A Perspective on Revolutions, Revisions, Rights, and Responsibilities in the Geosciences

https://CroninProjects.org/October2024/

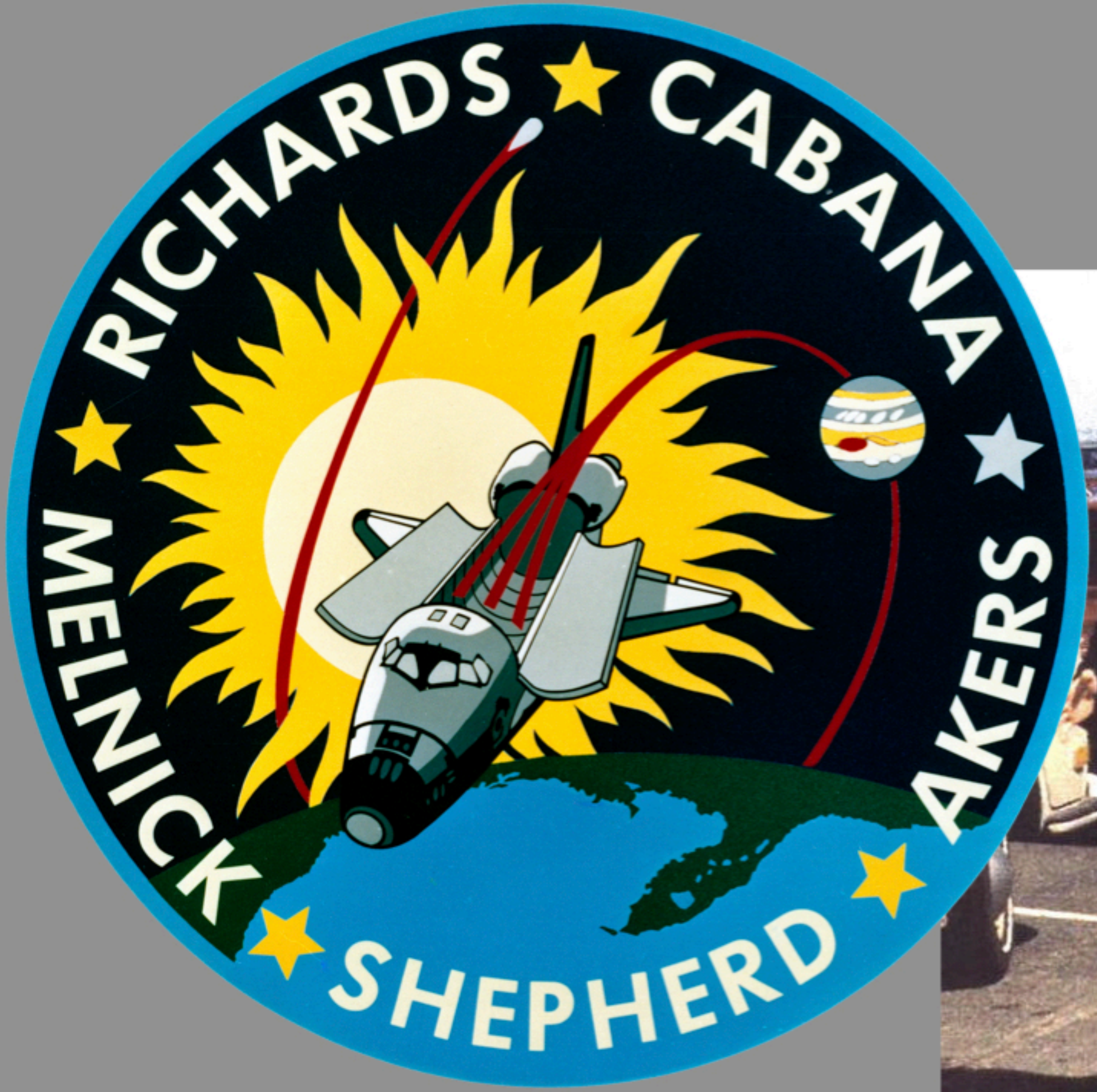
Kimberly, Australia, from Planet Snapshots, www.planet.com

The way most of us thought of Earth before December 24, 1968


Photo by Sebastian Gregorzyk

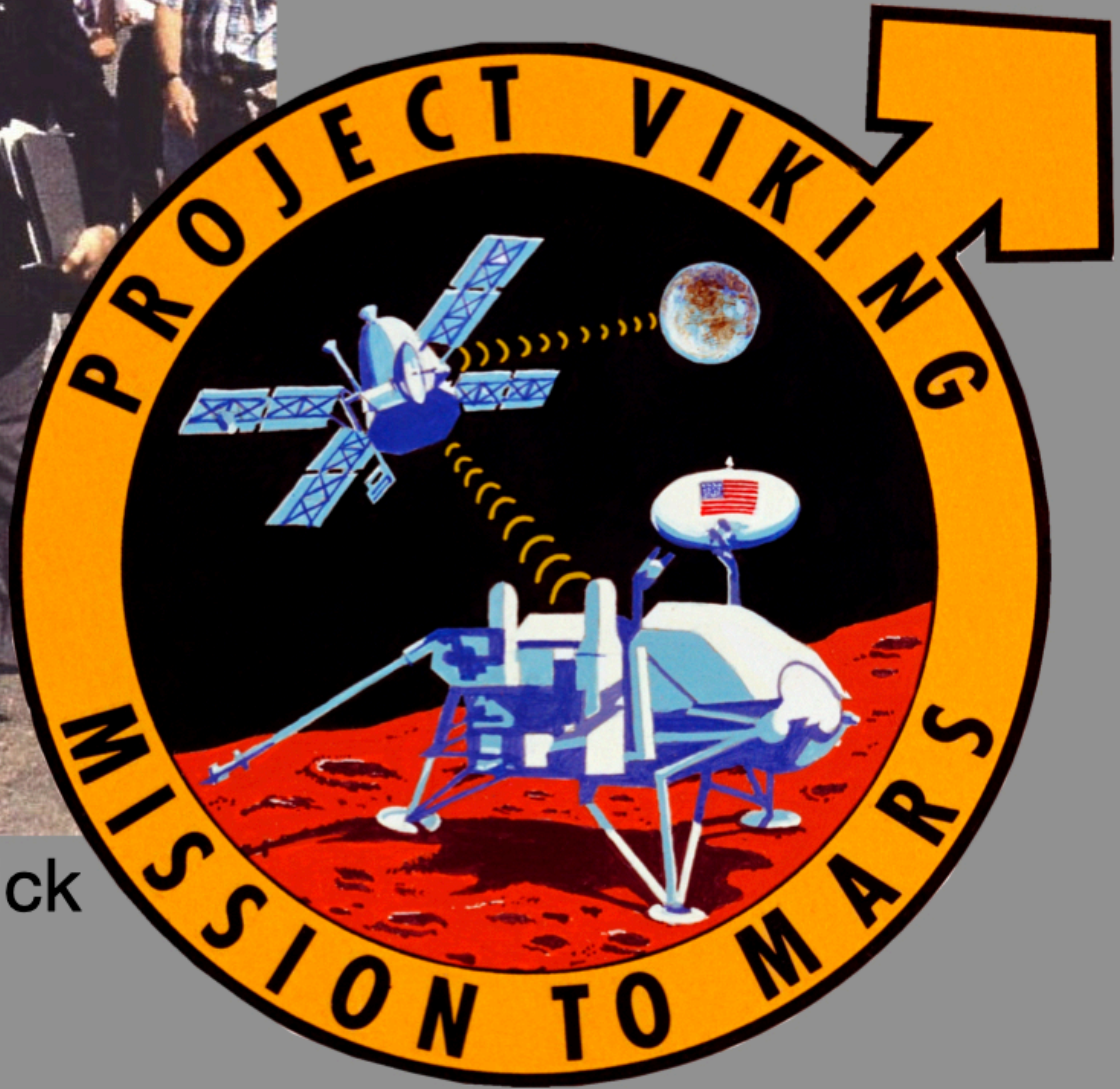
“Earthrise” photo taken by Bill Anders
from Apollo 8, December 24, 1968

Photo by Ron Evans on Apollo 17 ~18,300 miles
from Earth on his way to the Moon, December 7, 1972



STS-41 Logo


Shepherd, Cronin, Melnick



science

the best way we have devised to generate reliable information about physical reality

