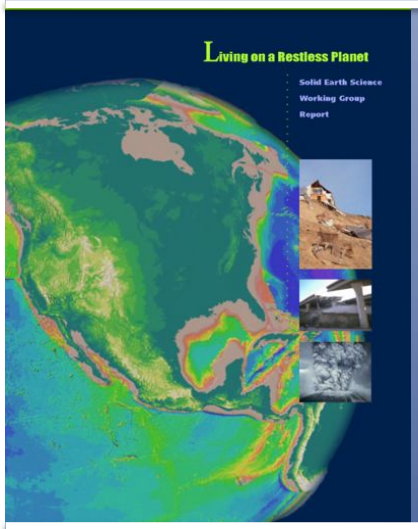
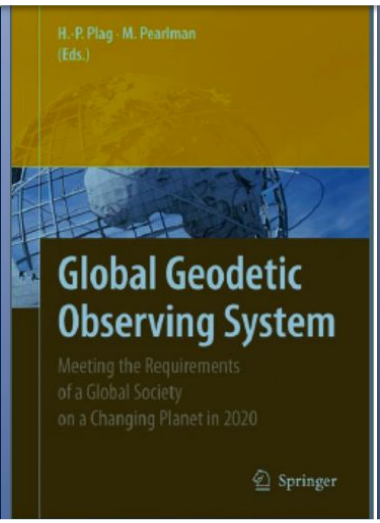
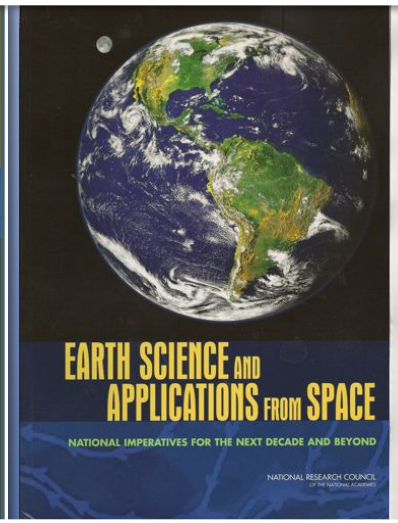
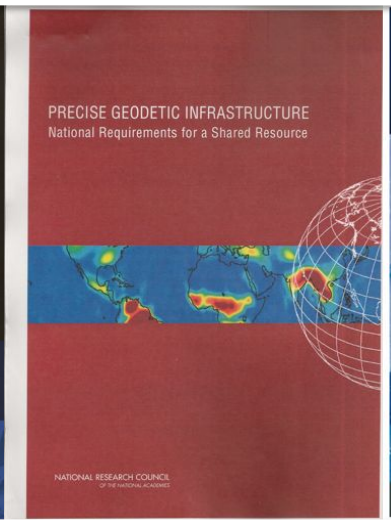
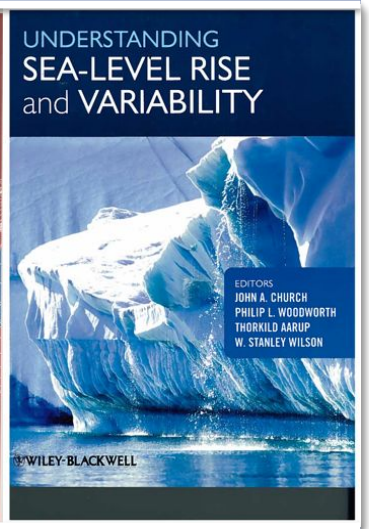
Meeting the Geodetic Challenge of the NRC's Decadal Survey







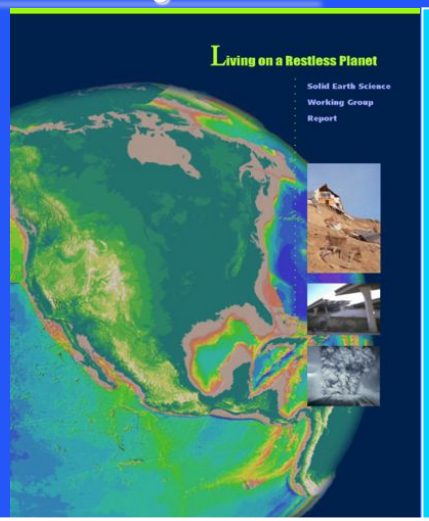




John LaBrecque
Lead, Earth Surface and Interior Focus Area
NASA Earth Science Division
Washington, DC 20546

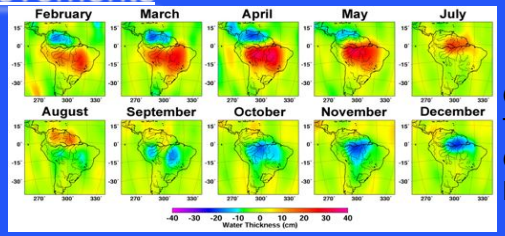
Earth Surface and Interior Focus Area
Strategic Plan: Living on a Restless Planet
http://solidearth.jpl.nasa.gov

ESI Strategic Goals-



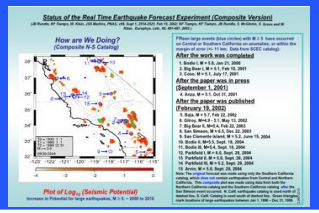
1. What is the nature of deformation at plate boundaries and what are the implications for earthquake hazards?
2. How do tectonics and climate interact to shape the Earth's surface and create natural hazards?
3. What are the interactions among ice masses, oceans, and the solid Earth and their implications for sea level change?
4. How do magmatic systems evolve and under what conditions do volcanoes erupt?
5. What are the dynamics of the mantle and crust and how does the Earth's surface respond?
6. What are the dynamics of the Earth's magnetic field and its interactions with the Earth system?

ESI Achievements



GRACE:1st Time Variable Gravity & Mass Flux

Earthquake Forecasting
13 of 14 Earthquakes



SRTM
1st Uniform Global Topography

ESI Component Programs

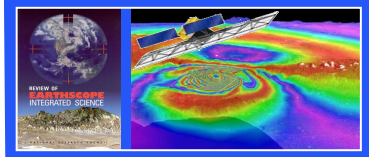
Natural Hazards
- Predictive Models
- Remote Sensing
- Natural Laboratories

Space Geodesy
- Celestial Ref Frame
- Terrestrial Ref Frame
- Earth Rotation
- Crustal Dynamics

Planetary Interior
- Geomagnetic Models
- Gravity Models
- Geodynamic Models

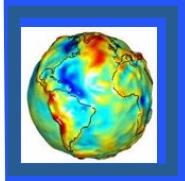
Overview of ES Focus Area

ESI Strategic Mission Priorities



1. Develop Geodetic Imaging Approach: DESDynI, International Partners

2. Renew Global Geodetic Network
Approach: GGOS Partnerships

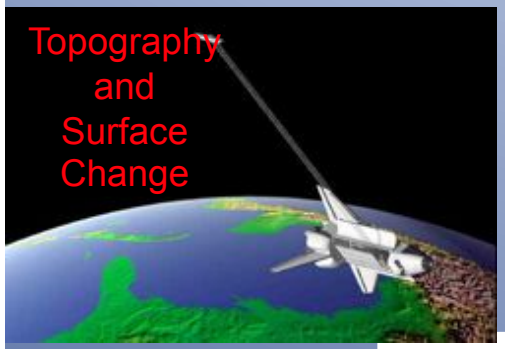


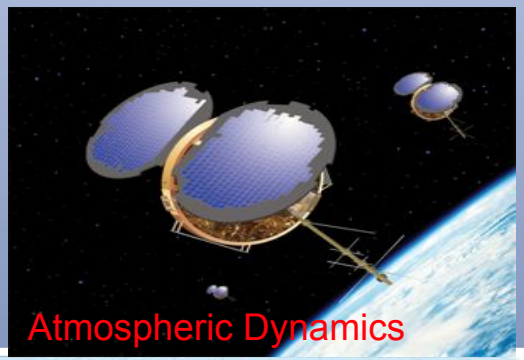
3. Expand Geopotential Field Exploration
Approach: GRACE-FO, International Partnerships, Technology Development, GRACE-II

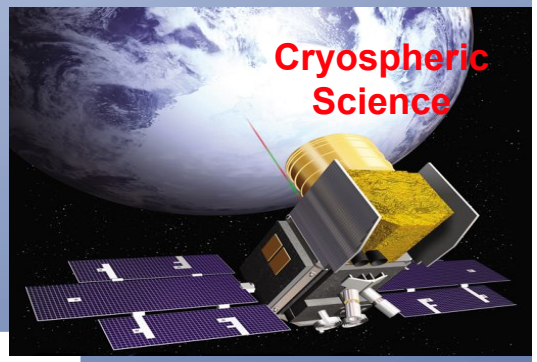
Presidents FY011 Budget Enables Next-Generation Space Geodetic Development

