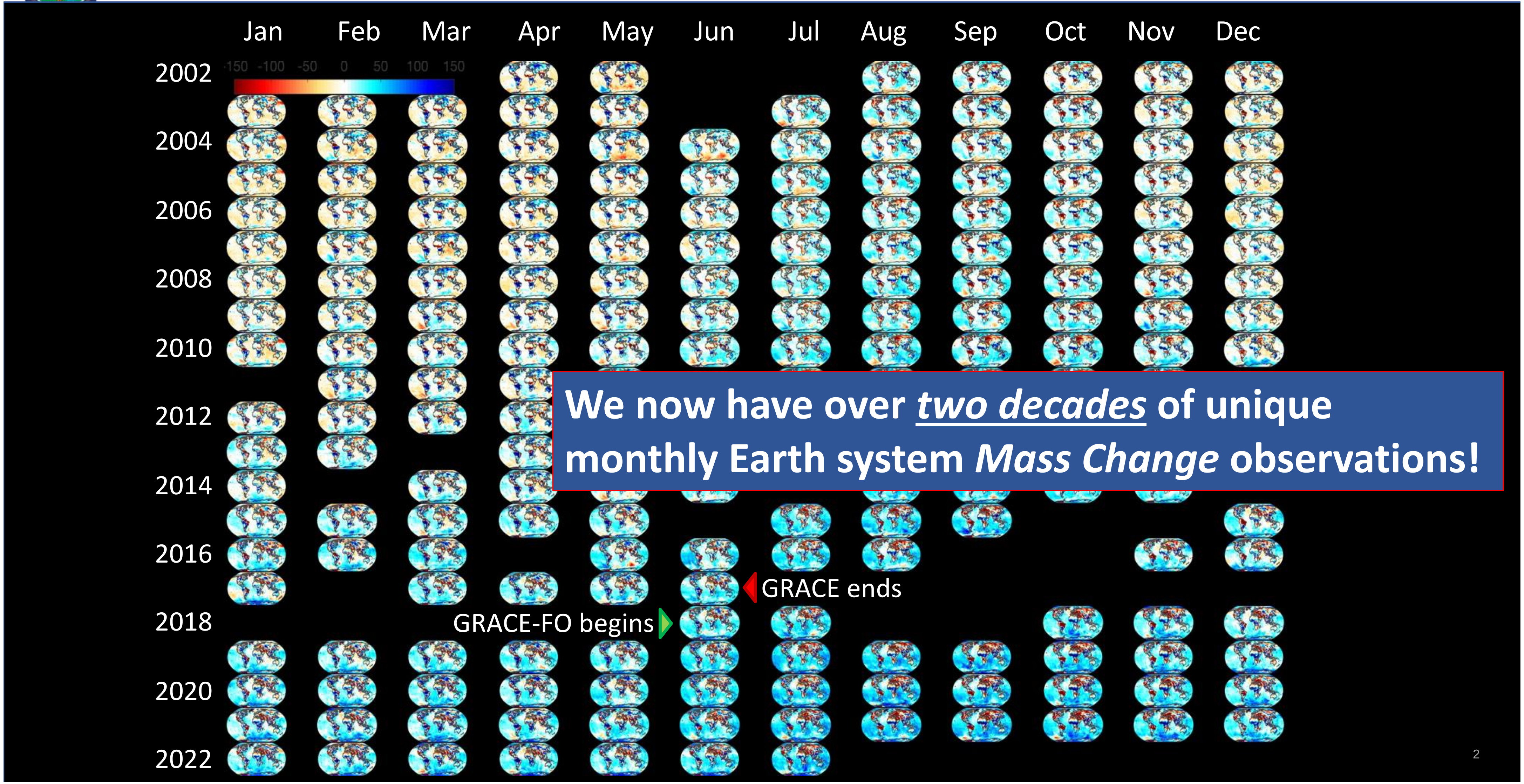
GRACE Measurement Principle



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.

Monthly Gravity Maps

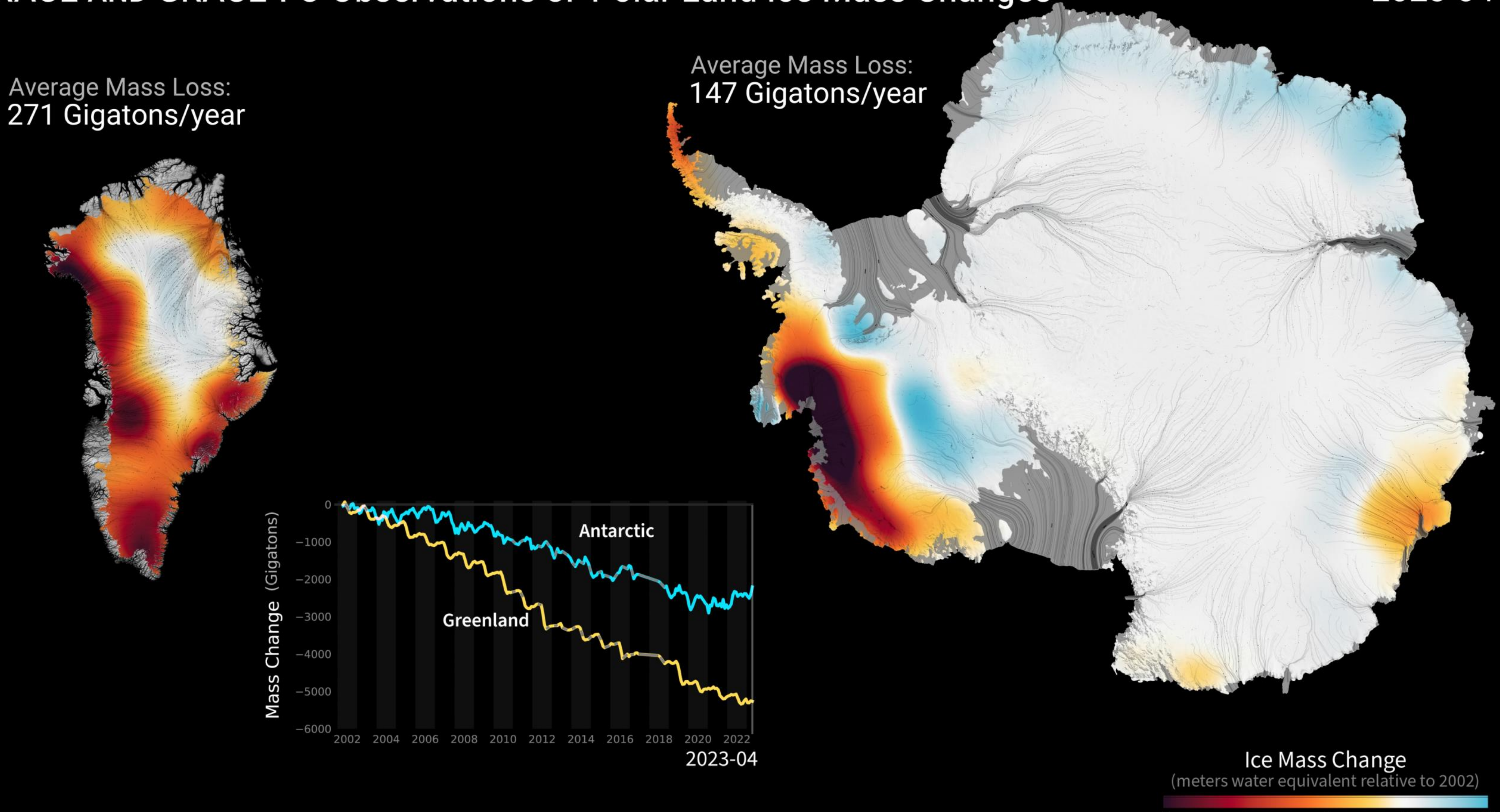


We now have over ***two decades*** of unique monthly Earth system *Mass Change* observations!