reproducible observations

testable hypotheses

curiosity

ethics & integrity

truth* seeking

scepticism

uncertainty

humility in the face of our ignorance

quantification

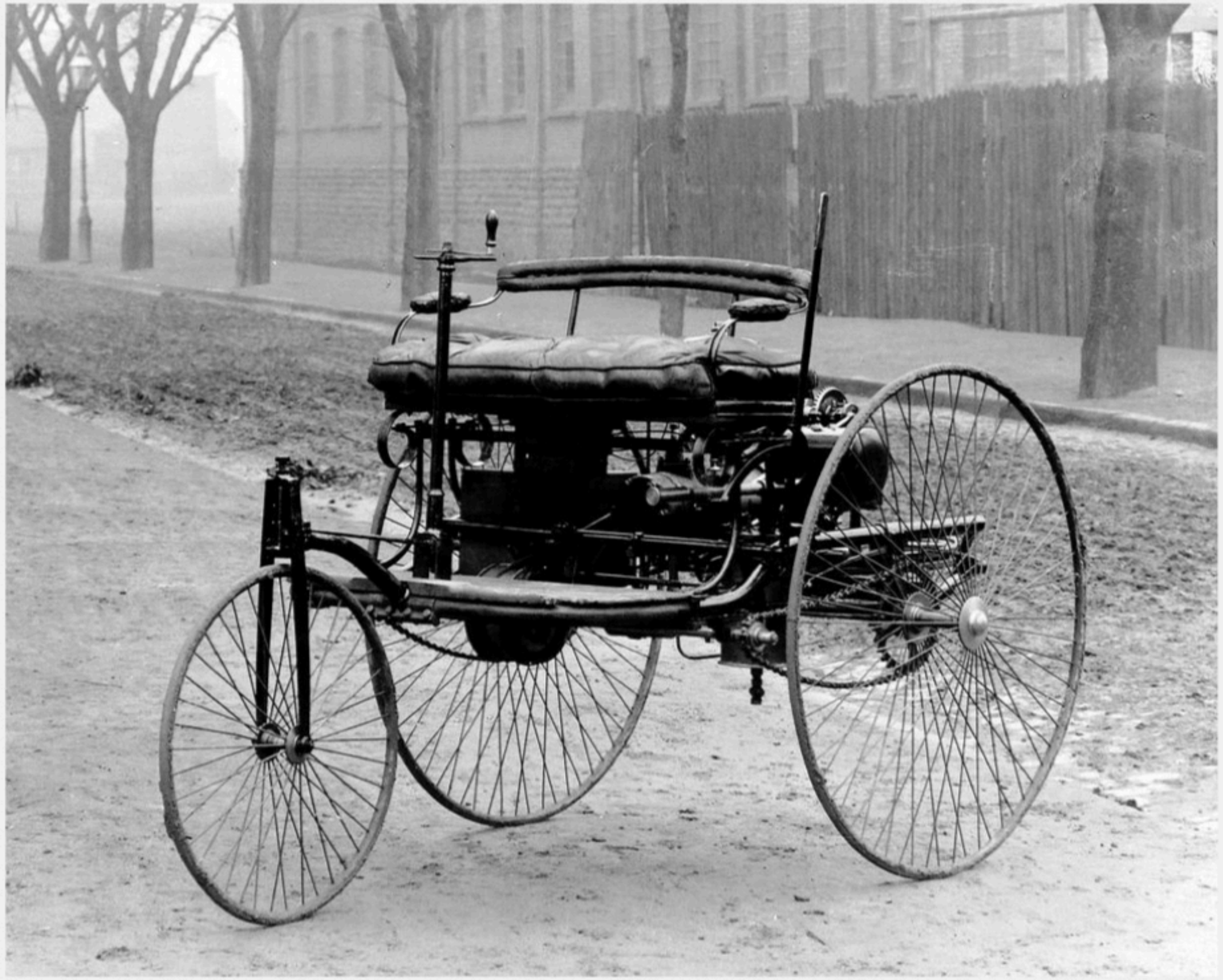
measurement

* “Truth is what stands the test of experience.” Einstein, 1953

$\pi = 3.14159265358979323846264338327950288419716939937510582097 4\ldots$

Informal Reference	Value Approx.	Accuracy
first order	3	95.5%
second order	3.1	98.7%
third order	3.14	99.9%

First Generation



1885 Benz Motorwagen
gasoline engine, 0.8 hp

Current Generation

2024 Honda Prologue EV
electric engine, 288 hp

The basis of our current understanding of plate tectonics: reference frames, precise positioning, and data collection enabled by satellite systems

https://CroninProjects.org/Oct2024/Introduction

Enabling Technologies

Basic Infrastructure

- Computer and data storage technology
- Communication technology (internet, optical fiber, cell transmission, communications satellites)
- Engineering (space, aeronautical, oceanic, software, geophysical networking)
- Mathematics and computer science

Enabling Technologies

Defining coordinate systems and finding positions

- Very-Long Baseline Interferometry (**VLBI**)
- Satellite Laser Ranging (**SLR**) and Lunar Laser Ranging (**LLR**)
- Global Navigation Satellite System (**GNSS**) with the US Global Positioning System (**GPS**)
- Doppler Orbitography and Radiopositioning Integrated by Satellite (**DORIS**)

Enabling Technologies

Defining the shape of Earth's surface (geodesy)

- Positioning technologies, especially GPS
- Satellite gravity measurements
- Satellite radar altimetry
- Synthetic Aperture Radar
- Laser imaging, detection, and ranging (LiDAR)

https://svs.gsfc.nasa.gov/11031

Very Long Baseline Interferometry

VLBI

Using Quasars to Measure the Earth: A Brief History of VLBI

International VLBI Service for Geodesy and Astronomy (IVS) sites and cooperating VLBI sites

12-meter radio telescope, used for VLBI geodesy

McDonald Geodetic Observatory near Ft. Davis, Texas — a joint project by The University of Texas at Austin Center for Space Research, McDonald Observatory, and NASA's Goddard Spaceflight Center

https://mcdonaldobservatory.org/research/telescopes/mgo

24 Hours with the 12-Meter Radio Telescope at the

McDonald Geodetic Observatory, Ft. Davis, Texas

Video by Eusebio Terrazas and University of Texas-Austin Center for Space Research