- **Development Studies**
  - Six US Agencies (NASA NGA, NOAA, NSF, USNO, and USGS) supporting the US National Research Council study National Requirements for Precision Geodetic Infrastructure.
  - NASA supports a Geodetic Study Group to develop the requirements for the next Generation Geodetic Network
    - Encouraged development of GGOS Standard based upon Sea level Change requirements. (1.0 mm accuracy, 0.1 mm/yr stability)
    - Funding Development of Network Performance Simulations
    - SLR Retro-reflector Standard
    - Placement of Retro-reflectors on the GPS III Satellites
    - Supporting Network and Communications Bureau of the GGOS
    - Supporting Central Bureaus of the IGS, IVS, ILRS
- **Instrument Development**
  - Prototype development of Next Gen Geodetic Observatory
  - NGSLR, VLB2010, TRIG GNSS Science Receiver
  - *Insitu* Continuous Co-location and Bias monitoring
  - Development of Decadal Study Missions:
  - SMAP, ICESAT-2, DESDynI Radar and Lidar, GRACE-FO, CLARREO
- **Development of Decadal Study Missions**
  - SMAP, ICESAT-2, DESDynI Radar and Lidar, GRACE-FO, CLARREO

Scientific and Societal Requirements for GNSS based Space Geodesy are Growing







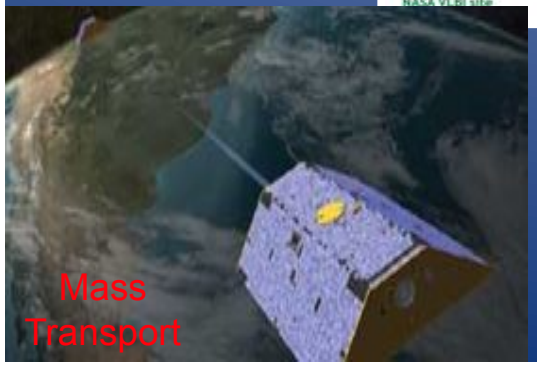
Climate Change Research

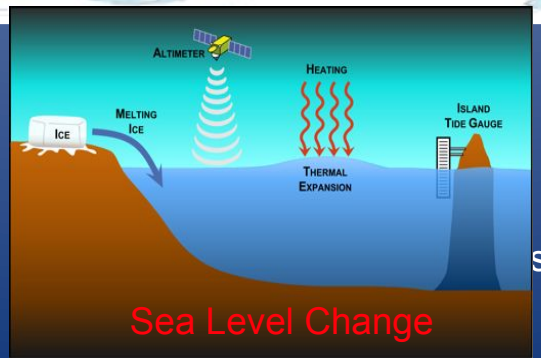
Geohazards Research and Mitigation

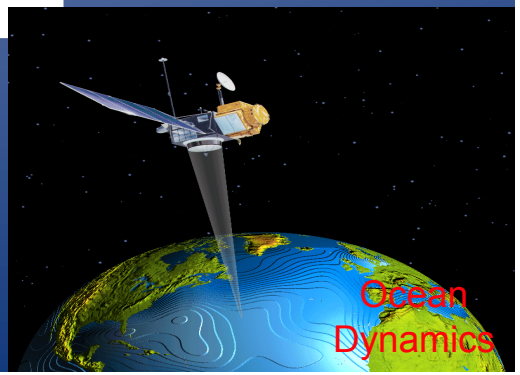
Navigation

Positioning

Time Transfer



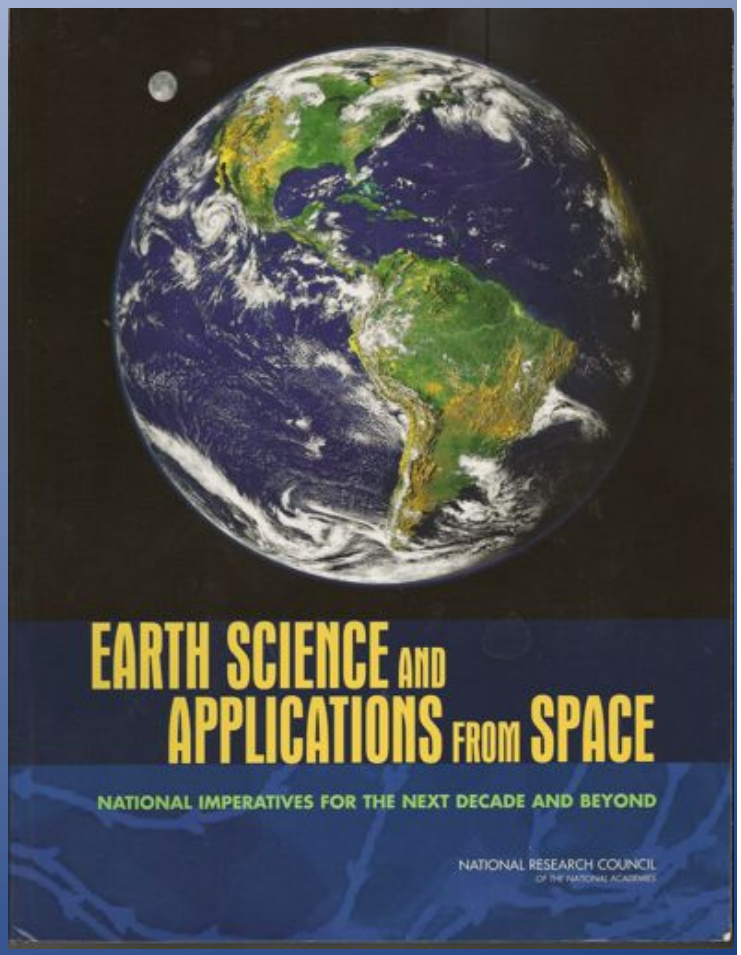




The Geodetic Challenge of the National Research Council's Decadal Study

$2.4 B in Space Missions that depend upon capable Geodetic Science, Geodetic Technology, and Geodetic Infrastructure.

Decadal Survey Mission	Mission Description	Orbit	Instruments	Rough Cost Estimate
Timeframe 2010 – 2013, Missions listed by cost				
CLARREO (NASA portion)	Solar radiation: spectrally resolved forcing and response of the climate system	LEO, Precessing	Absolute, spectrally-resolved interferometer	$200 M
SMAP	Soil moisture and freeze/thaw for weather and water cycle processes	LEO, SSO	L-band radar L-band radiometer	$300 M
ICESat-II	Ice sheet height changes for climate change diagnosis	LEO, Non-SSO	Laser altimeter	$300 M
DESDynI	Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	LEO, SSO	L-band InSAR Laser altimeter	$700 M
Timeframe: 2013 – 2016, Missions listed by cost				
HyspIRI	Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health	LEO, SSO	Hyperspectral spectrometer	$300 M
ASCENDS	Day/night, all-latitude, all-season CO_2 column integrals for climate emissions	LEO, SSO	Multifrequency laser	$400 M
SWOT	Ocean, lake, and river water levels for ocean and inland water dynamics	LEO, SSO	Ka-band wide swath radar C-band radar	$450 M
GEO-CAPE	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	GEO	High and low spatial resolution hyperspectral imagers	$550 M
ACE	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry	LEO, SSO	Backscatter lidar Multiangle polarimeter Doppler radar	$800 M
Timeframe: 2016 -2020, Missions listed by cost				
LIST	Land surface topography for landslide hazards and water runoff	LEO, SSO	Laser altimeter	$300 M
PATH	High frequency, all-weather temperature and humidity soundings for weather forecasting and SST[a]	GEO	MW array spectrometer	$450 M
GRACE-II	High temporal resolution gravity fields for tracking large-scale water movement	LEO, SSO	Microwave or laser ranging system	$450 M
SCLP	Snow accumulation for fresh water availability	LEO, SSO	Ku and X-band radars K and Ka-band radiometers	$500 M
GACM	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	LEO, SSO	UV spectrometer IR spectrometer Microwave limb sounder	$600 M
3D-Winds (Demo)	Tropospheric winds for weather forecasting and pollution transport	LEO, SSO	Doppler lidar	$650 M



ISBN: 0-309-66714-3, 456 pages, 8 1/2 x 11, (2007)

Download Free from:
http://www.nap.edu/catalog/11820.html

The Requirement for Precise Measurement and Maintenance of the Terrestrial Reference Frame: (*Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, NRC,2007)*

According to the NRC Decadal Survey:

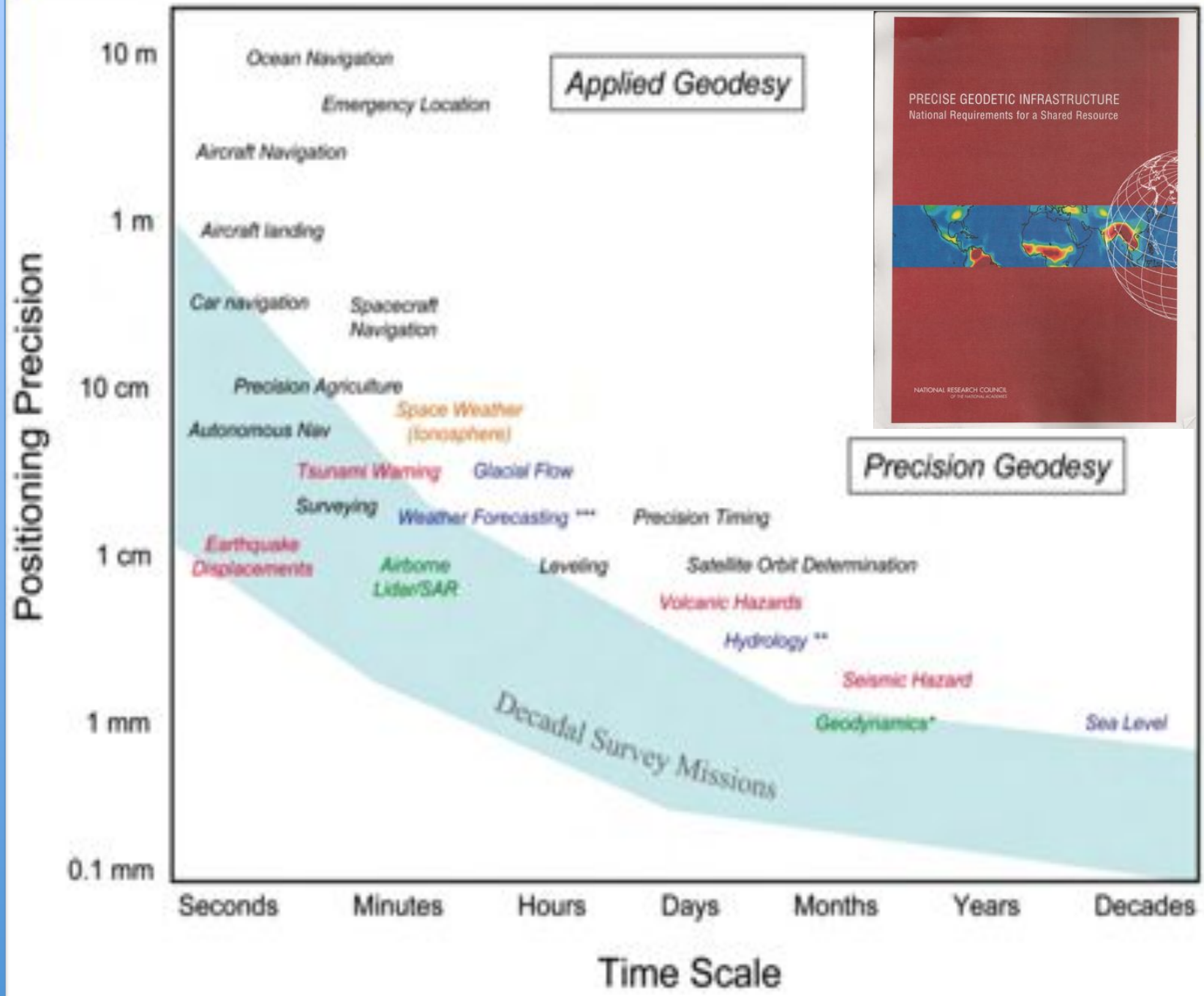
“The geodetic infrastructure needed to enhance, or even to maintain the terrestrial reference frame is in danger of collapse (cf. Chapter 1). Improvements in both accuracy and economic efficiency are needed. Investing resources to assure the improvement and the continued operation of this geodetic infrastructure is a requirement of virtually all the missions for every Panel in this study.

The terrestrial reference frame is realized through integration of the high precision networks of the Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR). It provides the foundation for virtually all space-based and ground-based observations in Earth science and global change, including remote monitoring of sea level, sea surface topography, plate motions, crustal deformation, the geoid, and time-varying gravity from space. It is through this reference frame that all measurements can be inter-related for robust, long-term monitoring of global change. A precise reference frame is also essential to interplanetary navigation and diverse national strategic needs.”

The Requirement for Precise Measurement and Maintenance of the Terrestrial Reference Frame: (*Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, NRC,2007)*

"The geodetic infrastructure needed to enhance, or even to maintain the terrestrial reference frame is in danger of collapse (cf. Chapter 1). Improvements in both accuracy and economic efficiency are needed. Investing resources to assure the improvement and the continued operation of this geodetic infrastructure is a requirement of virtually all the missions for every Panel in this study.

The terrestrial reference frame is realized through integration of the high precision networks of the Global Positioning System (GPS), Very Long Baseline Interferometry (VLBI), and Satellite Laser Ranging (SLR). It provides the foundation for virtually all space-based and ground-based observations in Earth science and global change, including remote monitoring of sea level, sea surface topography, plate motions, crustal deformation, the geoid, and time-varying gravity from space. It is through this reference frame that all measurements can be inter-related for robust, long-term monitoring of global change. A precise reference frame is also essential to interplanetary navigation and diverse national strategic needs."


Applied Geodesy
Precision Geodesy
PRECISE GEODETIC INFRASTRUCTURE
National Requirements for a Shared Resource
NATIONAL RESEARCH COUNCIL
Ocean Navigation
Emergency Location
Aircraft Navigation
Aircraft landing
Car navigation
Spacecraft Navigation
Precision Agriculture
Space Weather (Ionosphere)
Autonomous Nav
Tsunami Warning
Glacial Flow
Surveying
Weather Forecasting ***
Precision Timing
Earthquake Displacements
Airborne Lidar/SAR
Leveling
Satellite Orbit Determination
Volcanic Hazards
Hydrology **
Seismic Hazard
Geodynamics*
Sea Level
Decadal Survey Missions
10 m
1 m
10 cm
1 cm
1 mm
0.1 mm
Positioning Precision
Seconds
Minutes
Hours
Days
Months
Years
Decades
Time Scale

Strengthened GNSS- Global Geodetic Observing System Collaboration will improve GNSS performance and Scientific Productivity

International Terrestrial Reference Frame (ITRF)

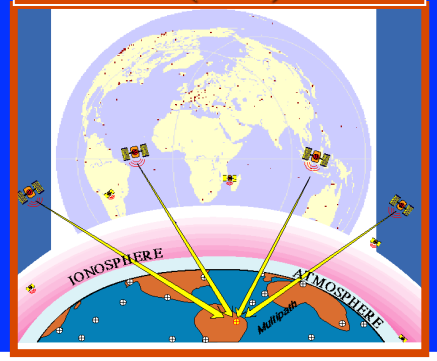
International Earth Rotation Service (IERS)

Precision GPS Orbits and Clocks, Earth Rotation Parameters, Station Positions

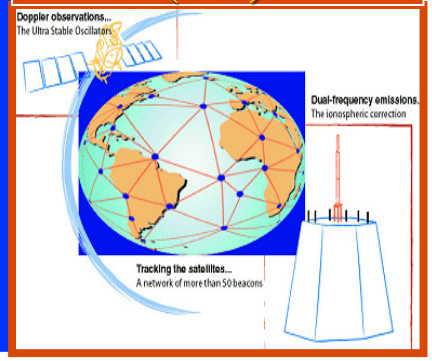
Very Long Baseline Interferometry (IVS)

Satellite Laser Ranging (ILRS)

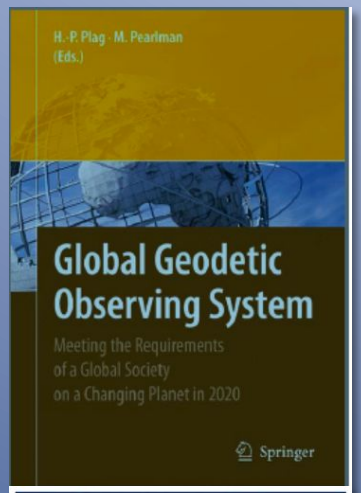
Global Navigation Satellite Systems (IGS)

