The Global Geodesy Supply Chain
Importance to Science and Society

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Expert Consultation on Strengthening the
Global Geodesy Supply Chain

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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

• **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
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
Sea Level Change
Radar Altimetry Measurement Principle

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.
Ice Sheet Height Change
Introducing ICESat-2: 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. In this series of laser and infrared remote sensors, ICESat-2 will create the most detailed portrait yet of heights across the globe including ice sheets, oceans and vegetation.

**ANATOMY OF A SPACE LASER**

- **Laser**: A 10,500 laser beams, each wavelength of 1064 nanometers - signals generate over 100,000 laser pulses per track.
- **Optical Flight Laser**: Sits the single laser beam into the sensor before modeling the laser beam's path.
- **Telescope**: Collects the reflected laser beams that are directed in a conical shape to a small laser point as they pass through the telescope to focus the beams in the sensor.
- **Laser Reference System**: Localization of the ICESat-2 spacecraft by the Global Positioning System (GPS) satellites.
- **Scan Trajectory**: Collects the reflected laser beams in the orbits. By comparing the beam from the same laser track in an area wide, the precision enables up to 1% accuracy.

Sea Ice: New models for sea ice determine how much of the sea is covered by ice. For example, if the sea is covered by sea ice, the ICESat-2 will measure the thickness of the sea ice.

Land Ice: Including glaciers and ice sheets, from a snowfall accumulates over centuries and millennia. Land ice melting into the ocean elevates global sea levels. ICESat-2 will measure the annual rise or fall of ice sheets to within a fraction of an inch.

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

Average Mass Loss:
271 Gigatons/year

Average Mass Loss:
147 Gigatons/year

Source: NASA Scientific Visualization Studio
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.
Crustal Deformation
Advanced Rapid Imaging and Analysis (ARIA)

Source: aria.jpl.nasa.gov
2011 Tohoku-Oki

Cumulative Displacement (H)
Cumulative Displacement (Up)

ARIA Project
CALTECH / JPL

Time From Mainshock: ~8,000 min

http://tectonics.caltech.edu/slip_history/2011_taiheiyo-oki/Displacement/
Damage Proxy Maps
Damage Proxy Map (Earthquake & Tsunami)

NASA / JPL-Caltech / ARIA / EOS Product

Original data ALOS-2 PALSAR-2 Product - JAXA (2018)
Sentinel Asia, Google Earth
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
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