Satellite Laser Rangefinding
SLR

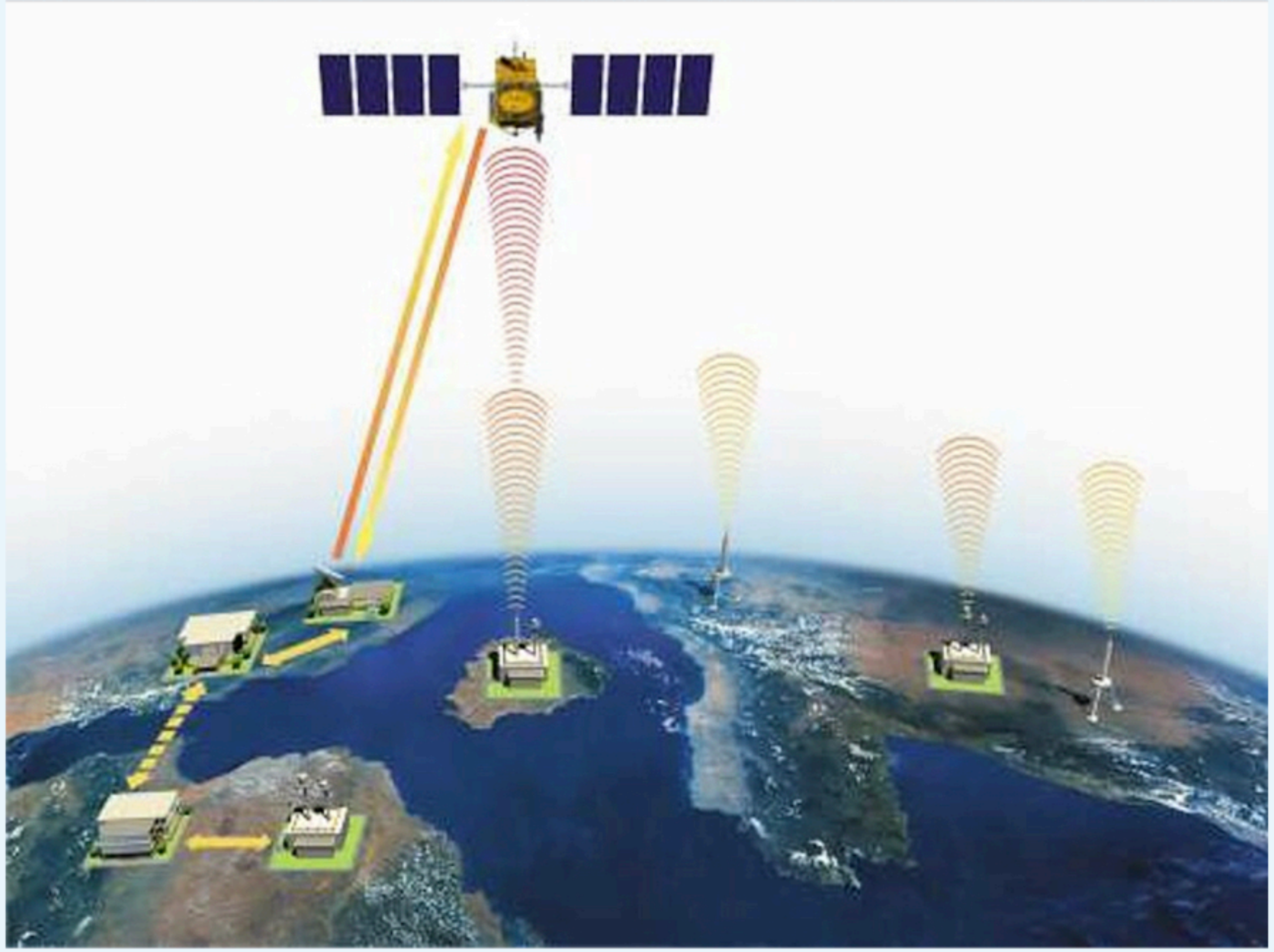
https://svs.gsfc.nasa.gov/11031

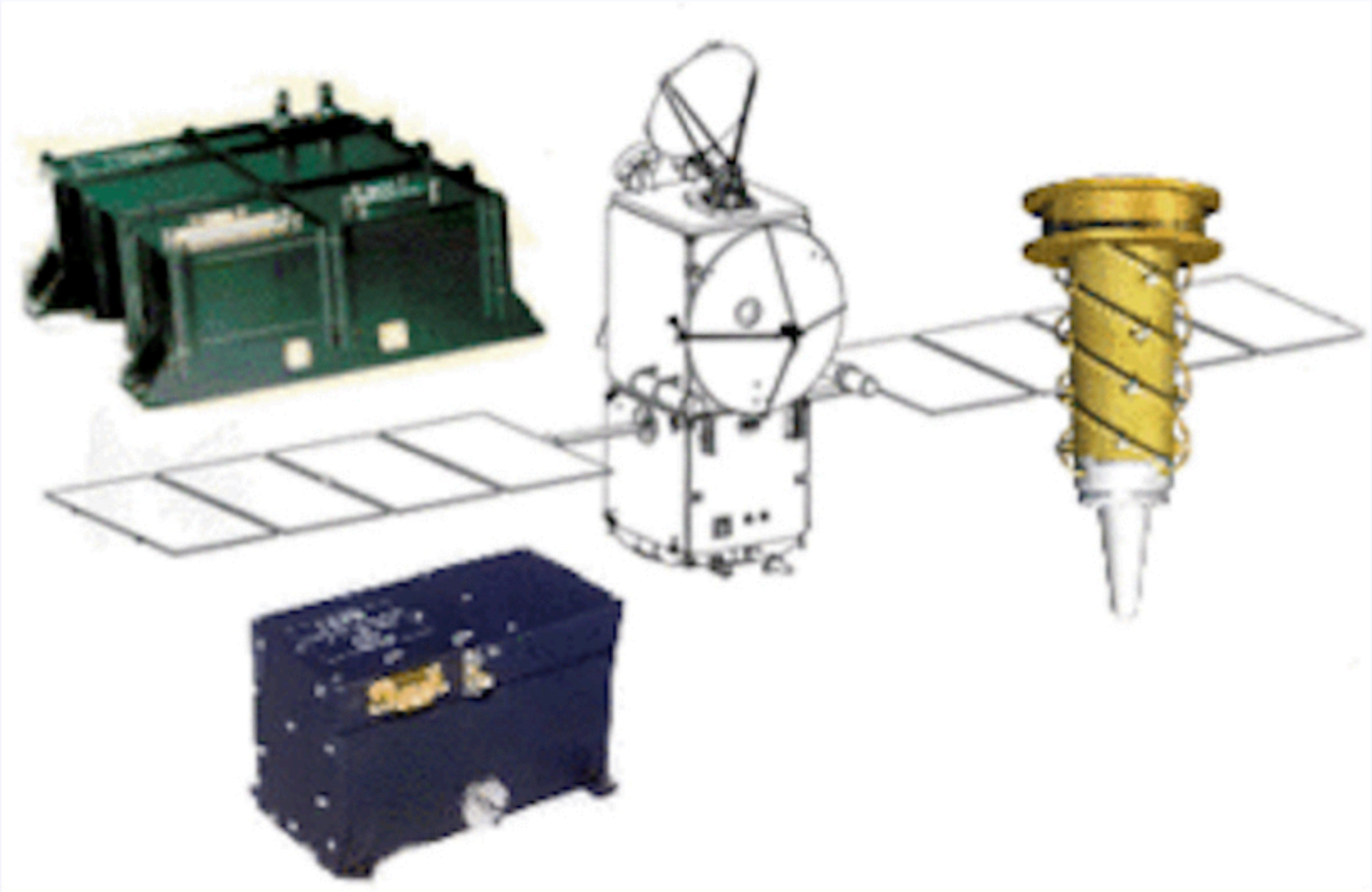
Doppler Orbitography and Radiopositioning Integrated by Satellite

DORIS

DORIS

Doppler Orbitography and Radiopositioning Integrated by Satellite

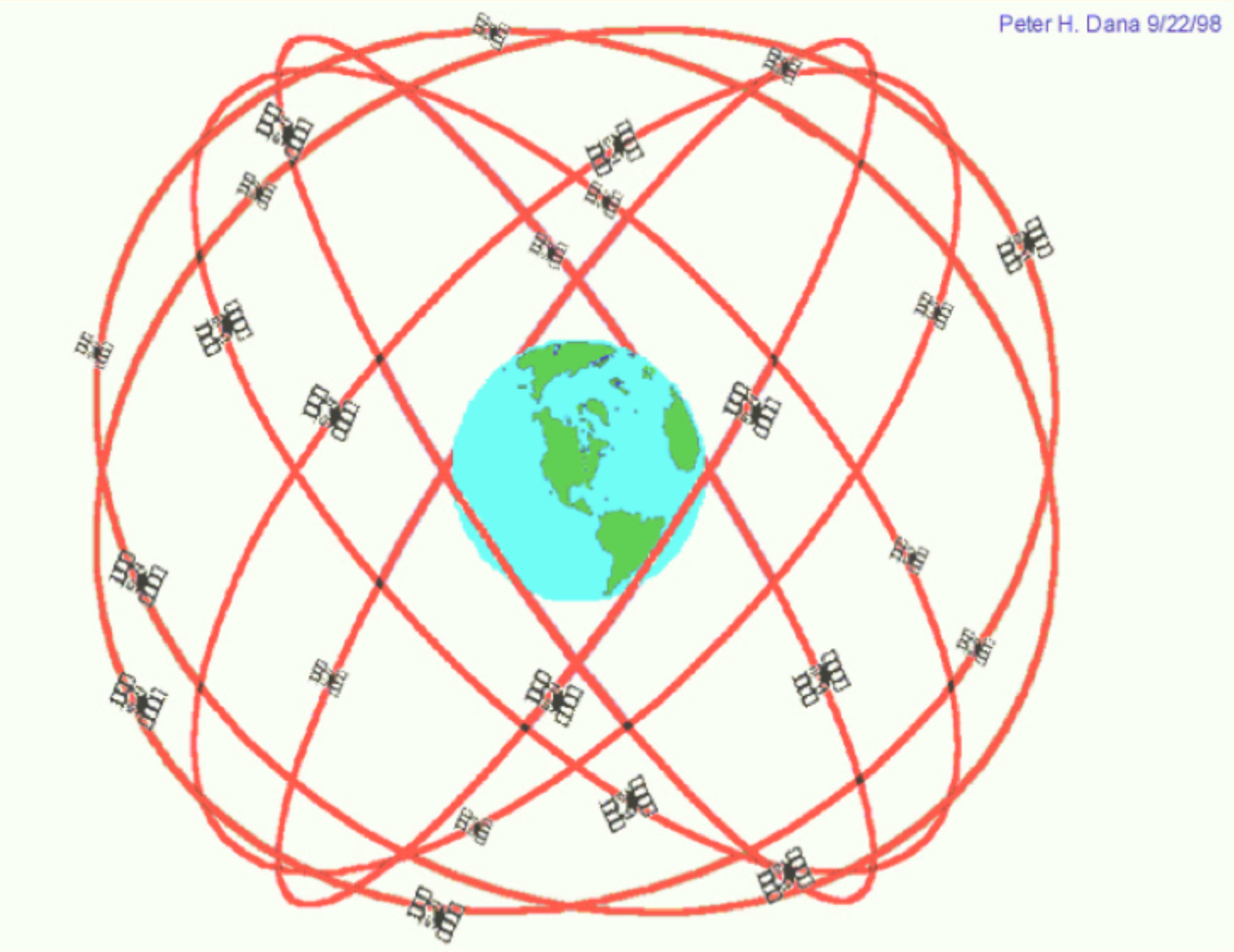




DORIS’s unique network of ground stations and its highly accurate positioning capability are valuable for geodesy and geophysics applications: measuring lithospheric motions, supporting the local geodesical network, monitoring deformation of the crust, determining the rotation and gravity parameters of the Earth, and contributing to the international referenc system. Adapted from www.aviso.altimetry.fr ameters of the Earth and contributing to the international reference system.

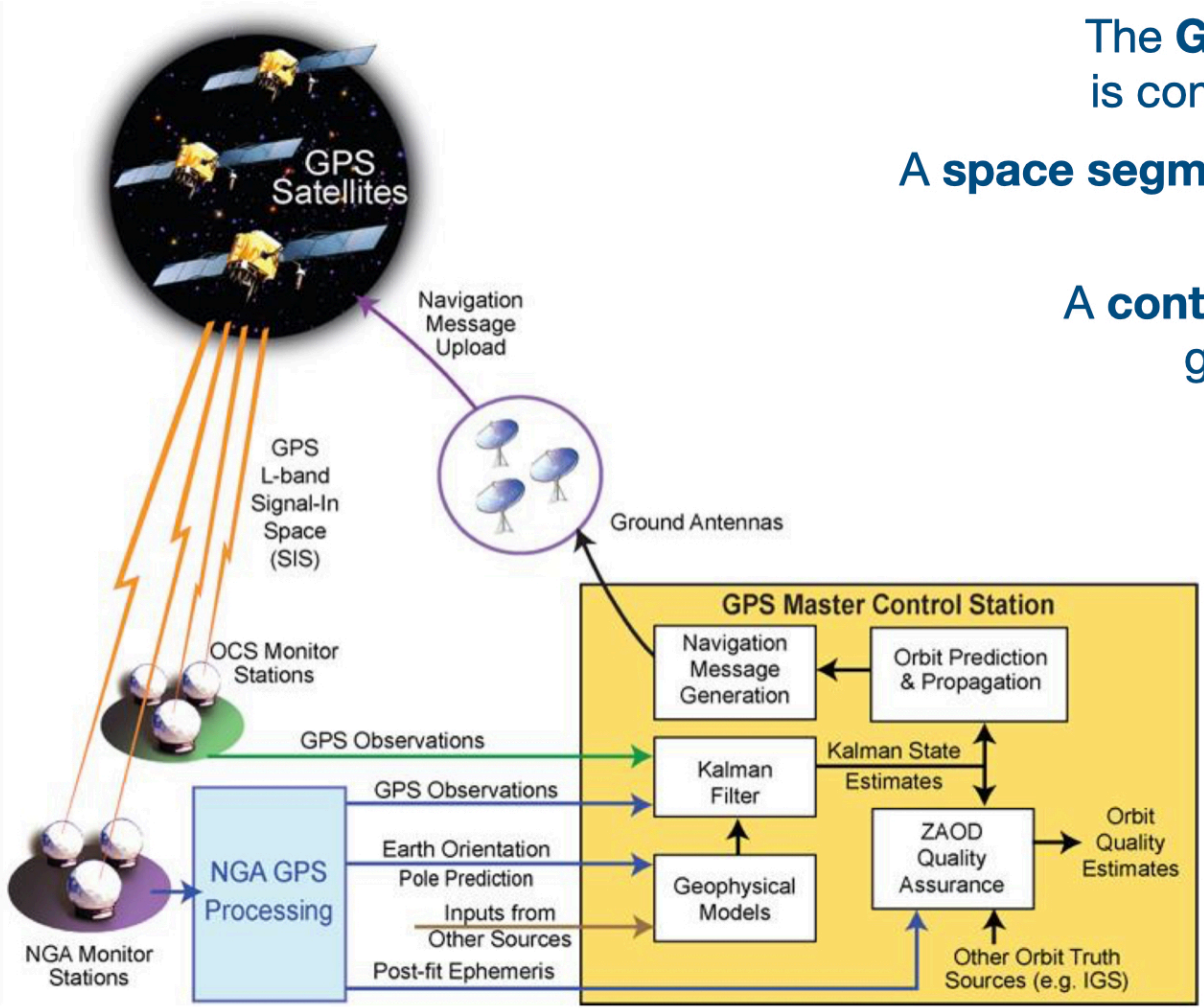
Global Positioning System
GPS

A few words about the Global Positioning System…



- Constellation of at least 24 satellites (31 today)
- Each satellite follows one of 6 circular orbits 20,200 km above Earth inclined 55° to the equator
- At least 6 satellites always "visible" from any place on Earth
- 11 hr 58 min orbital period
- 16 ground monitoring stations
- Each satellite passes over a ground monitoring station every few hours

Adapted from UNAVCO EO presentation, 2007



The **Global Positioning System** is comprised of three segments.