Source: Landerer et al., 2022

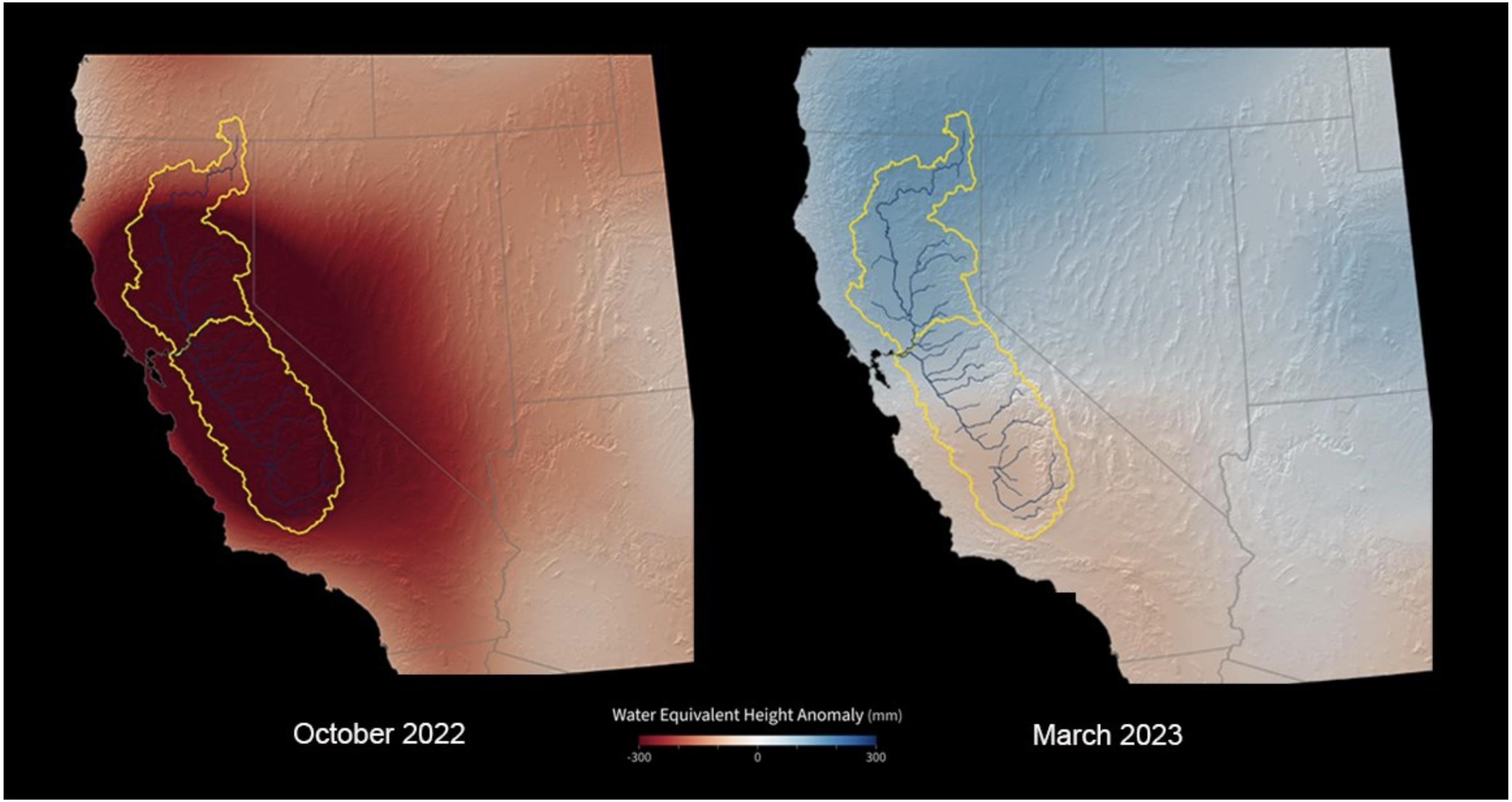
GRACE AND GRACE-FO Observations OF Polar Land Ice Mass Changes

2023-04



Source: NASA Scientific Visualization Studio

Terrestrial Water Storage Change



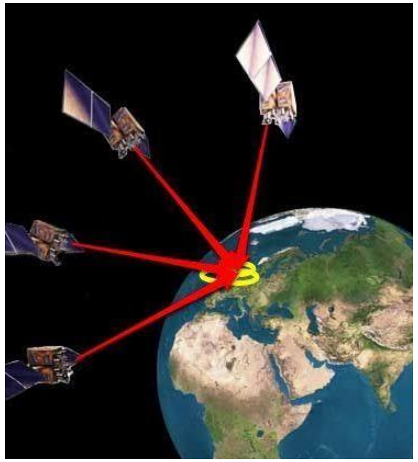
Thanks to a wet winter, California saw tremendous gains in the amount of water in the San Joaquin, Sacramento, and Tulare river basins (outlined in yellow) from October 2022 to March 2023, GRACE-FO data shows. The measurement includes water in lakes, rivers, reservoirs, snowpack, and groundwater aquifers.

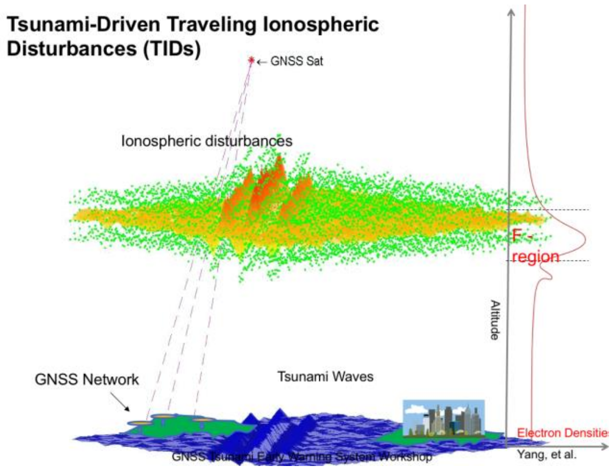
Source: NASA Scientific Visualization Studio