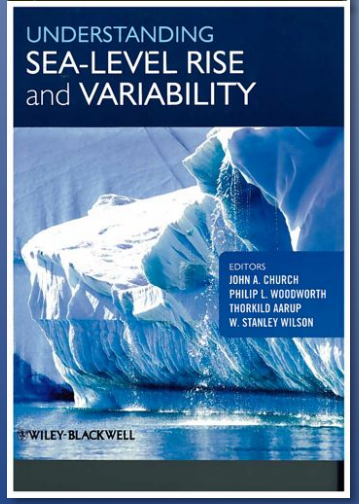


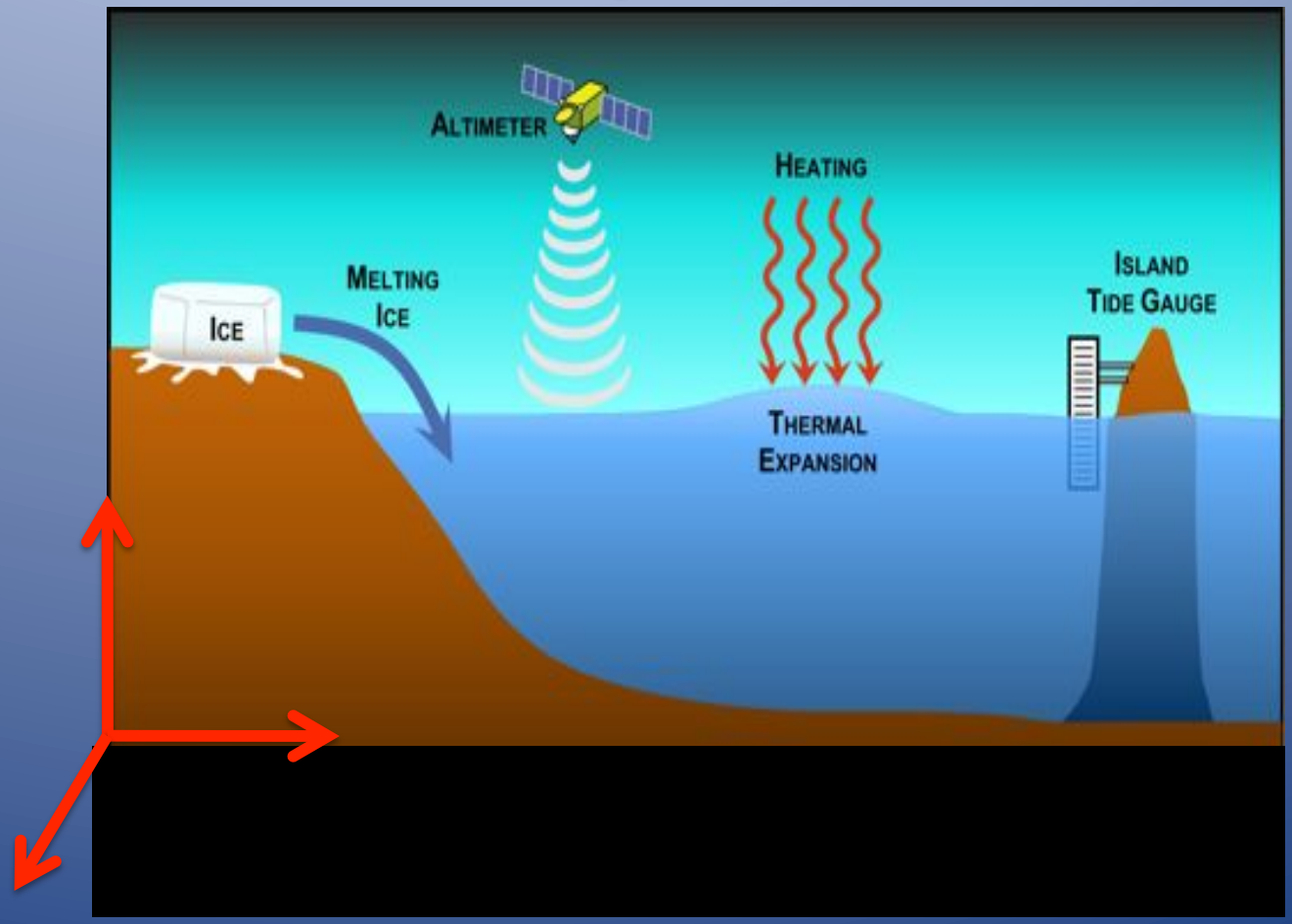
Doppler Orbit Determination and Radiopositioning Integrated on Satellite (IDS)



Improving the performance of the Global Geodetic Observing System is critical to understanding the future impact of Sea level Change







The GGOS Geodetic Reference Frame Requirement for Sea Level Measurement

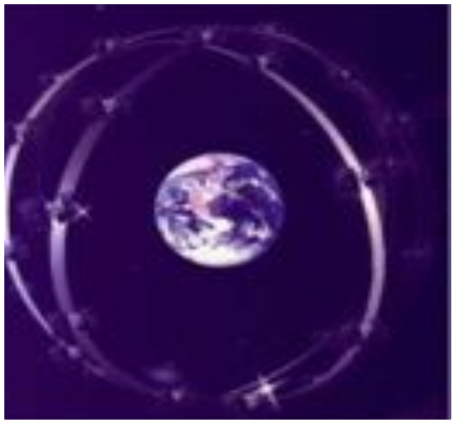
1 mm reference frame accuracy and 0.1 mm/yr stability

GNSS Challenge: 60 to 90 High Precision Radio Sources Within the Decade (+ QZSS & GAGAN)

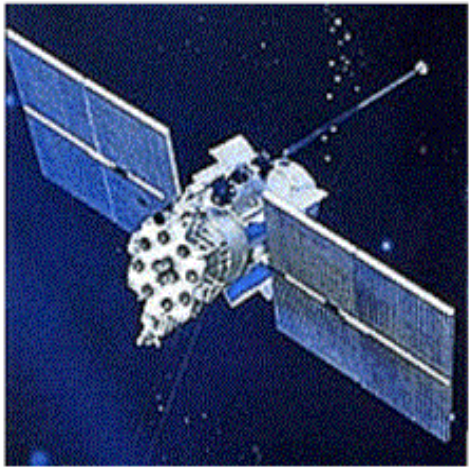
- Will the Signals be interoperable?
- Will the Scientific Geodetic Community have access to the precise signals?
- Will real time access to the relevant codes be available for scientific geodesy?
- Will the GGOS provide Precision Tracking via GNSS, SLR, and VLBI Networks?

GPS | Galileo | GLONASS | Beidou





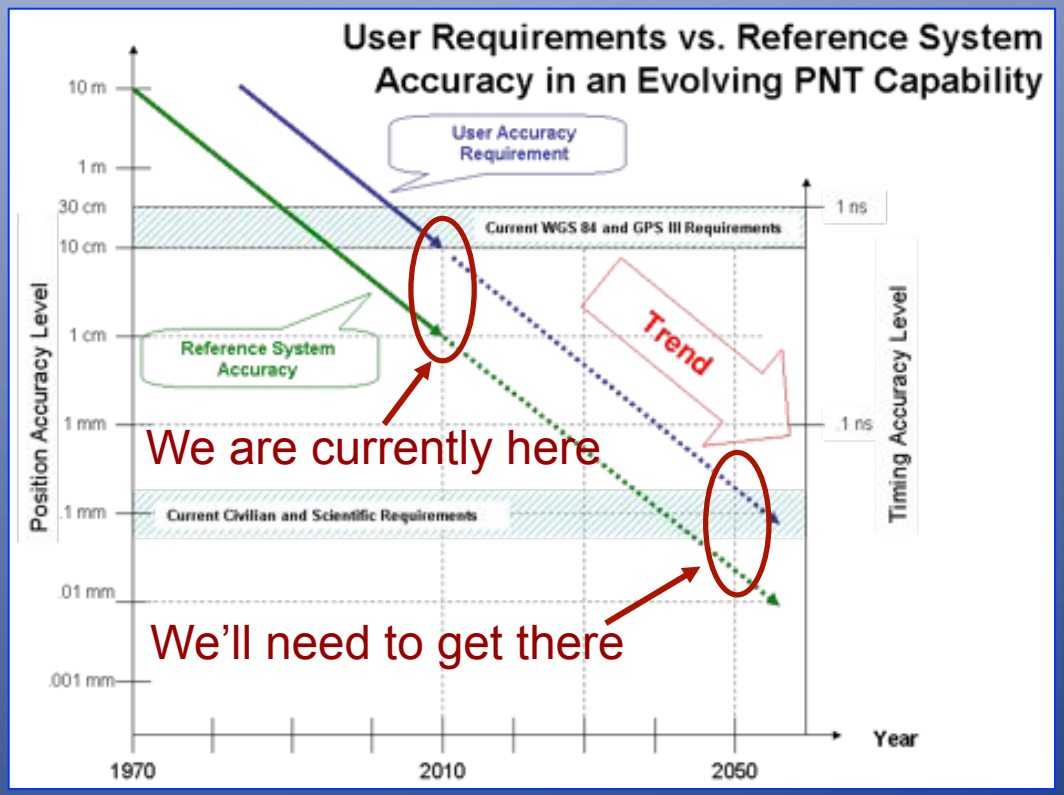





Achieving ITRF Requirements Through Satellite Laser Ranging

SLR Enables:

- Comparison of collocated radiometric and optical measurements used for model improvements
- Isolation of systematic errors in GNSS constellations and improves the reference frame accuracy
  - Variation of range and phase centers important for space users because they sample the signals far off the transmit boresight
- Improved models and reference frames necessary to support civilian and scientific requirements for higher PNT accuracy
  - Global sea height change measurement from space requires 1 mm/year precision, so reference frame needs to be constant to 0.1 mm/yr



ILRS Retro-reflector Standard for GNSS Satellites

- Retro-reflector payloads for the GNSS satellites GPS, GLONASS, and COMPASS should have an “effective cross-section” of 100 million sq. meters (5 times that of GPS-35 and -36) for GNSS satellite; GLONASS is first to comply.
- The parameters necessary for the precise definition of the vectors between the effective reflection plane, the radiometric antenna phase center and the center of mass of the spacecraft be specified and maintained with an accuracy of a mm;
- Further Recommendation: Retro-reflector payloads for satellites such as Galileo in higher orbits should scale the “effective cross-section” to compensate for the R**4 reduction in signal strength;

GPS 35/36

ETS VIII

A 16 Station SLR Network Tracking a GNSS constellation could provide 4mm/yr origin and .02mm/yr scale accuracy

(results/sqrt 52, Pavlis et al, 2010)

Error in ITRF Origin [mm]