A **space segment** of signal-broadcasting satellites.

A **control segment** of monitoring ground stations that upload accuracy-enhancing corrections.

And a **user segment** of position-calculating receivers.

https://www.gps.gov/cgsic/meetings/2018/kawakami.pdf

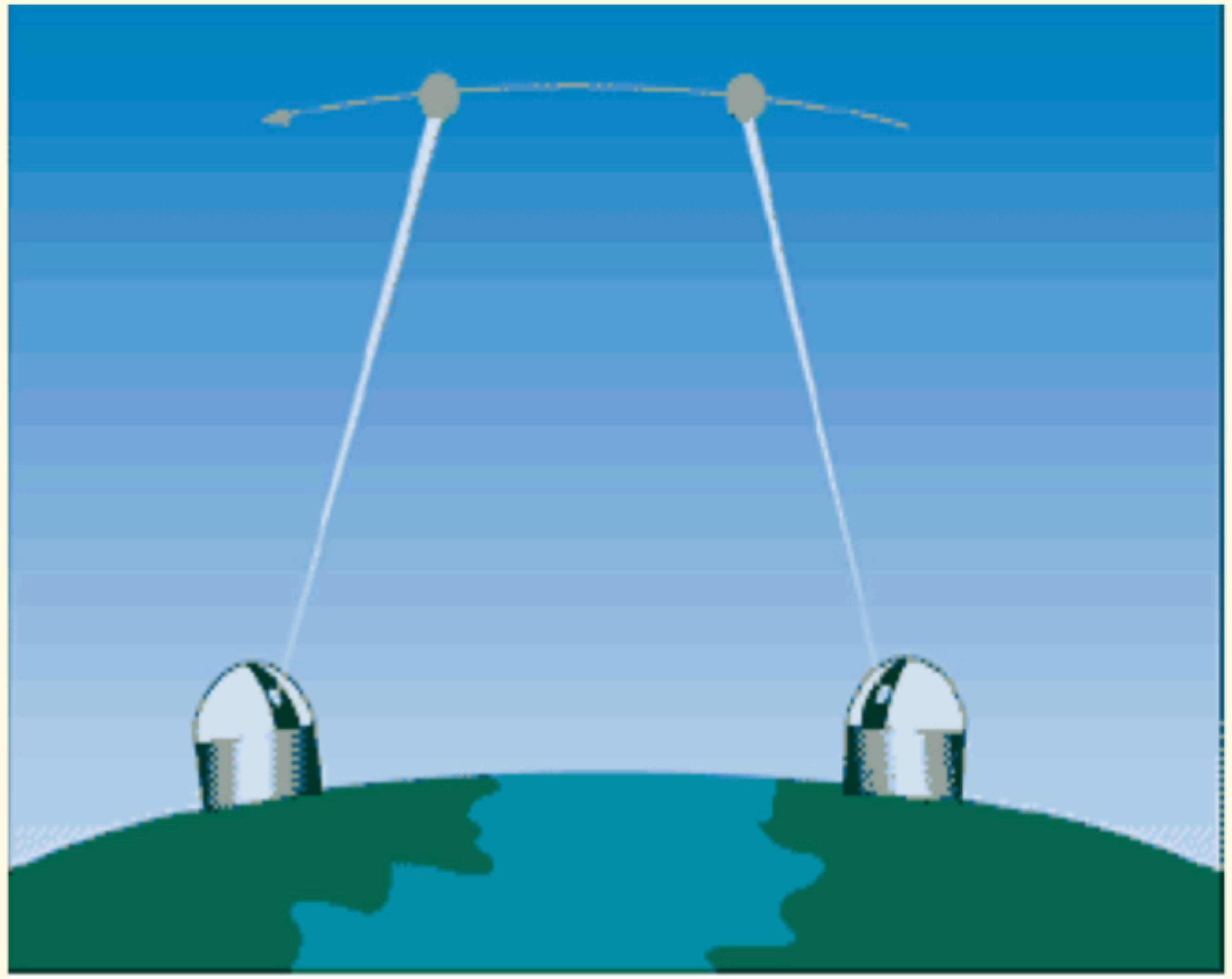
Space Segment of GPS

Orbital	Slot 1			Slot 2			Slot 3			Slot 4			Slot 5			Slot 6		
Plane	SVN	Type	Clock	SVN	Type	Clock	SVN	Type	Clock	SVN	Type	Clock	SVN	Type	Clock	SVN	Type	Clock
A	65	IIF	RB	52	IIR-M	RB	64	IIF	RB	48	IIR-M	RB	—	—	—	79	III	RB
B	56	IIR	RB	62	IIF	RB	44	IIR	RB	58	IIR-M	RB	71	IIF	RB	77	III	RB
C	57	IIR-M	RB	57	IIF	RB	72	IIF	CS	53	IIR-M	RB	59	IIR	RB	—	—	—
D	61	IIR	RB	—	—	—	45	IIR	RB	67	IIF	RB	78	III	RB	75	III	RB
E	69	IIF	RB	73	IIF	CS	50	IIR-M	RB	51	IIR	RB	76	III	RB	—	—	—
F	70	IIF	RB	55	IIR-M	RB	68	IIF	RB	74	III	RB	—	—	—	43	IIR	RB

SVN	Satellite Vehicle Number
Type	Satellite block type (design model)
Clock	RB = rubidium clock
	CS = cesium clock

Operational GPS Satellites and their Orbital Planes & Slots on September 1, 2024

https://www.navcen.uscg.gov/gps-constellation



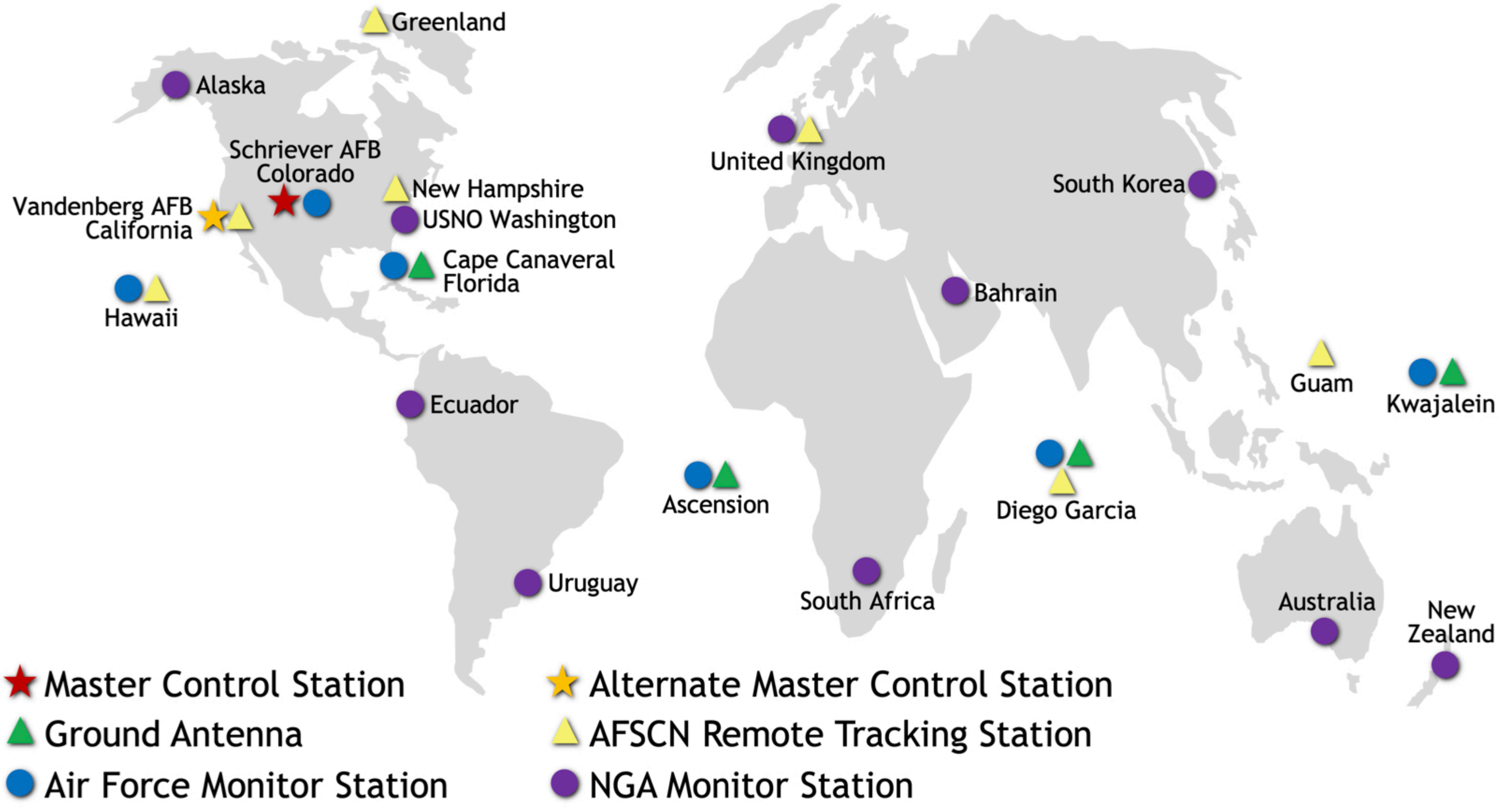
The current Block III GPS satellites carry laser reflectors (bottom photo) so their orbits can be measured using SLR to sub-cm precision.