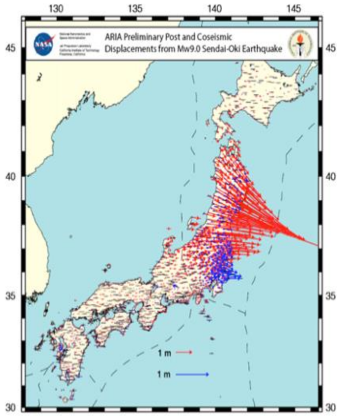
Tsunami Early Warning

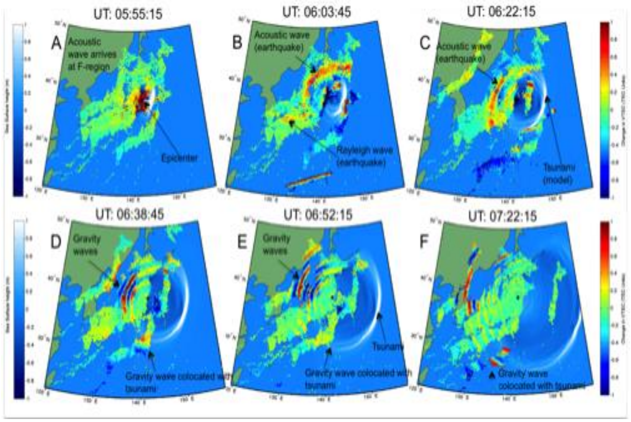
GNSS Tsunami Early Warning System (GTEWS)

- Properly positioned GNSS receivers will measure both the ground displacement and the ionospheric dynamics induced by tsunami formation and propagation.
- Real time data distribution and analysis will provide significant improvements to accuracy, timeliness, and efficiency in tsunami warning.
- GTEWS is viewed as an augmentation to build upon existing disaster warning capabilities where they exist.
- GTEWS relies upon real time mesoscale density of GNSS networks and advanced computational facilities for its effectiveness.



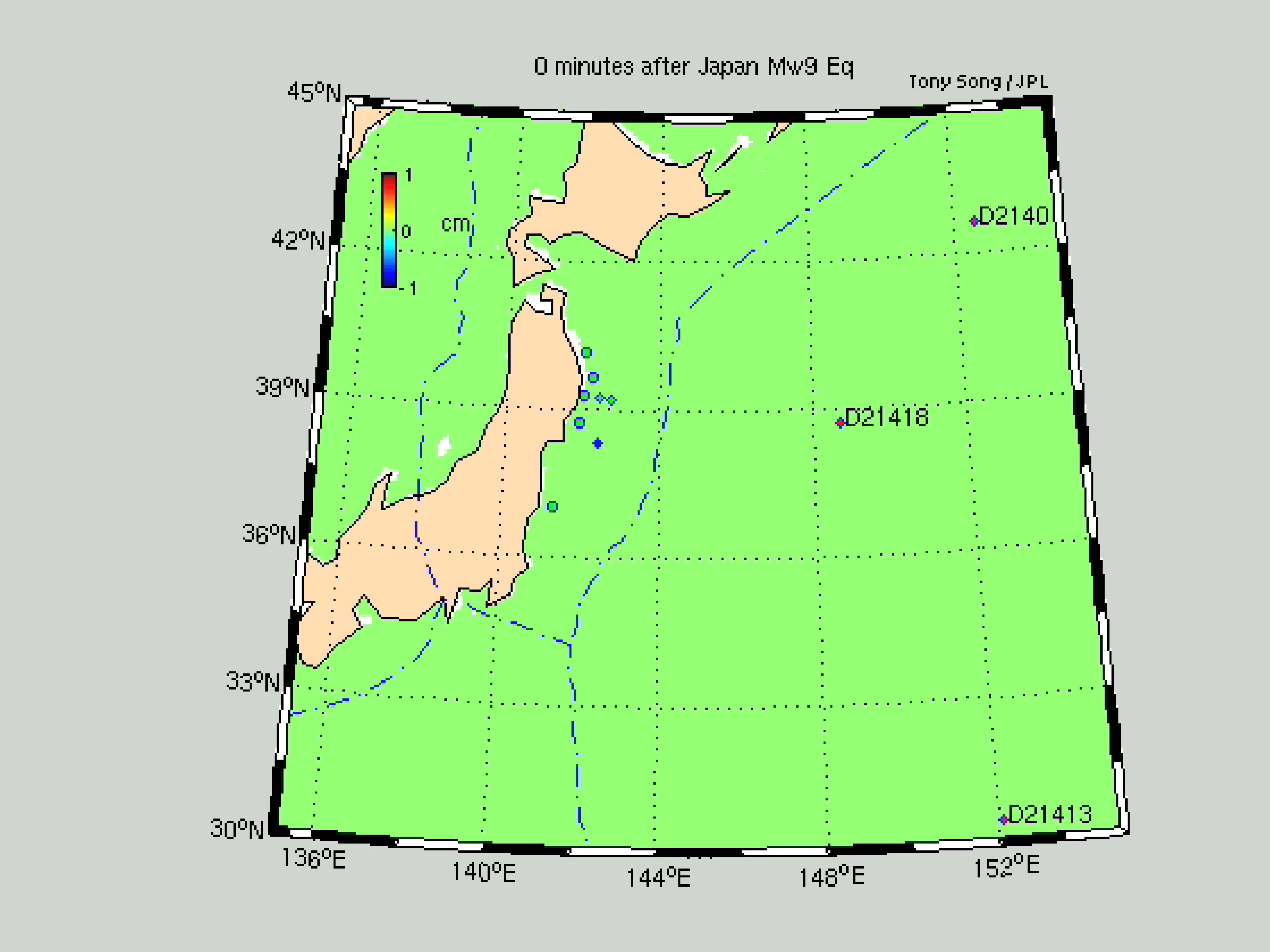






Source: LaBrecque, 2023

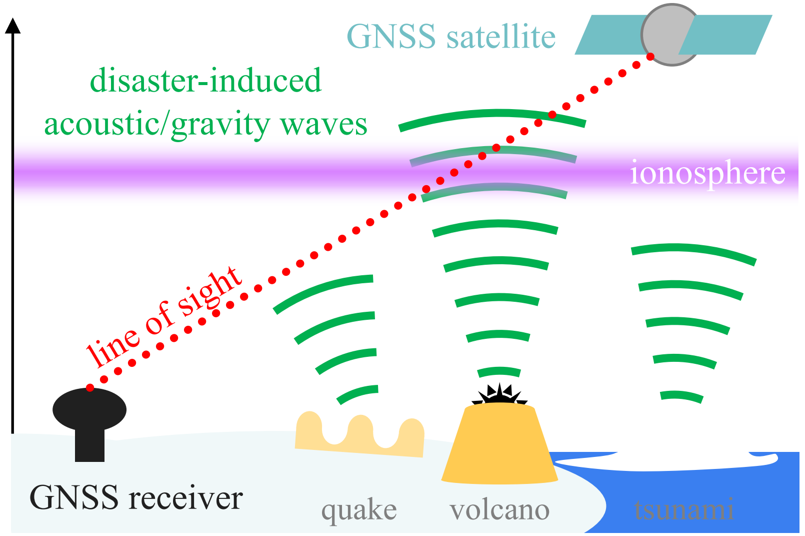
2011 Tohoku-Oki Tsunami



Source: Tony Song, JPL

JPL's GUARDIAN Near-Real-Time Ionospheric Monitor

Natural hazards (tsunamis, volcanic eruptions, earthquakes, *etc.*) generate **atmospheric waves** which cause perturbations in **the ionosphere**, which can be detected by measuring the **Total Electron Content (TEC)**.