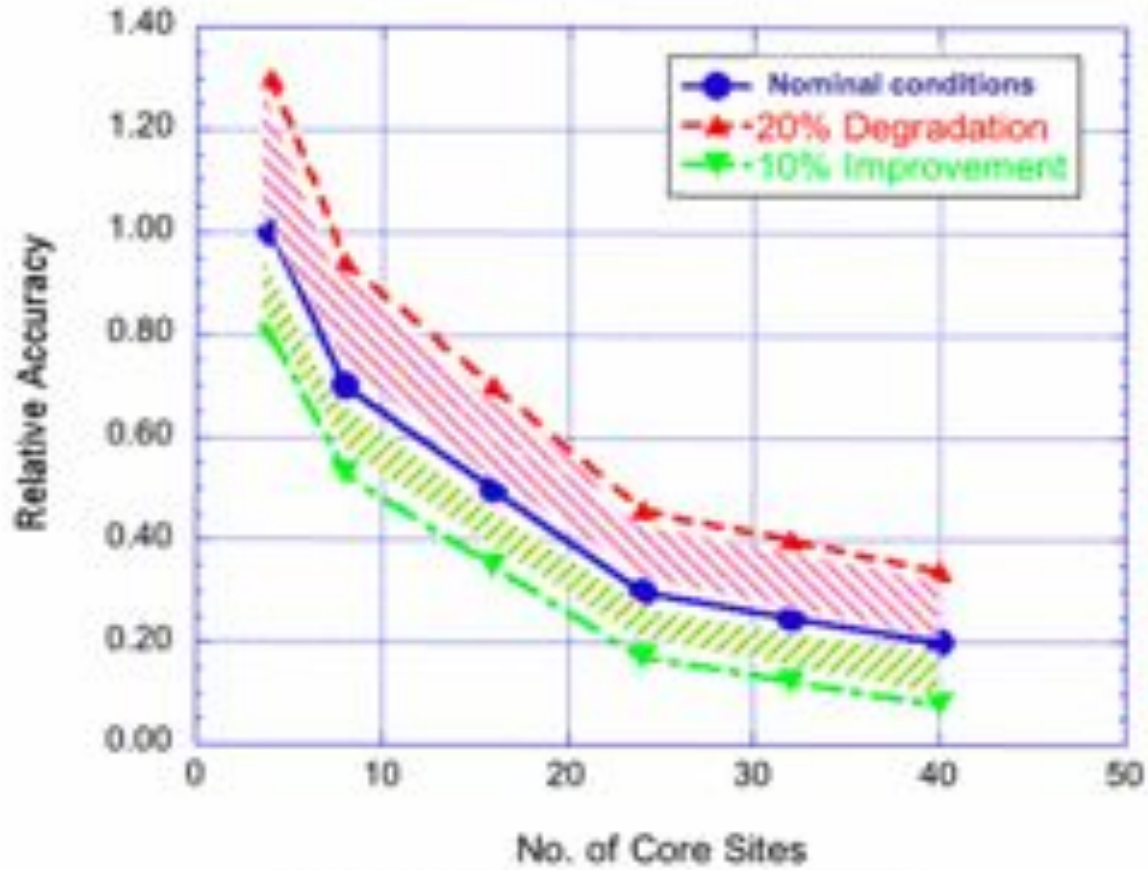
Days Tracked	1 SVN	2 SVN	3 SVN	4 SVN	5 SVN	6 SVN
1	395.9	561.3	263.0	136.7	107.6	70.3
2	399.0	56.9	50.9	43.3	44.1	61.5
3	745.6	93.0	99.3	43.8	38.0	43.2
4	486.7	49.4	78.8	50.2	44.8	68.9
5	436.5	77.6	54.9	48.0	43.8	31.0
6	475.7	78.4	55.7	51.2	47.2	30.6
7	276.0	97.0	54.7	49.0	44.7	28.4

Error in ITRF Scale [mm]

Days Tracked	1 SVN	2 SVN	3 SVN	4 SVN	5 SVN	6 SVN
1	782.4	30.0	10.6	9.1	6.0	3.7
2	329.6	21.8	8.7	8.1	6.3	3.5
3	362.4	25.9	8.1	2.9	1.3	2.7
4	315.1	12.3	6.1	2.8	1.8	1.9
5	199.9	10.6	3.8	3.0	1.8	1.1
6	190.5	7.2	5.2	3.3	1.3	1.3
7	99.8	8.5	4.9	3.1	2.6	0.6

Network Size

Network size vs. "x" Parameter Accuracy



"x": Origin, Scale, EOP, their rates, etc.

GGOS Networks, Communications and Infrastructure WG Meeting, Perugia, Italy, 9 July, 2007

NASA is Building the Next Generation Geodetic Observatory at GGAO

VLBI

SLR

Continuous monitoring of
Instrument co-location

DORIS

Real Time
Communications Network
For
Data Analysis
Network Control

GNSS

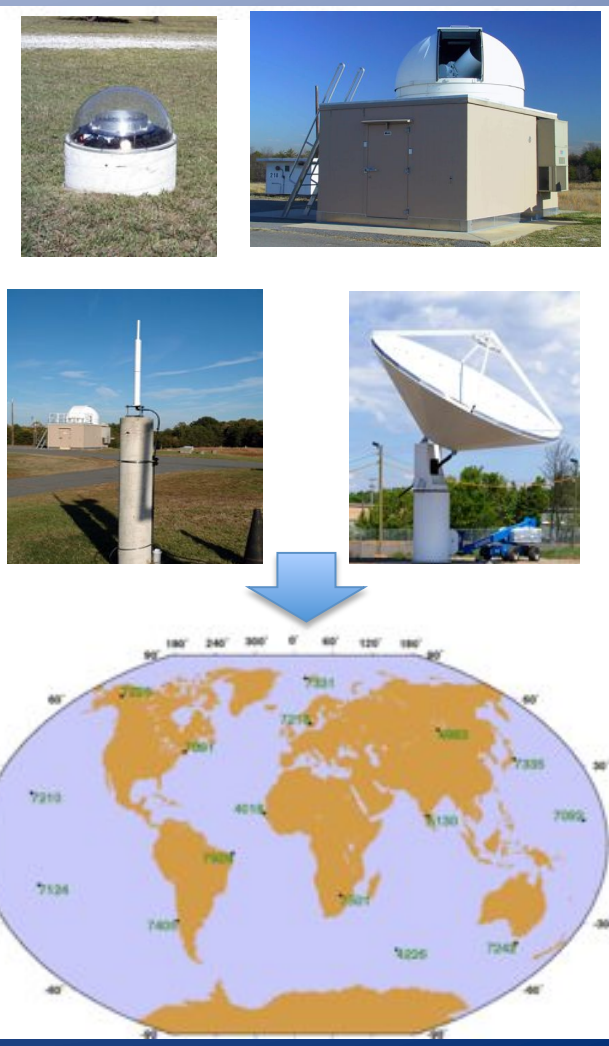
NASA's Climate Initiative Supports the Development of an Improved Observing System Earth System Mass Transport

Rebuild the Satellite Observing System

Decadal Survey Mission	Mission Description	Orbit	Instruments	Rough Cost Estimate
Timeframe 2010 – 2013, Missions listed by cost				
CLARREO (NASA portion)	Solar radiation: spectrally resolved forcing and response of the climate system	LEO, Precessing	Absolute, spectrally-resolved interferometer	$200 M
SMAP	Soil moisture and freeze/thaw for weather and water cycle processes	LEO, SSO	L-band radar L-band radiometer	$300 M
ICESat-II	Ice sheet height changes for climate change diagnosis	LEO, Non-SSO	Laser altimeter	$300 M
DESDynI	Surface and ice sheet deformation for understanding natural hazards and climate; vegetation structure for ecosystem health	LEO, SSO	L-band InSAR Laser altimeter	$700 M
Timeframe: 2013 – 2016, Missions listed by cost				
HyspIRI	Land surface composition for agriculture and mineral characterization; vegetation types for ecosystem health	LEO, SSO	Hyperspectral spectrometer	$300 M
ASCENDS	Day/night, all-latitude, all-season CO_2 column integrals for climate emissions	LEO, SSO	Multifrequency laser	$400 M
SWOT	Ocean, lake, and river water levels for ocean and inland water dynamics	LEO, SSO	Ka-band wide swath radar C-band radar	$450 M
GEO-CAPE	Atmospheric gas columns for air quality forecasts; ocean color for coastal ecosystem health and climate emissions	GEO	High and low spatial resolution hyperspectral imagers	$550 M
ACE	Aerosol and cloud profiles for climate and water cycle; ocean color for open ocean biogeochemistry	LEO, SSO	Backscatter lidar Multiangle polarimeter Doppler radar	$800 M
Timeframe: 2016 -2020, Missions listed by cost				
LIST	Land surface topography for landslide hazards and water runoff	LEO, SSO	Laser altimeter	$300 M
PATH	High frequency, all-weather temperature and humidity soundings for weather forecasting and SST[a]	GEO	MW array spectrometer	$450 M
GRACE-II	High temporal resolution gravity fields for tracking large-scale water movement	LEO, SSO	Microwave or laser ranging system	$450 M
SCLP	Snow accumulation for fresh water availability	LEO, SSO	Ku and X-band radars K and Ka-band radiometers	$500 M
GACM	Ozone and related gases for intercontinental air quality and stratospheric ozone layer prediction	LEO, SSO	UV spectrometer IR spectrometer Microwave limb sounder	$600 M
3D-Winds (Demo)	Tropospheric winds for weather forecasting and pollution transport	LEO, SSO	Doppler lidar	$650 M