This provides the finest precision orbital determinations we are currently able to compute.

The GPS satellite constellation is integral to define ITRFxx reference frames.

https://www.gps.gov/cgsic/meetings/2018/kawakami.pdf

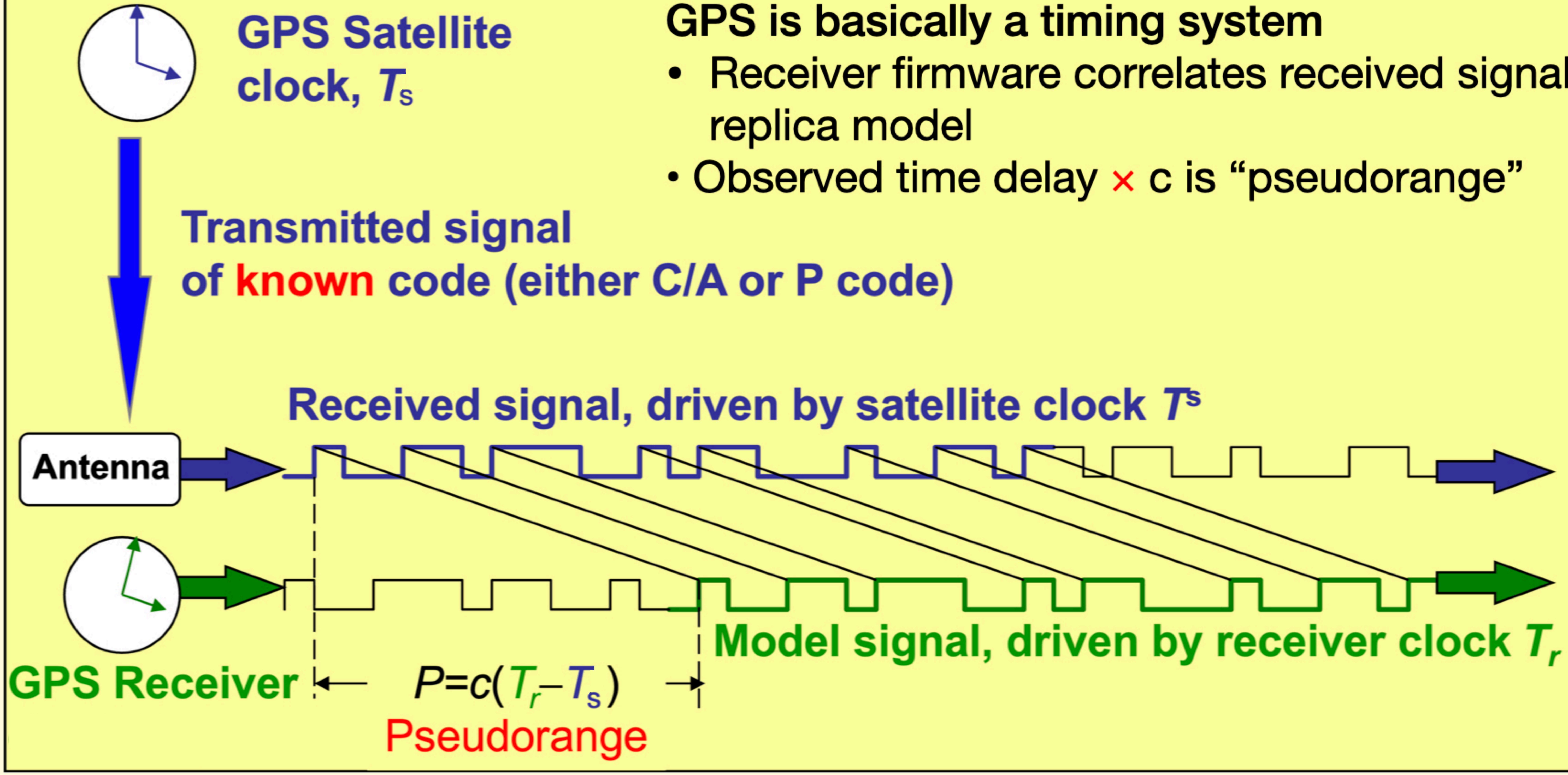
GPS Control Segment



A few words about the GPS Signal…

GPS is basically a timing system

- Receiver firmware correlates received signal with replica model
- Observed time delay × c is "pseudorange"



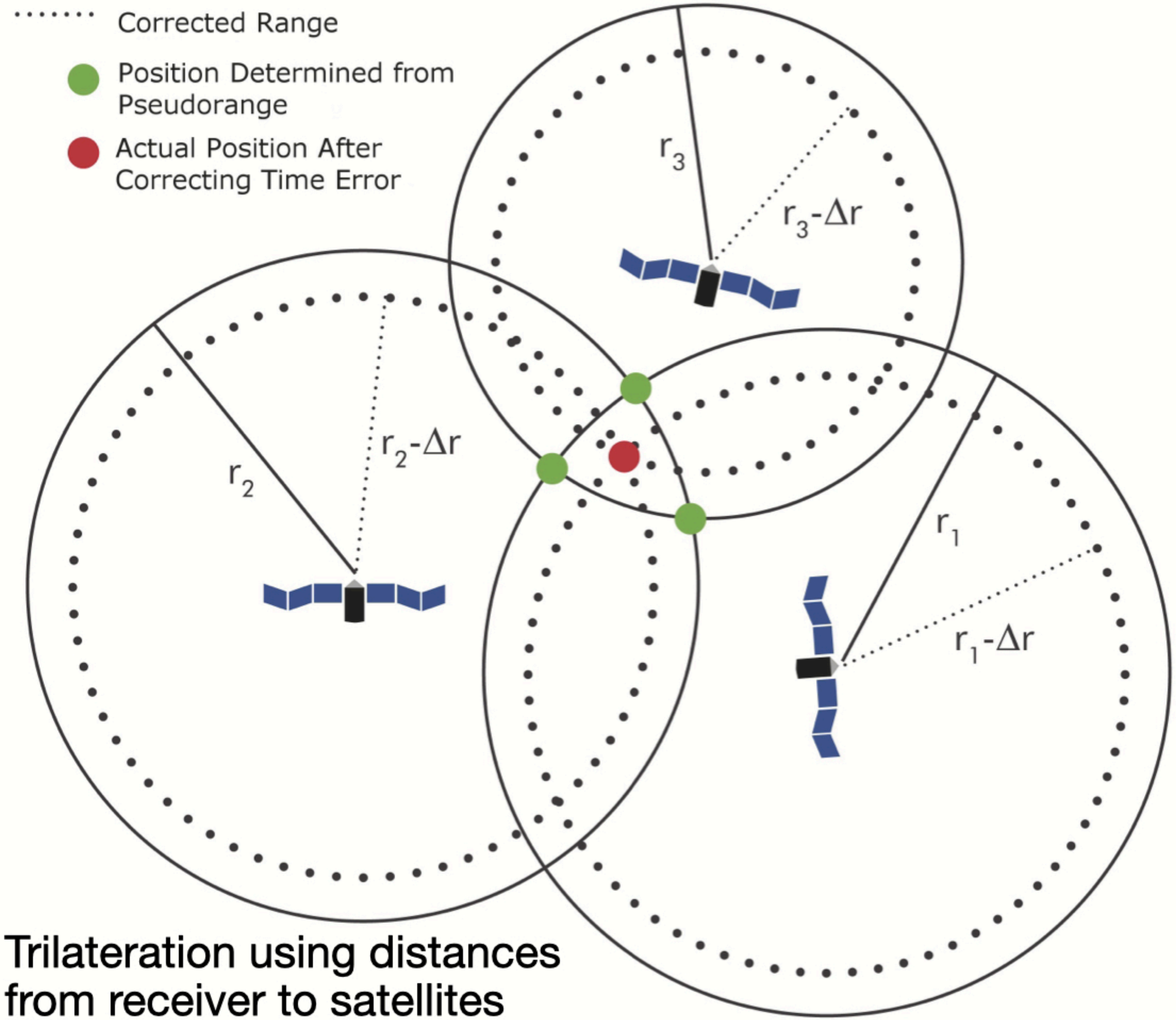
(Mayer and Olds, 2007, after Blewitt, 2002)