Source: Leo Martire, JPL

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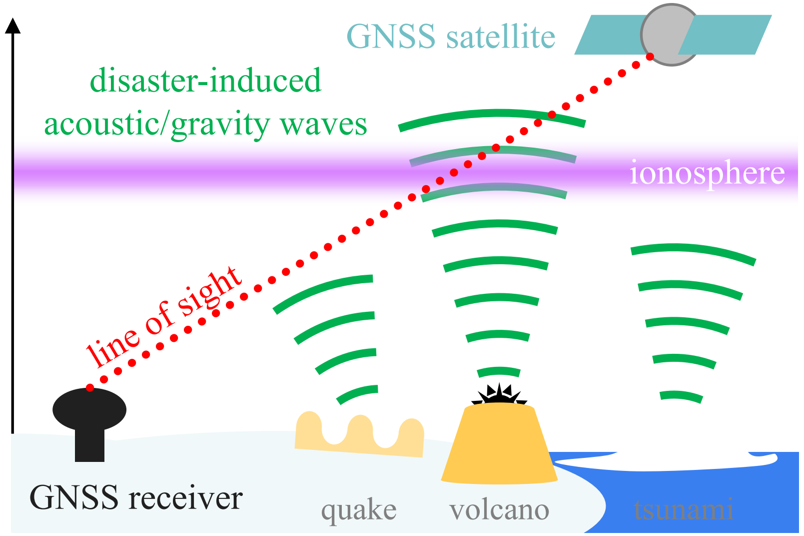
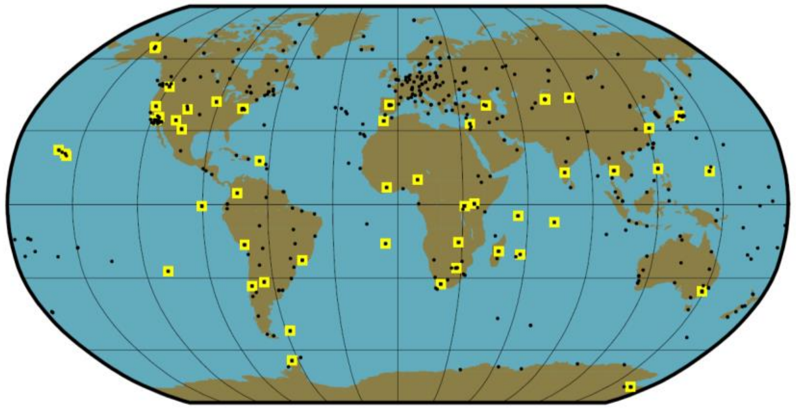


GNSS ground networks (such as the IGS', NASA's, and JPL's GDGPS's) are used to measure TEC, **for each satellite-station pair** and **in near-real-time**.



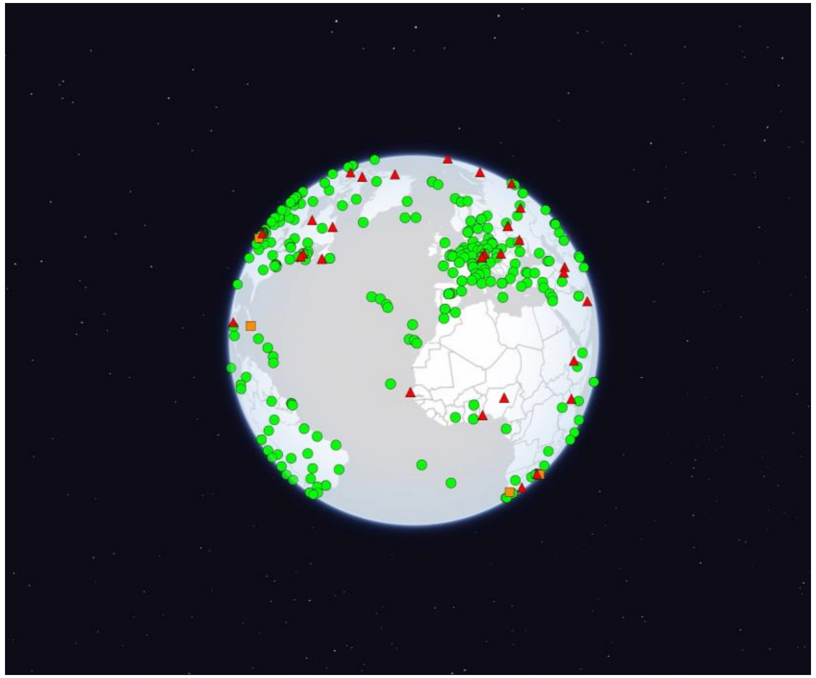


Figure: ground GNSS networks.
Top: NASA and GDGPS.
Right: International GNSS Service (IGS).