Rebuild the Global Geodetic Observing Network

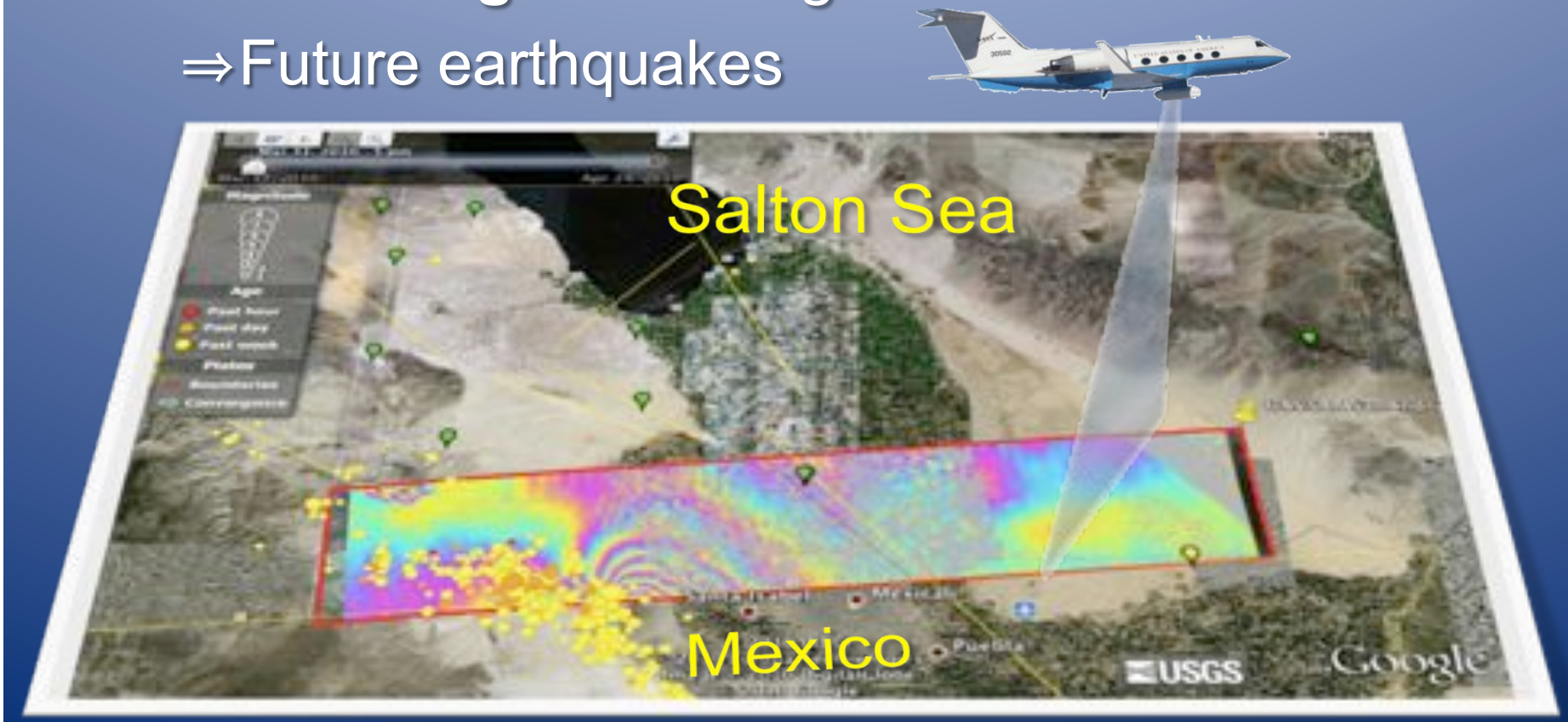
NRC Geodetic Science Missions



First UAVSAR Measurement of an Earthquake
http://uavsar.jpl.nasa.gov

- **Response:** Displacement and disturbance maps
- **Forecasting:** Strain migration

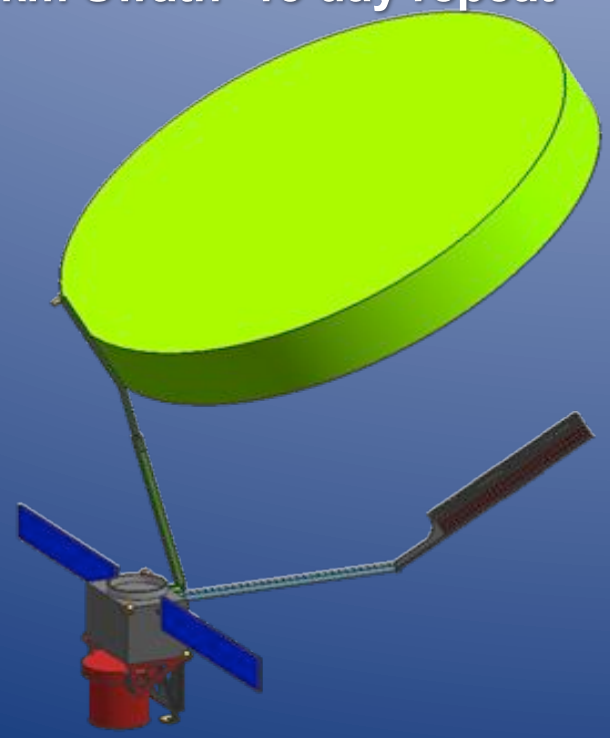
  ⇒Future earthquakes



DESDynI is a Dual Spacecraft Mission
2017 Launch

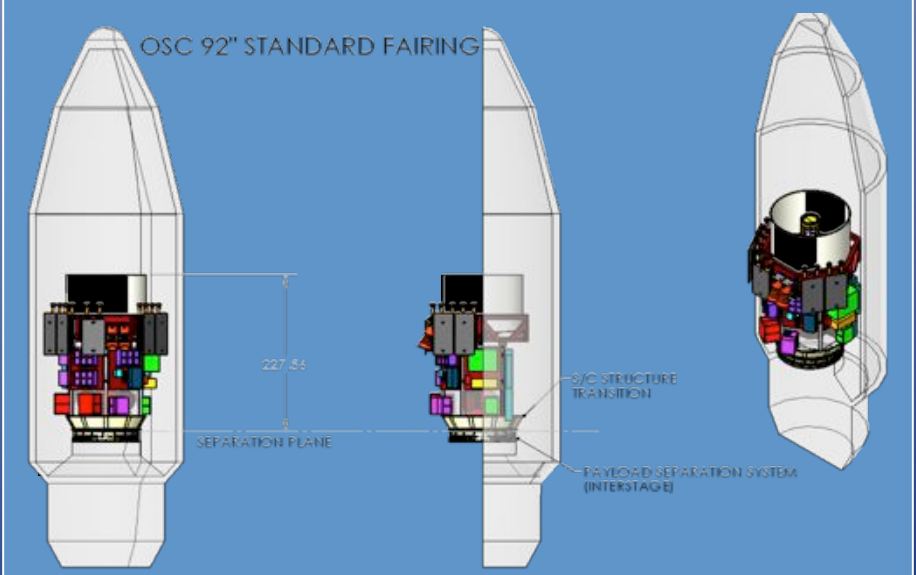
D-SAR

L-Band Sweep SAR Quad-Pol.
700 km Orbit-
Dawn-Dusk Orbit
3 year lifetime
270 km Swath -13 day repeat