A few words about the GPS positioning precision…

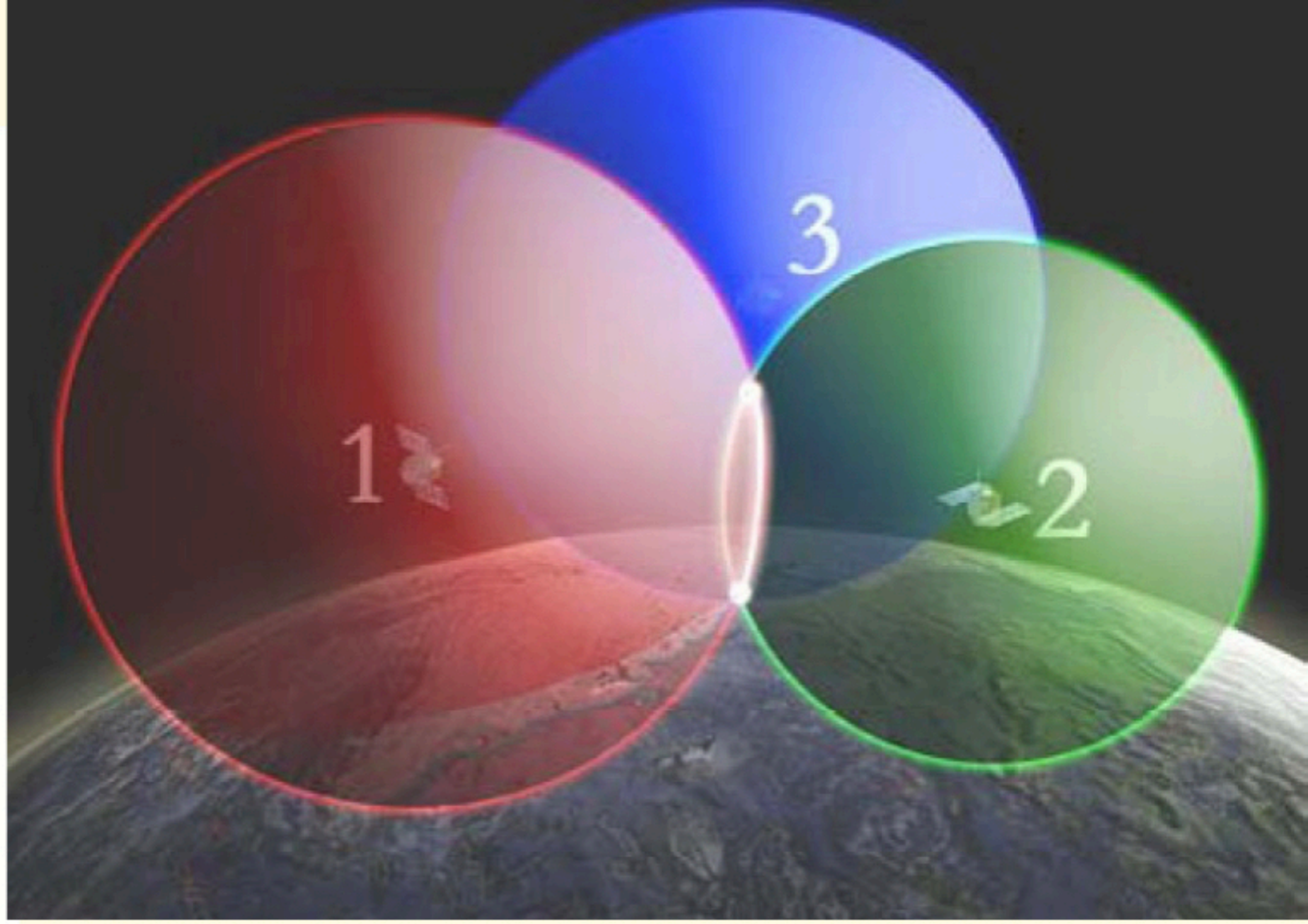
- Pseudorange positioning
  - hand-held GPS: a few meters
  - hand held GPS receiving differential corrections: ~1 meter
  - differential pseudorange with "carrier smoothing:" ~10 cm
  - limited by multipath errors
- Dual-frequency carrier phase positioning
  - hand-held GPS using RTK base station: ~1 cm relative
  - geodetic GPS (global): 2-3 mm horizontal, 7 mm vertical
  - geodetic GPS (regional): 1-2 mm horiz., 3-5 mm vertical

(Mayer and Olds, 2007, after Blewitt, 2002)

Space Segment of GPS



Trilateration using distances from receiver to satellites



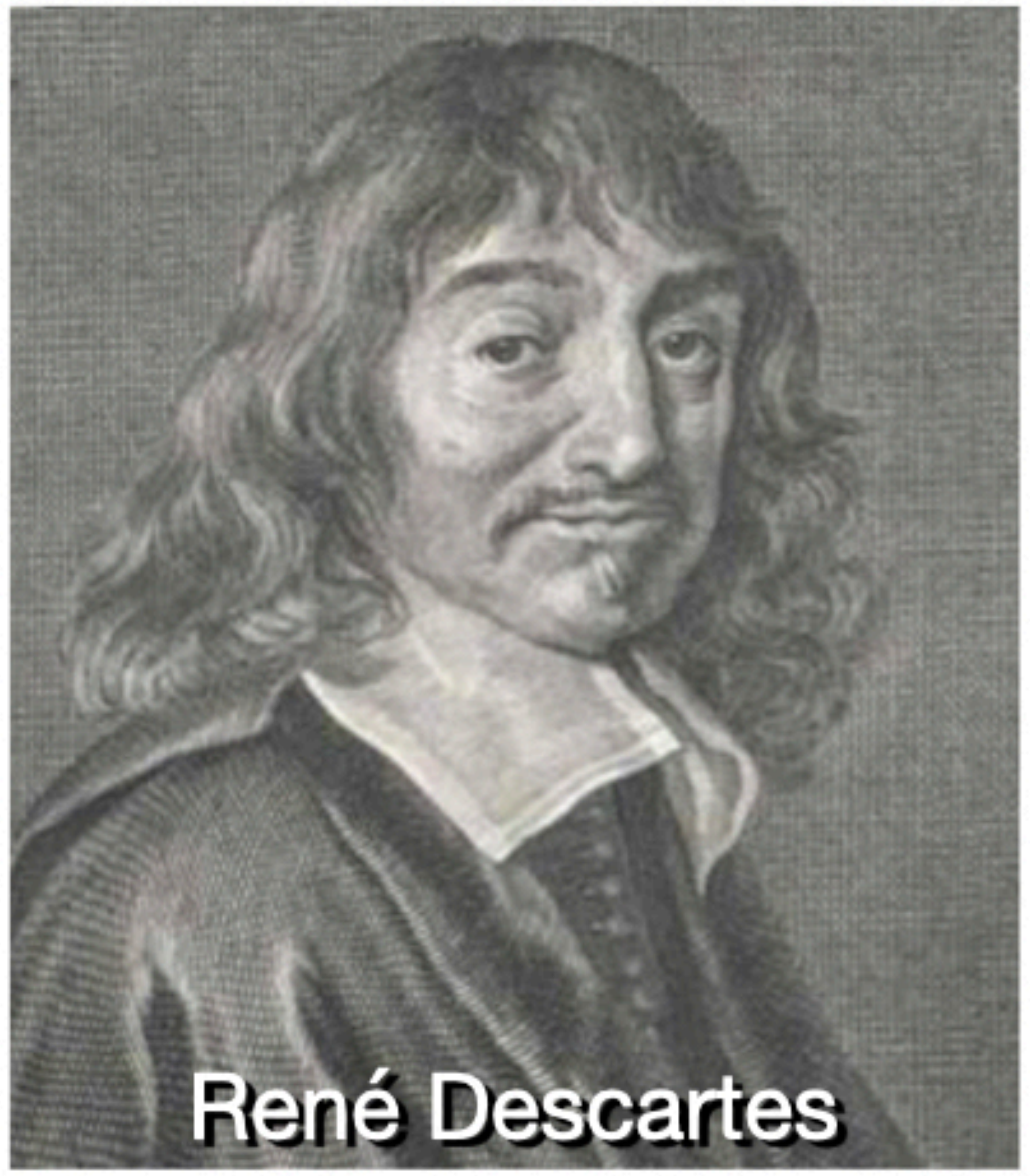
Signals from four GPS satellites are needed to solve for the four unknowns of location (X, Y, Z) and time.