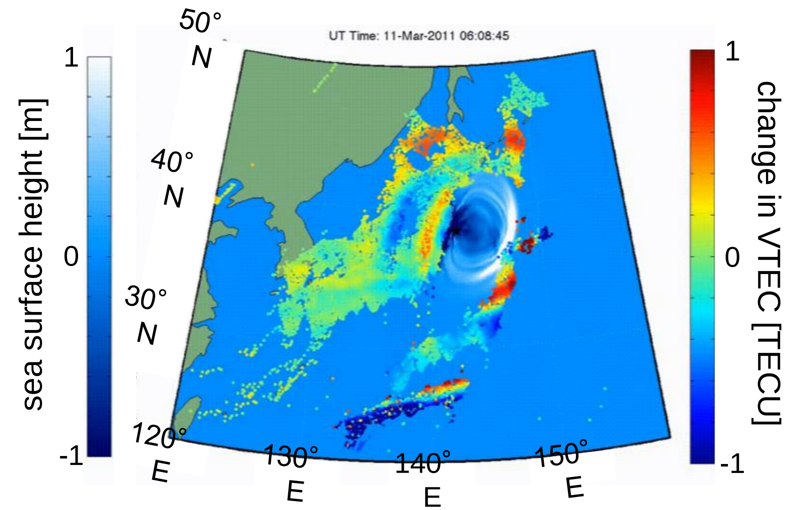
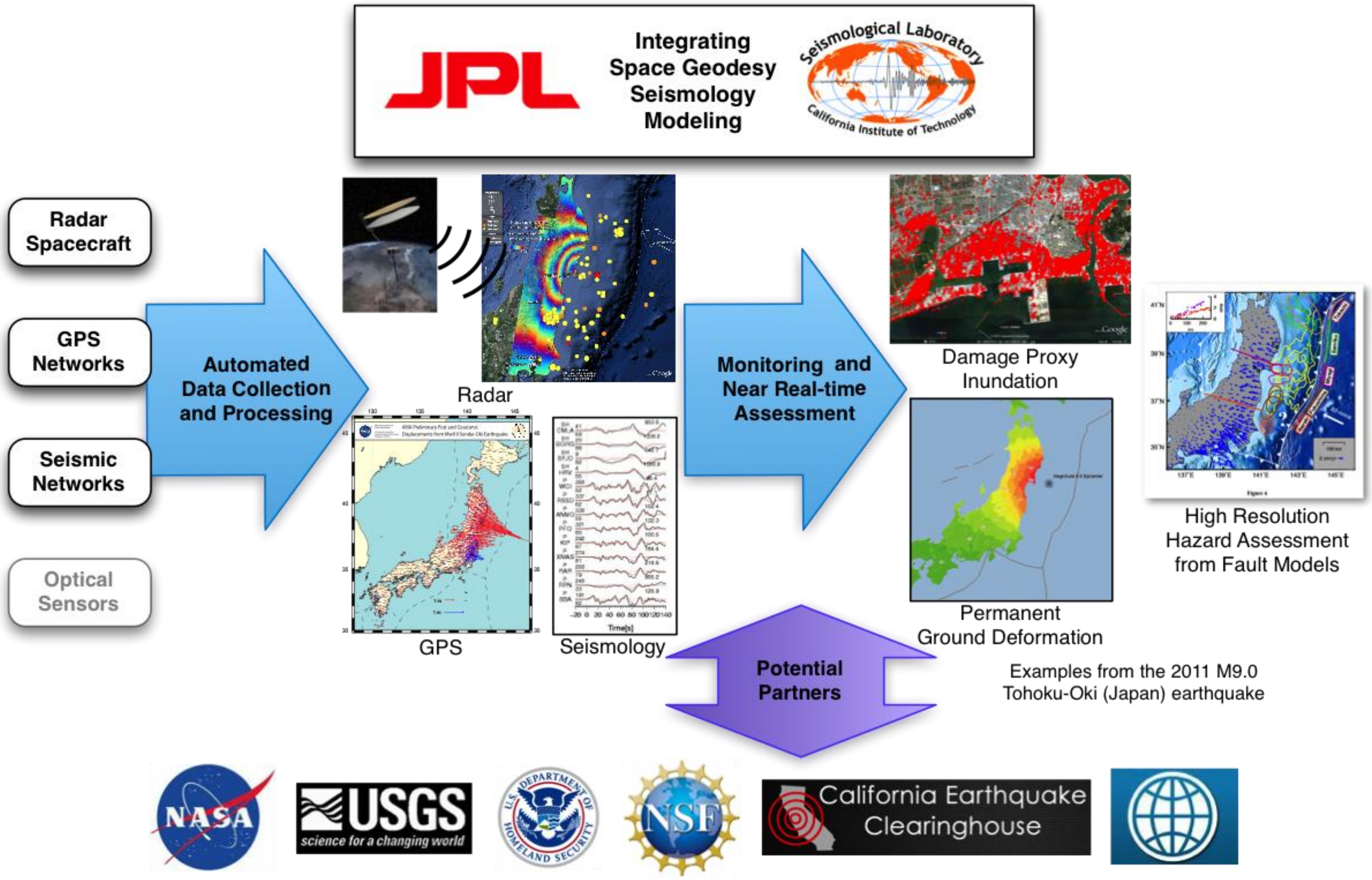


Figure: Ionospheric TEC and sea surface height map for the 2011 Tōhoku-Oki event (Galvan *et al.*, 2012).

Source: Leo Martire, JPL

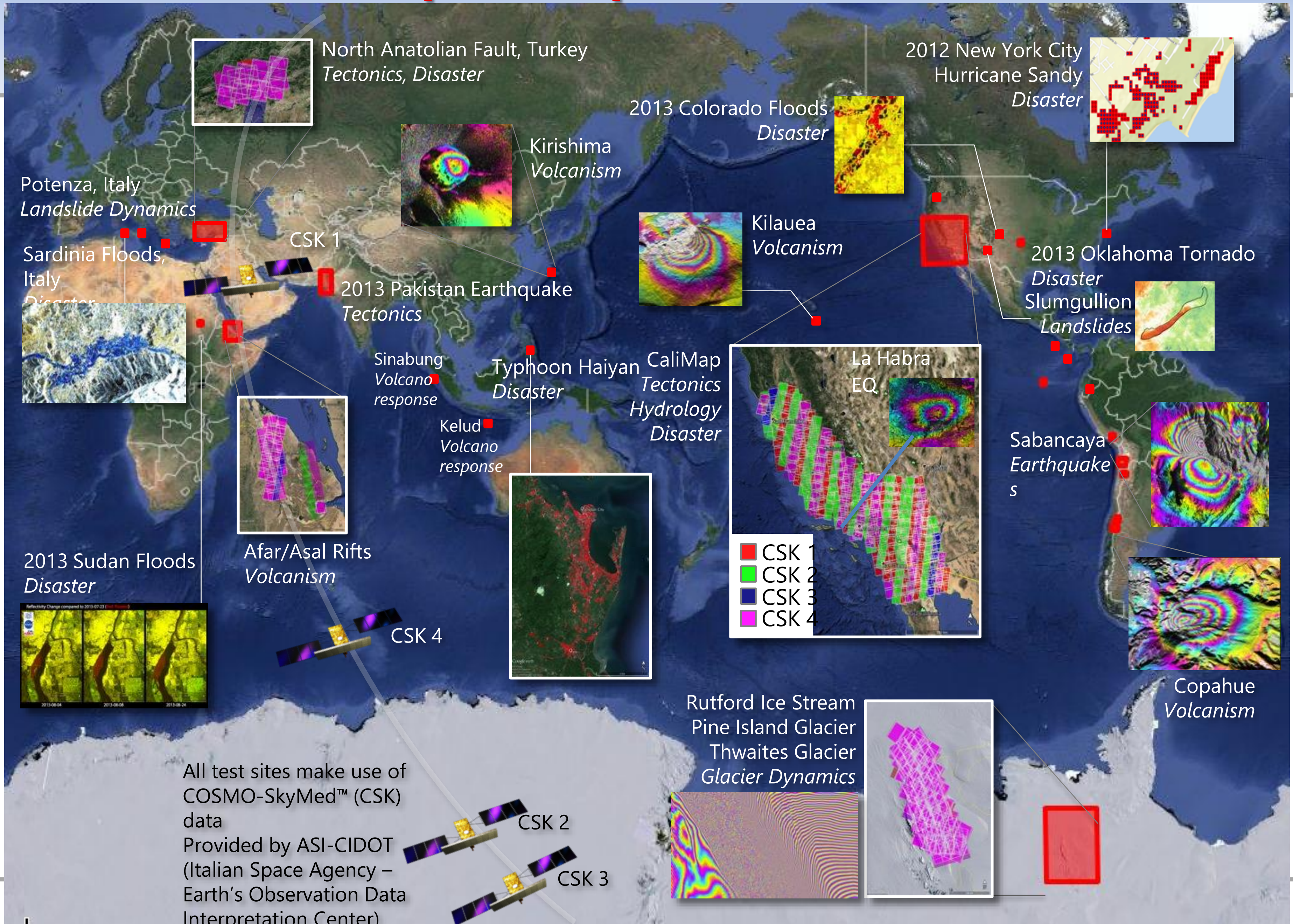
Crustal Deformation

Advanced Rapid Imaging and Analysis (ARIA)