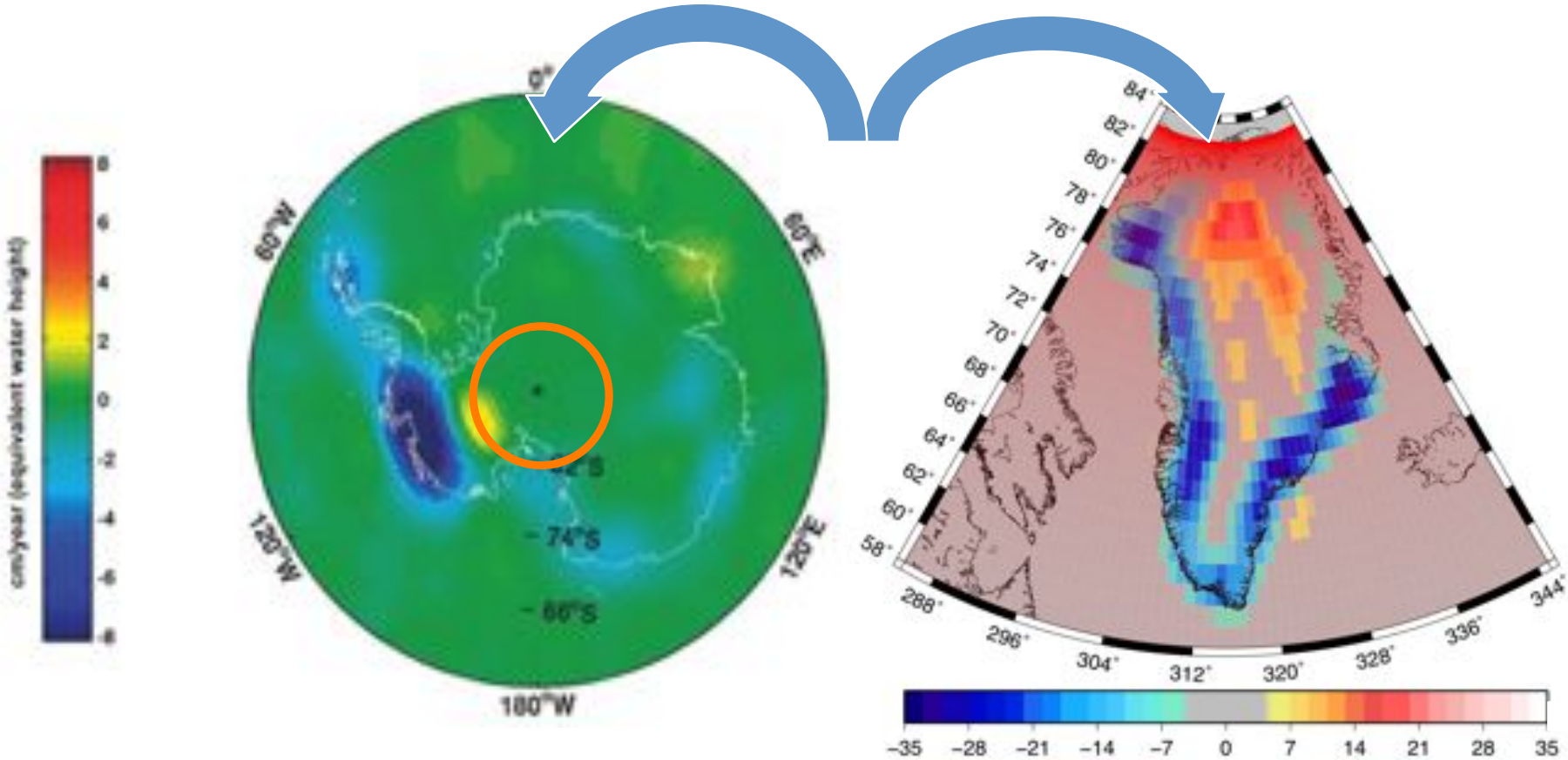
D-Lidar

1 m telescope (~393 km orbit)
Fixed, nadir orientation
5 Beams (35% duty cycle)
2 year lifetime
Dawn-Dusk Orbit
91 day Repeat

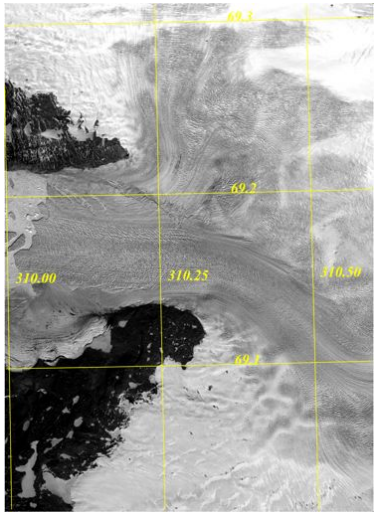


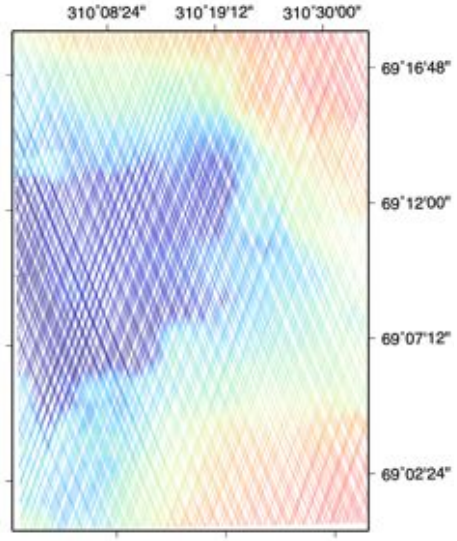
DESDynI Lidar tracks over GRACE mass anomalies *(Luthcke et al.).*

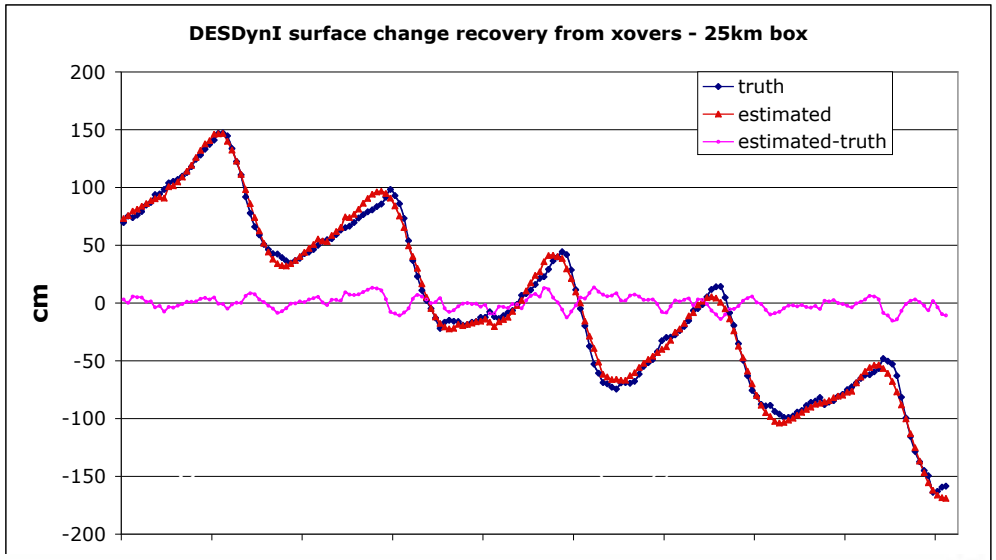
420 nm radius DESDynI Lidar Donut hole coverage
86.4 % Antarctic 99% of Greenland