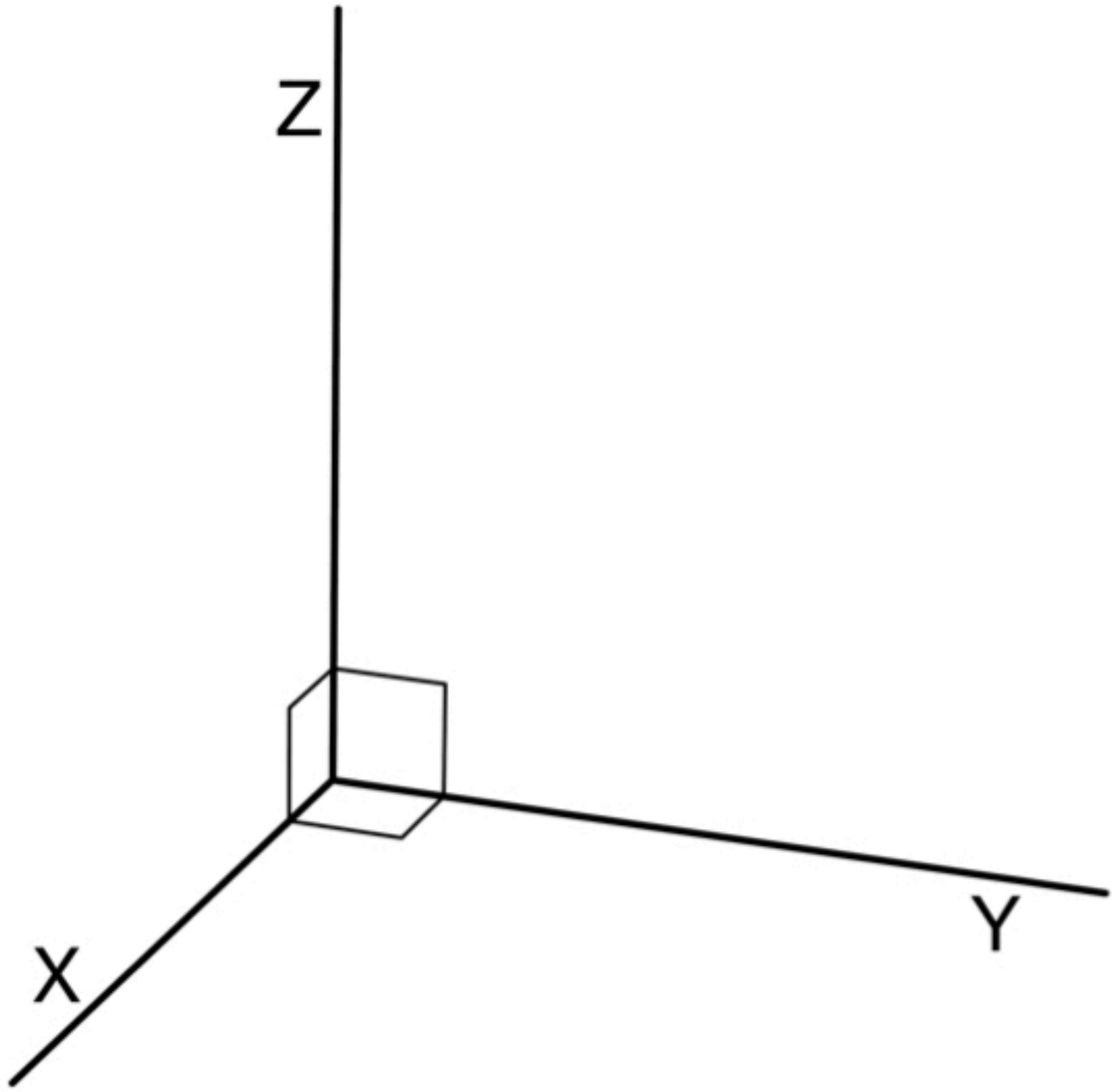
Coordinate systems and reference frames

A reference frame is needed to specify position or velocity

The reference frames we will use are all Cartesian right-orthogonal coordinate systems. The three coordinate axes have the same scale, and are all oriented at right angles (90°) to each other.

The Y axis is a right-handed (anticlockwise) rotation from X around Z. The Z axis is a right-handed rotation from Y around X. The X axis is a right-handed rotation from Z around Y.



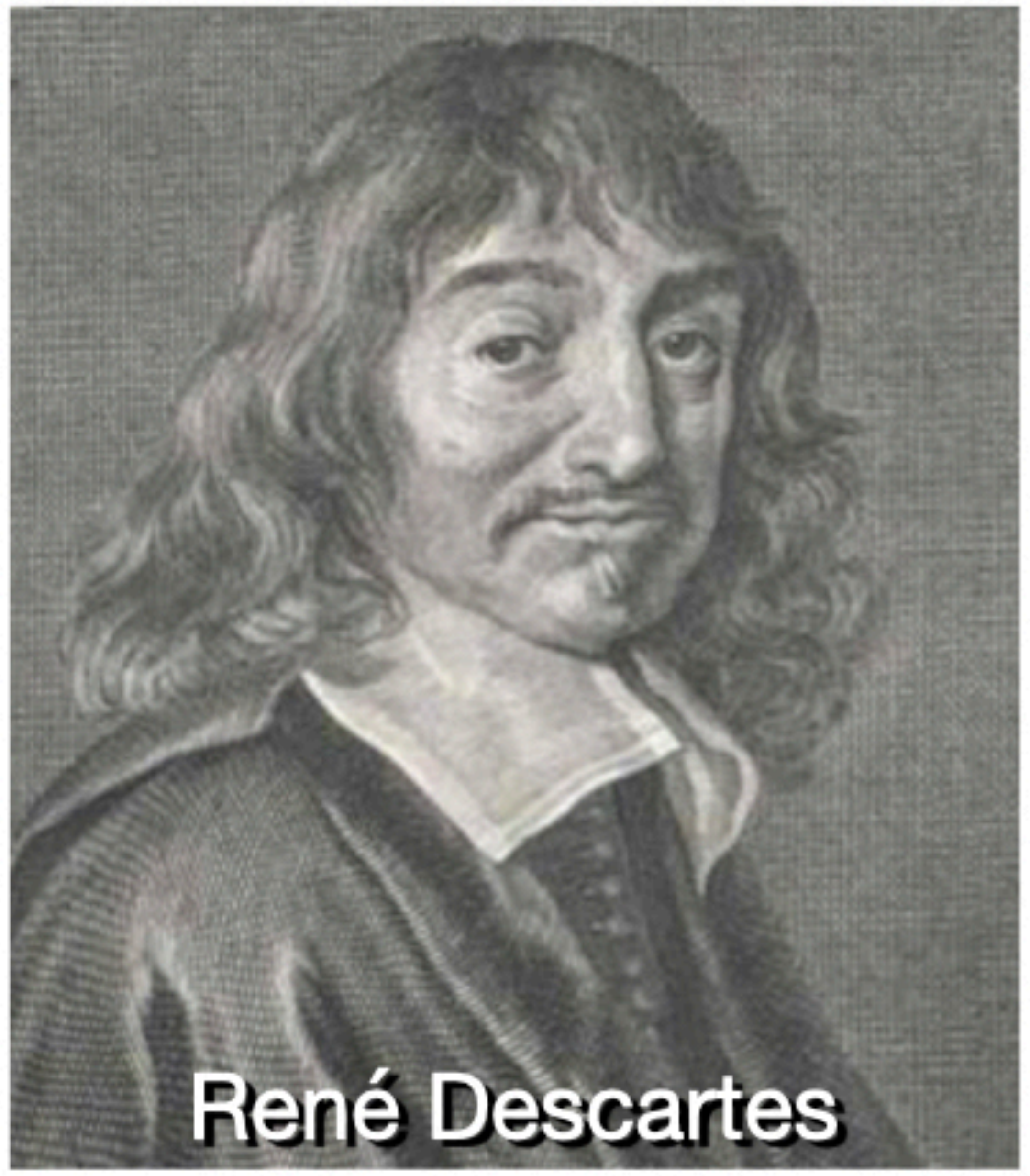


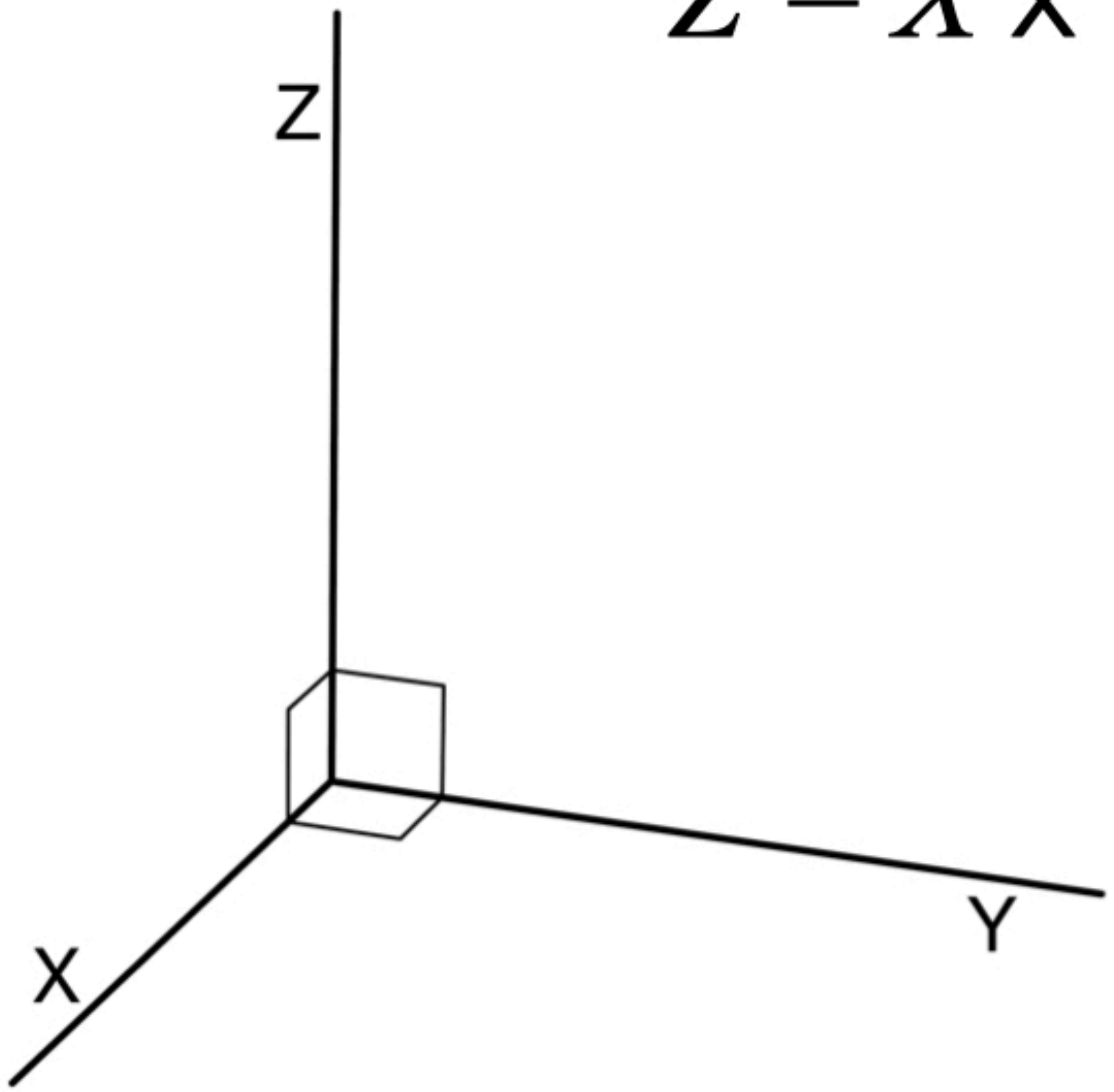
A reference frame is needed to specify position or velocity

The reference frames we will use are all Cartesian right-orthogonal coordinate systems. The three coordinate axes have the same scale, and are all oriented at right angles (90°) to each other.