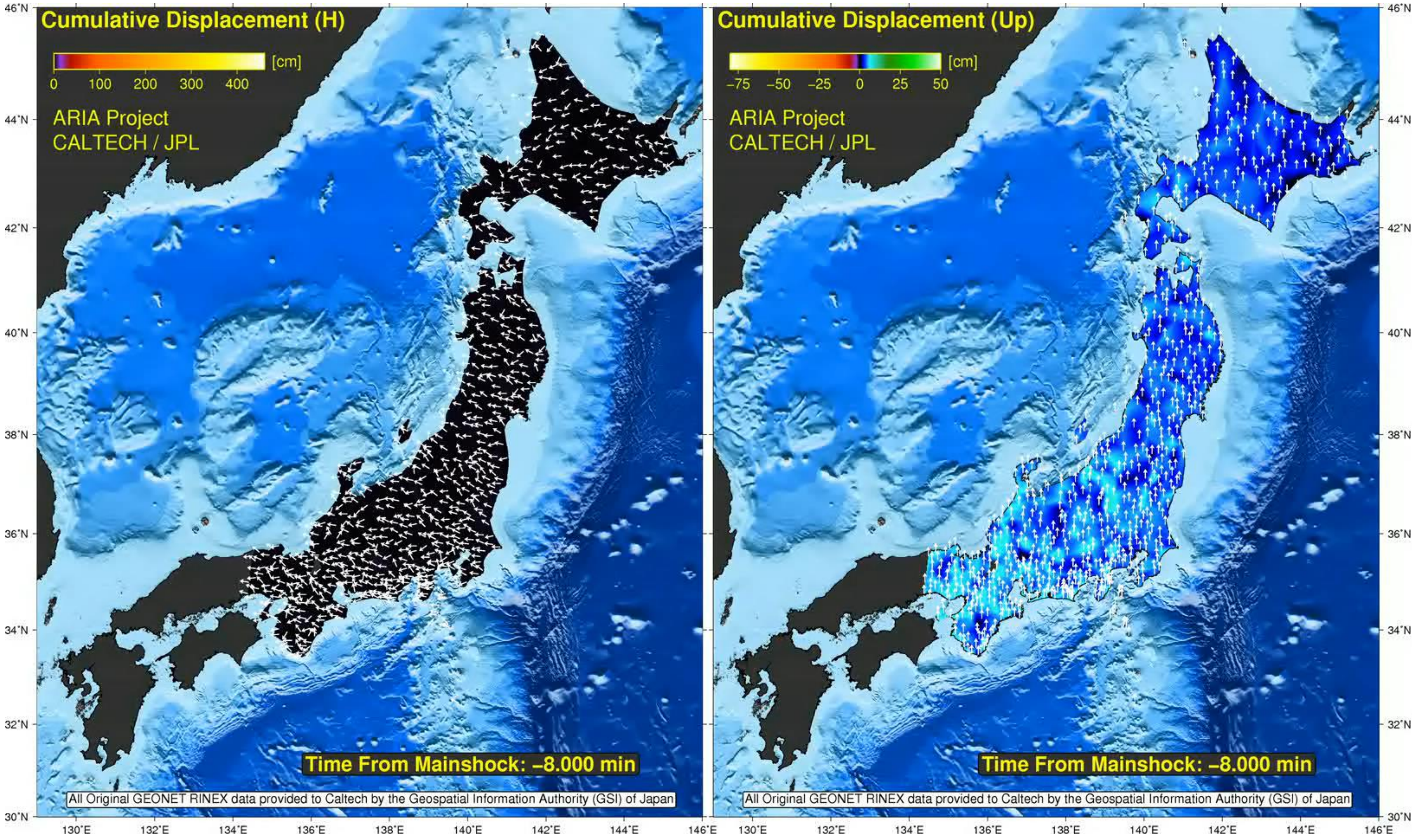
Source: aria.jpl.nasa.gov

Examples of ARIA response products



Source: aria.jpl.nasa.gov

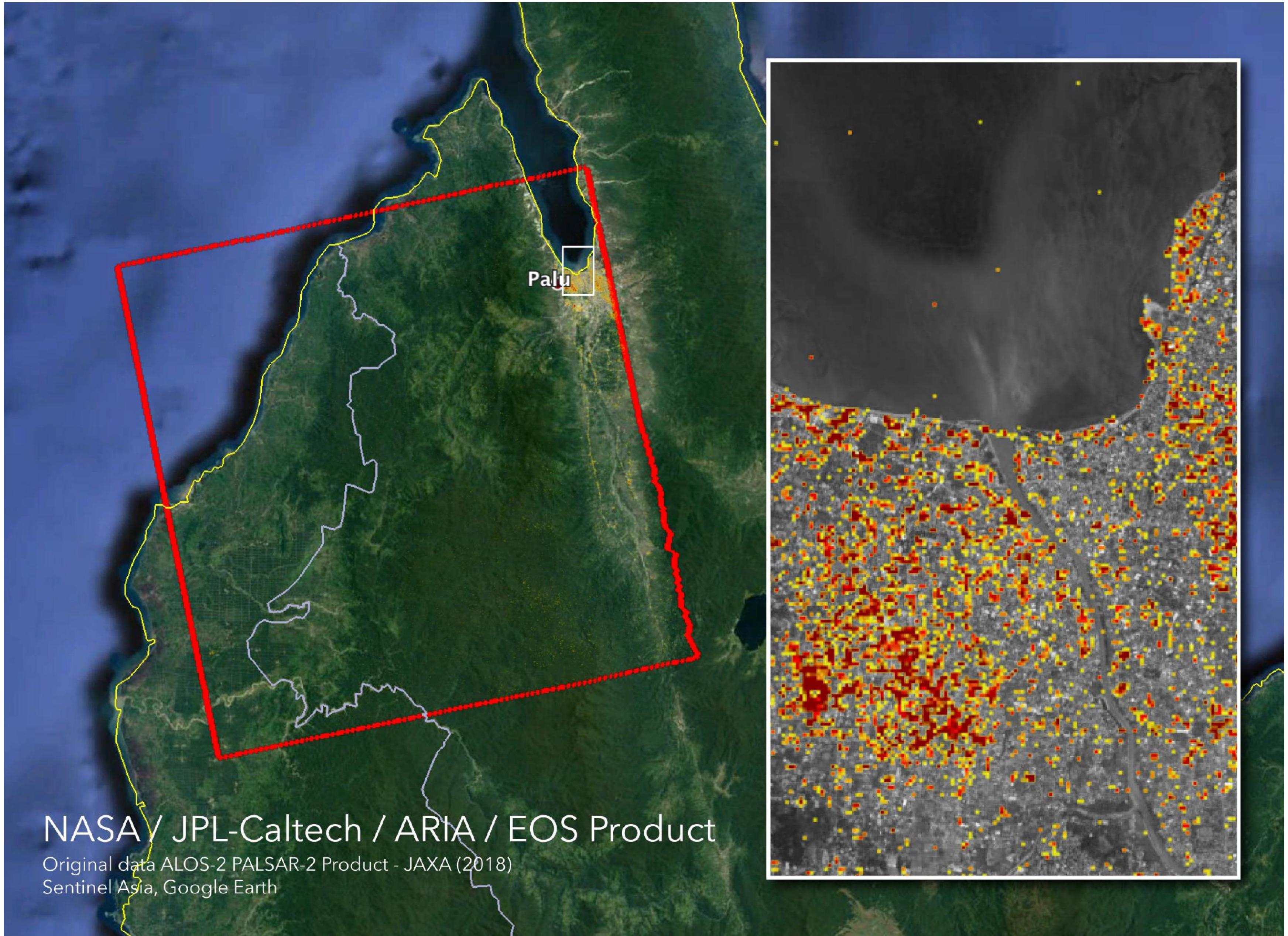