DESDynI-Lidar simulated Recovery of Jakobshavn Isbrae Topographic Change



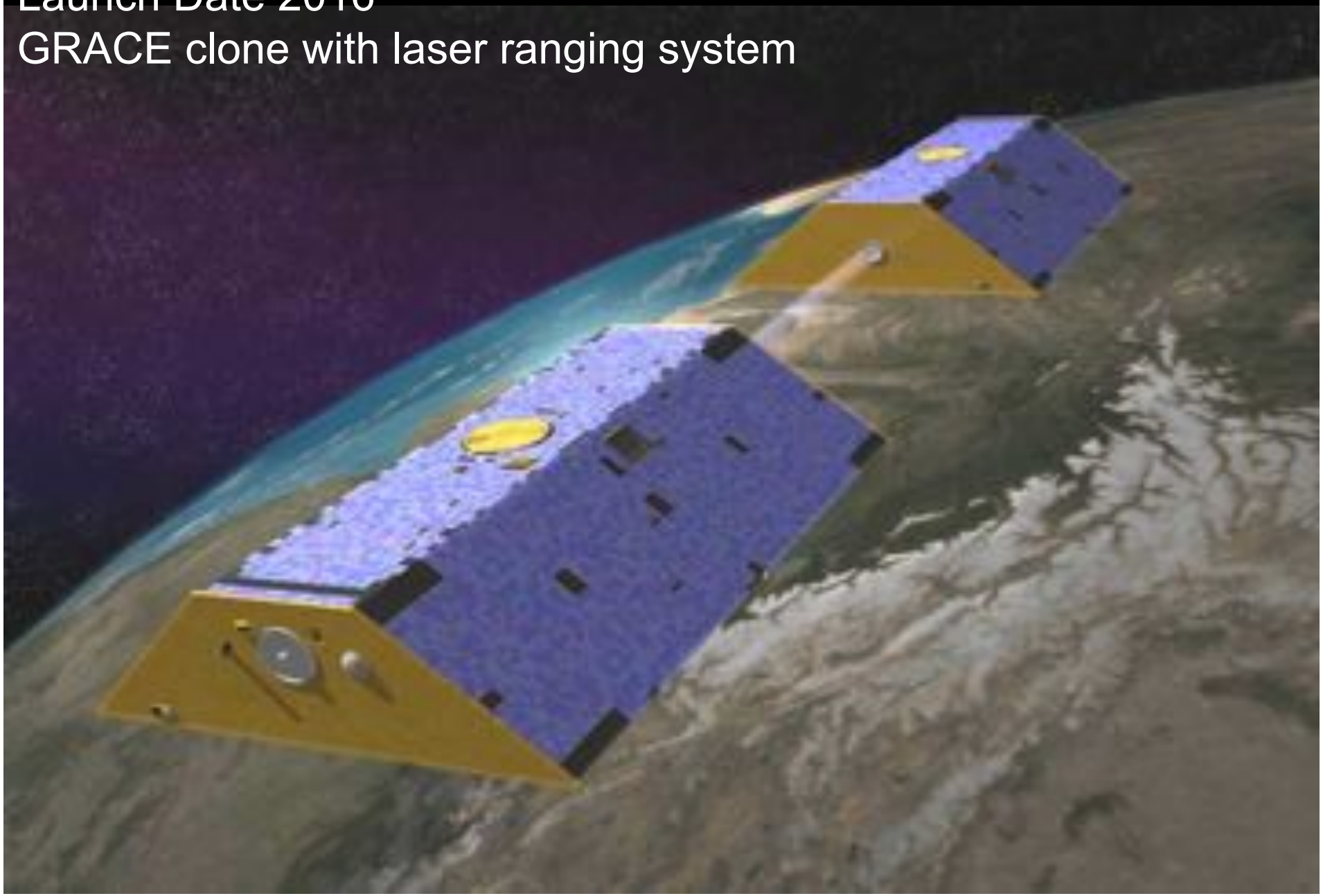




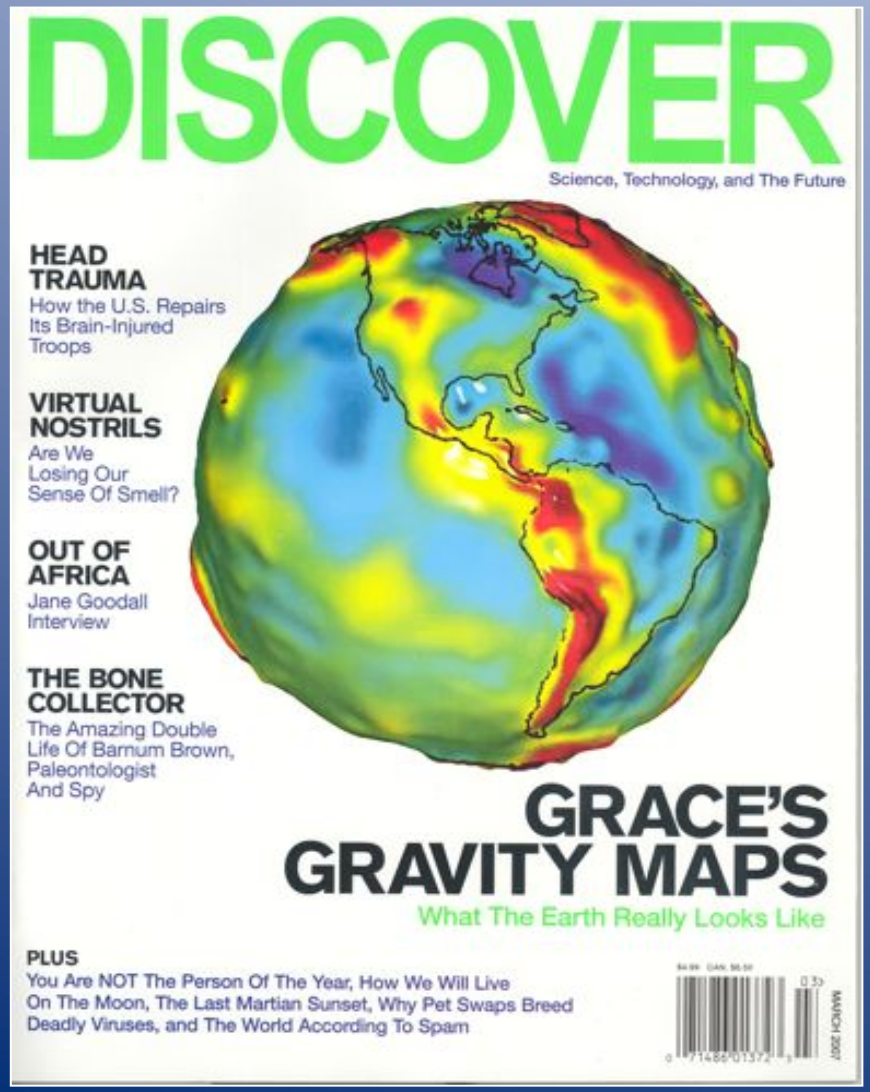
1σ Error in Recovered Signal (ABS(truth-estimated))

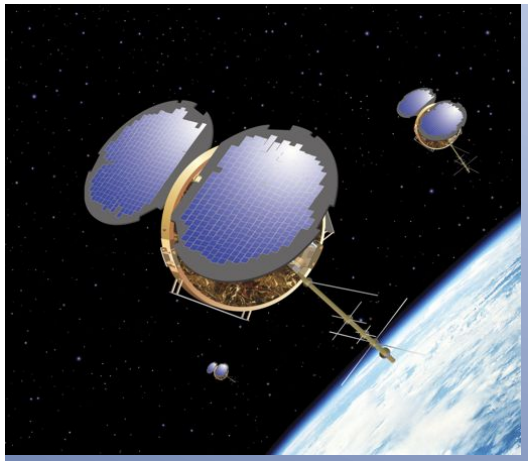
Mission Configuration and data used 1. 50% random pass loss from clouds unless otherwise noted. 2. 30 m along-track sampling unless otherwise noted.	Spatial Resolution (km X km)	3 Year Trends (cm/yr)	1 Year Trends (cm/yr)	6 month change (cm)	No. of Obs.	Post-fit Obs. Residual (m)
DESDynI 5-year mission	25	1.0	7.2	7.5	12658	1.33
	10	1.1	11.29	19.9	2850	1.52
	5	4.3	19.4	25.7	719	1.48
	2.5	4.4			179	1.44

GRACE-Follow-ON:
Launch Date 2016
GRACE clone with laser ranging system



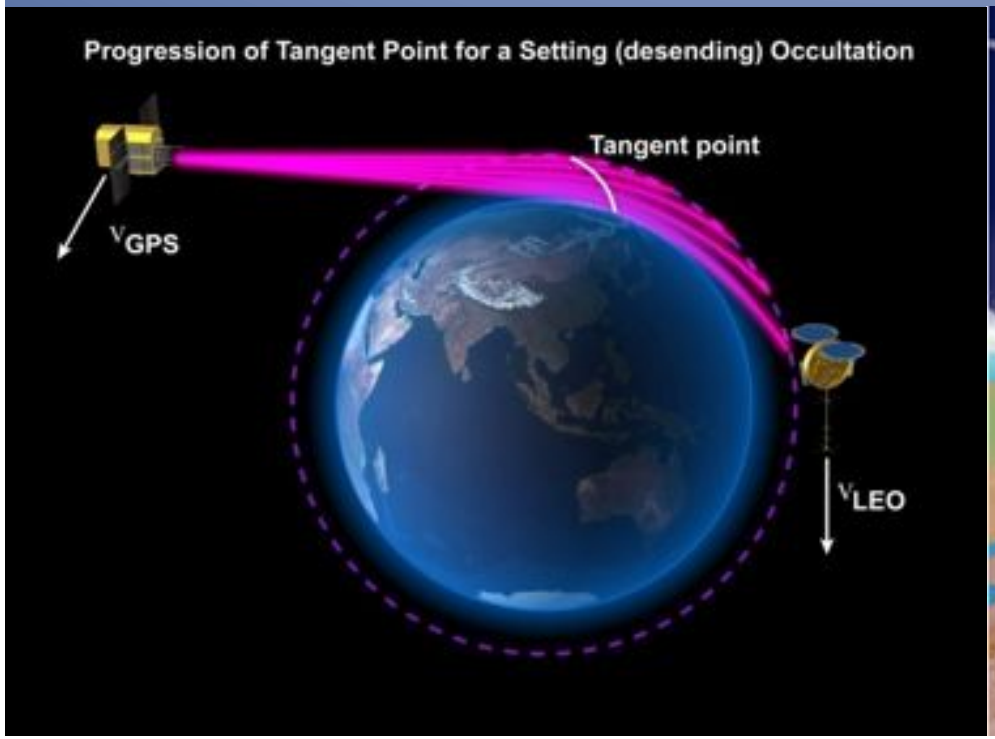
Space Geodesy is a Science that Cuts a Wide and Important Swath through the Scientific Landscape



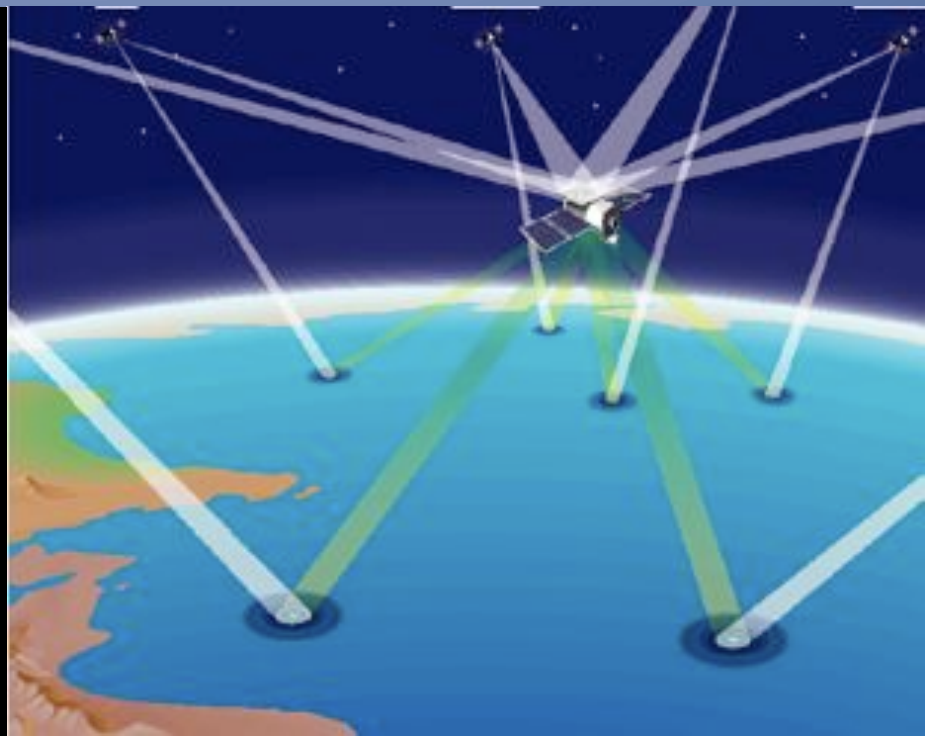


Next Generation Constellations of GNSS Remote Sensing Satellites will Provide Tomographic Measurements of the Ionosphere, Atmosphere and Characterize the Earth's Surface Using

REFRACTION



REFLECTION



Will the NRC missions of GRACE FO + DESDynI + SMAP+Geodetic Networks Provide High Resolution Separable Measurements of Hydrology and Tectonics?