2011 Tohoku-Oki



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

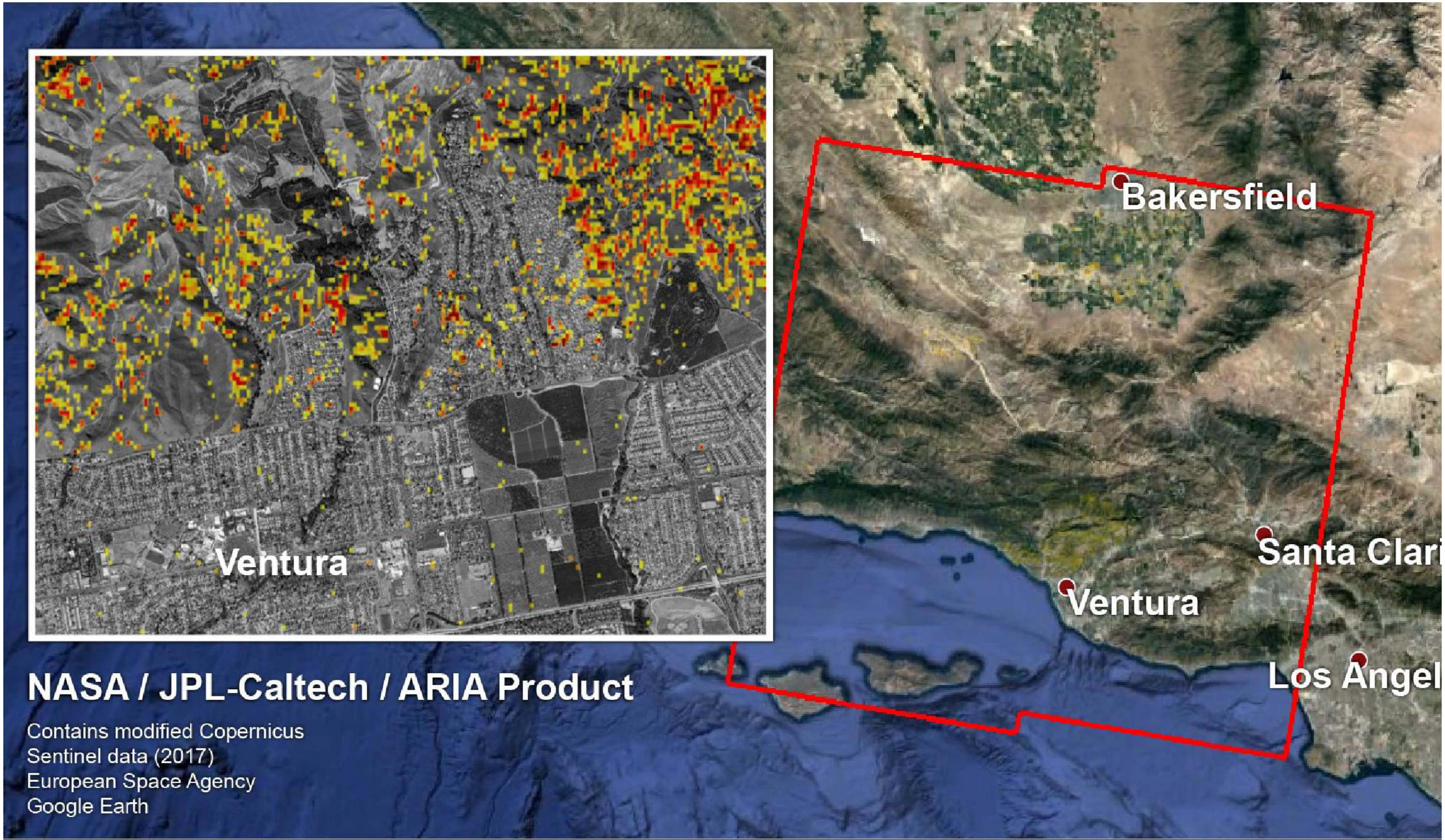
Damage Proxy Maps

Damage Proxy Map (Earthquake & Tsunami)



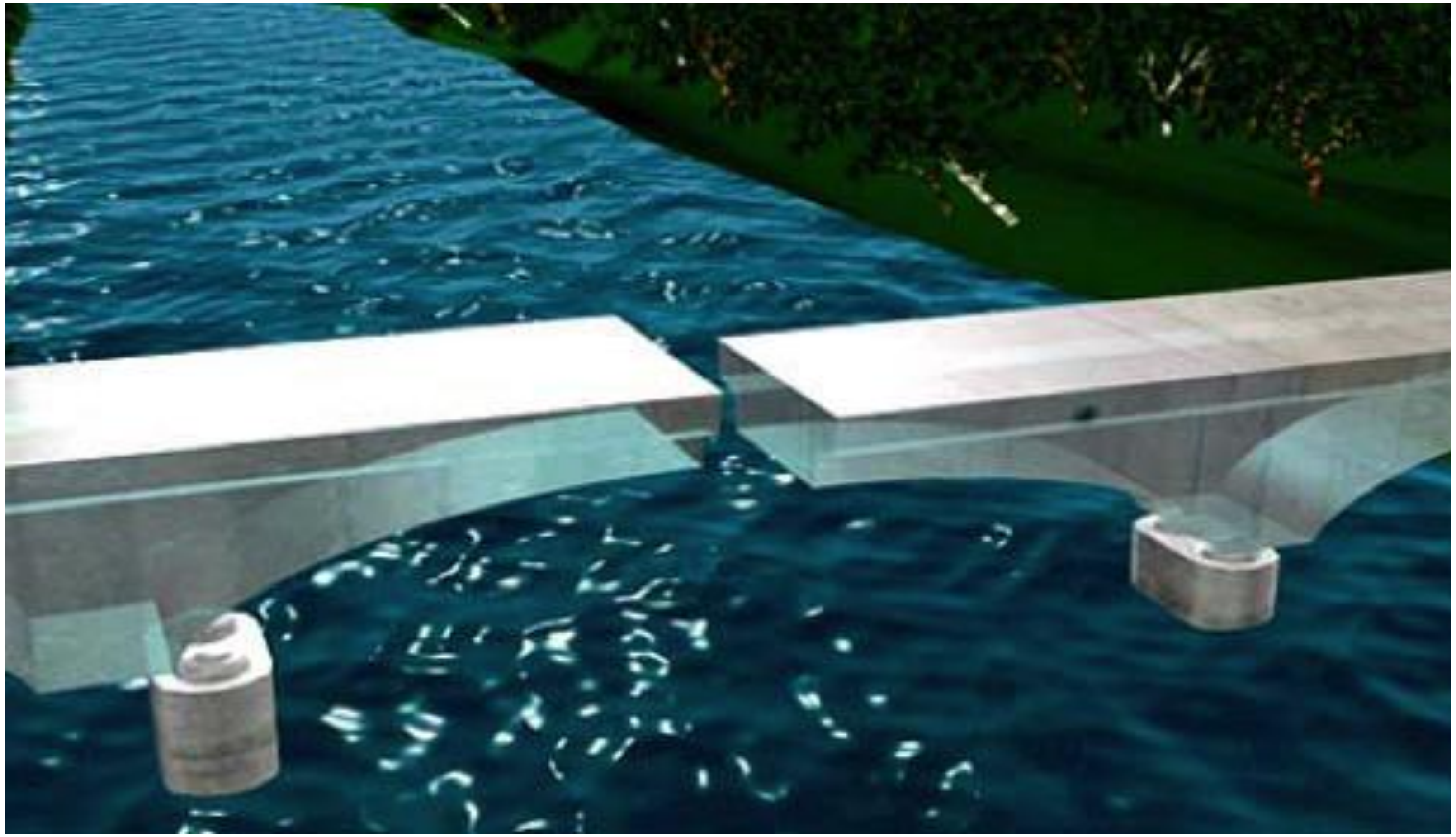
Damage Proxy Map (Cyclone)

Damage Proxy Map (Wildfire)

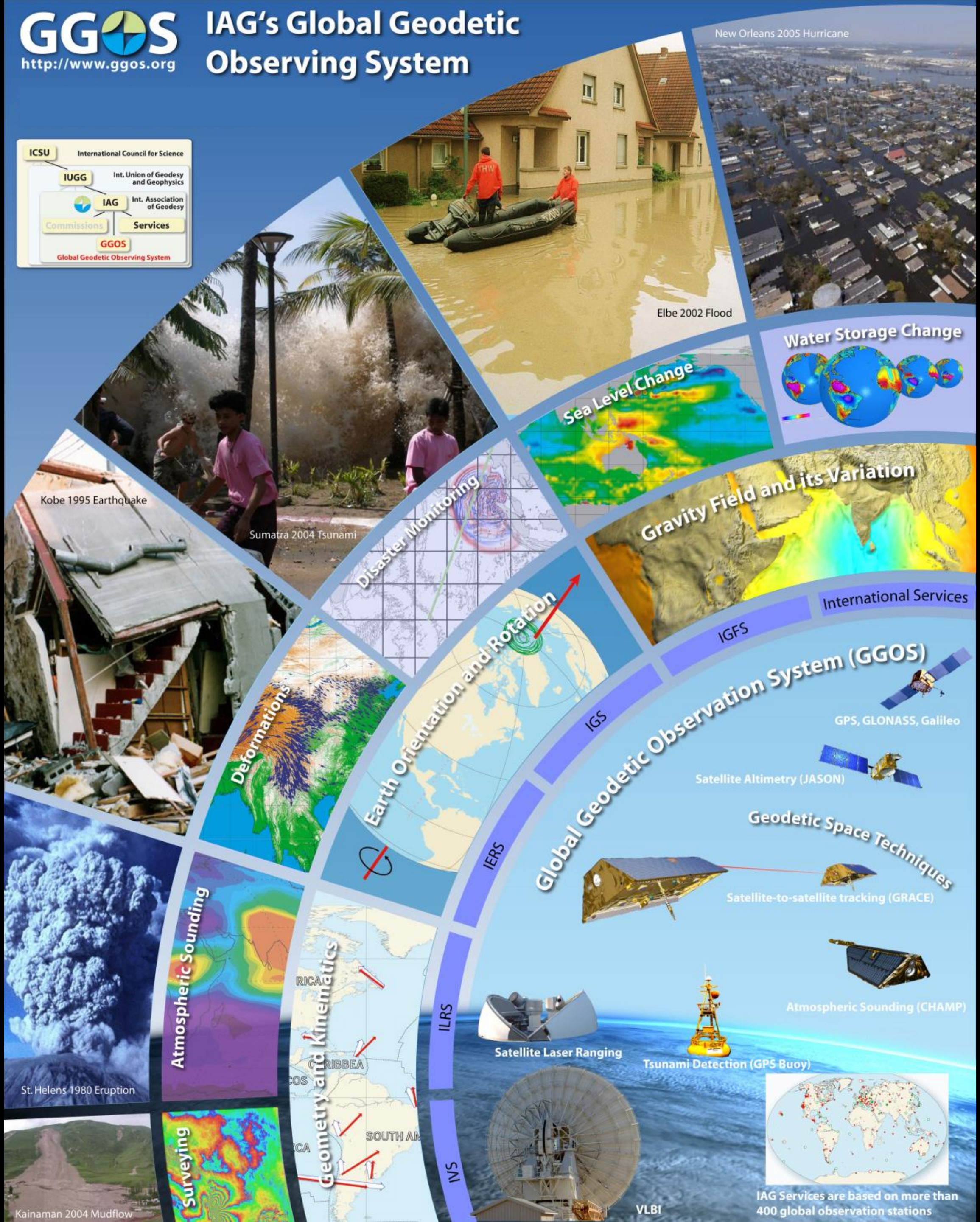


Engineering Geodesy

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.


GGOS
http://www.ggos.org
IAG's Global Geodetic Observing System
ICSU
International Council for Science
IUGG
Int. Union of Geodesy and Geophysics
IAG
Int. Association of Geodesy
Commissions
Services
GGOS
Global Geodetic Observing System
New Orleans 2005 Hurricane
Elbe 2002 Flood
Sumatra 2004 Tsunami
Kobe 1995 Earthquake
St. Helens 1980 Eruption
Kainaman 2004 Mudflow
Water Storage Change
Sea Level Change
Gravity Field and its Variation
Disaster Monitoring
Earth Orientation and Rotation
Deformations
Atmospheric Sounding
Geometry and Kinematics
Surveying
International Services
IGFS
IGS
IERS
ILRS
IVS
Global Geodetic Observation System (GGOS)
GPS, GLONASS, Galileo
Satellite Altimetry (JASON)
Geodetic Space Techniques
Satellite-to-satellite tracking (GRACE)
Atmospheric Sounding (CHAMP)
Satellite Laser Ranging
Tsunami Detection (GPS Buoy)
VLBI
IAG Services are based on more than 400 global observation stations