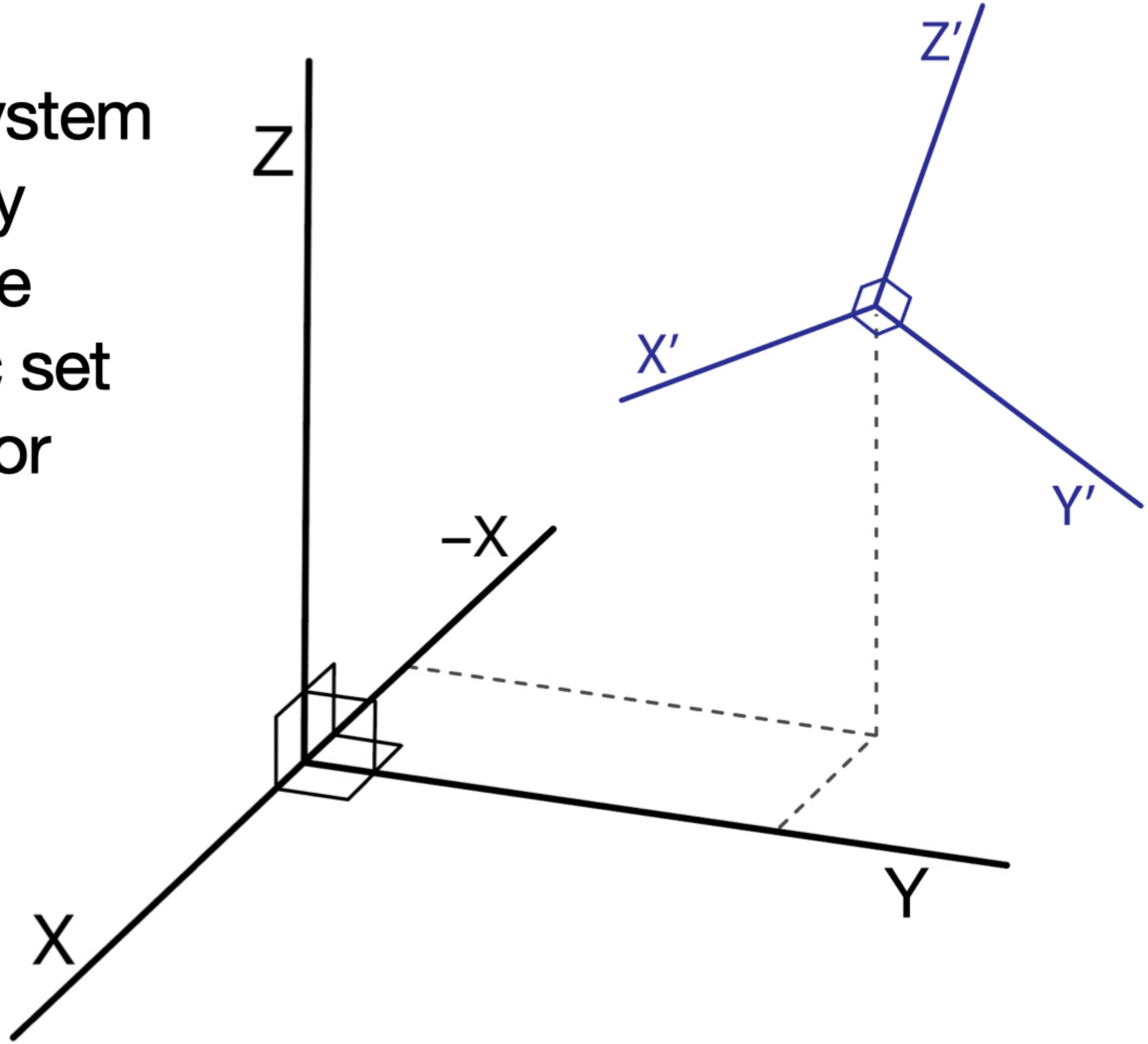
In vector (matrix) math:

$$Y = Z \times X$$
$$X = Y \times Z$$
$$Z = X \times Y$$





A Cartesian coordinate system can be transformed to any other Cartesian coordinate system through a specific set of translations, rotations, or scale conversions



Reference Frames: Overview

International Celestial Reference Frame

An ***inertial reference frame*** whose origin is at the barycenter of the solar system and whose axes are fixed with respect to very distant objects beyond the galaxy (mostly quasars). The coordinates of these objects are are determined by Very Long Baseline Interferometry (VLBI).

International Terrestrial Reference Frame

An Earth-centered Earth-fixed no-net-rotation reference frame

World Geodetic System 1984 (WGS84)

The reference ellipsoid used by GPS as the average shape of Earth; generally aligned with ITRF

Local tangent-plane reference systems

Used for small areas where the curvature of Earth is not significant

Reference Frames: Overview

International Celestial Reference Frame (ICRF)

An ***inertial reference frame*** whose origin is at the barycenter of the solar system and whose axes are fixed with respect to very distant objects beyond the galaxy (mostly quasars). The coordinates of these objects are are determined by Very Long Baseline Interferometry (VLBI).

The barycenter is the center of mass of the solar system, around which the Sun and planets orbit. Its position changes in a predictable way as the positions of the planets change.

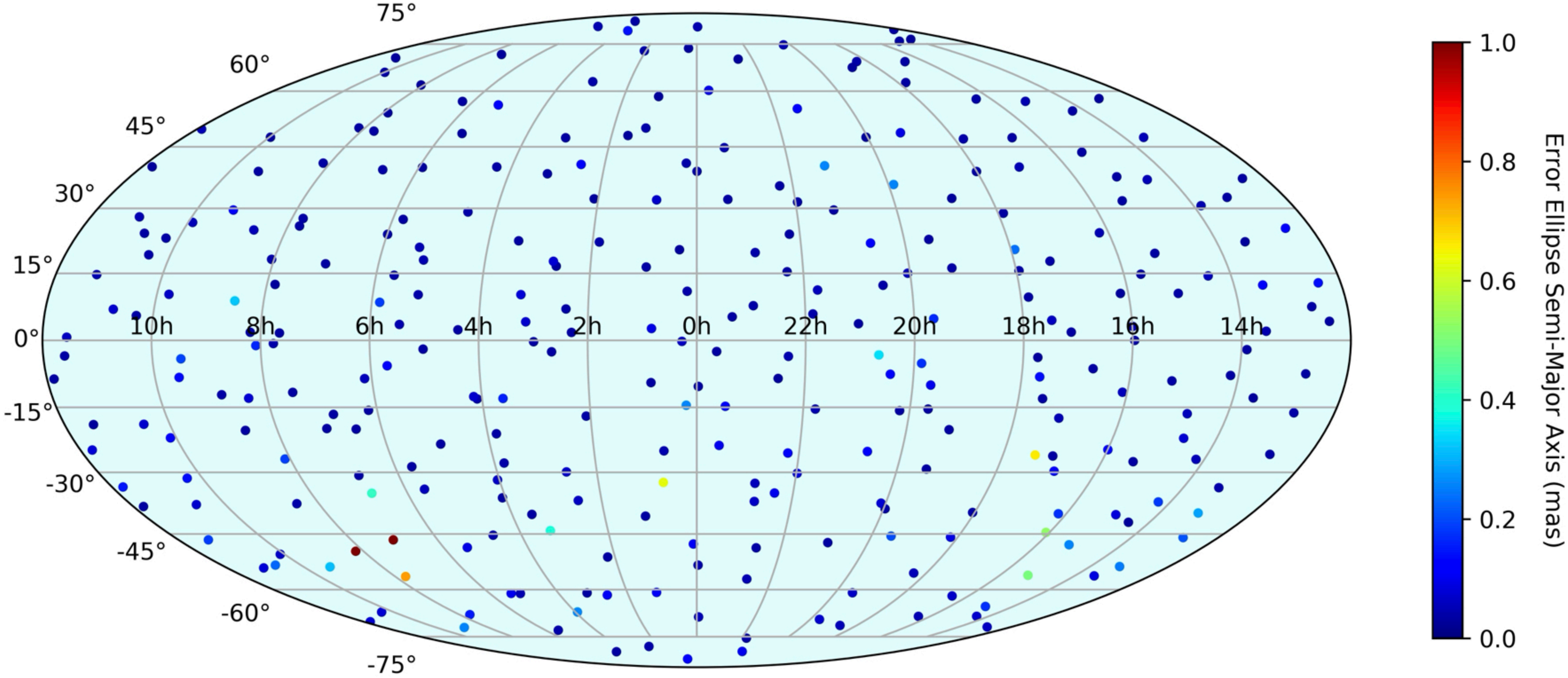
The X and Y axes are on the ecliptic plane, and the Z axis is perpendicular to that plane. The X axis passes through Earth's center at the vernal equinox.

The ICRF maintained by the International Earth Rotation and Reference Systems Service (IERS) of the International Astronomical Union.


Earth
Photo from Curiosity Rover on Mars
~99 million miles from Earth, January 31, 2014

ICRF3X Defining Sources Only
Error Ellipse Semi-Major Axis (mas)
International Celestial
Reference Frame
(functionally inertial)
Z
Y
X
Sun
Solar System
Barycenter
Earth at Vernal
Equinox
~93 million miles
Ecliptic Plane
Earth's path around the Sun

Map of Extra-Galactic Sources (mostly quasars) for ICRF-3X



The International Celestial Reference System is maintained by the International Astronomical Union (IAU) and the International Earth Rotation and Reference Systems Service (IERS)
https://www.iers.org/IERS/EN/Home/home_node.html

Reference Frames: Overview

International Terrestrial Reference Frame (ITRF)

The ITRF's origin is Earth's center of mass (oceans & atmosphere included. The uncertainty in the location of the origin is on the order of a centimeter.

The positive Z axis is along Earth's average spin axis, which passes through Earth's center of mass.

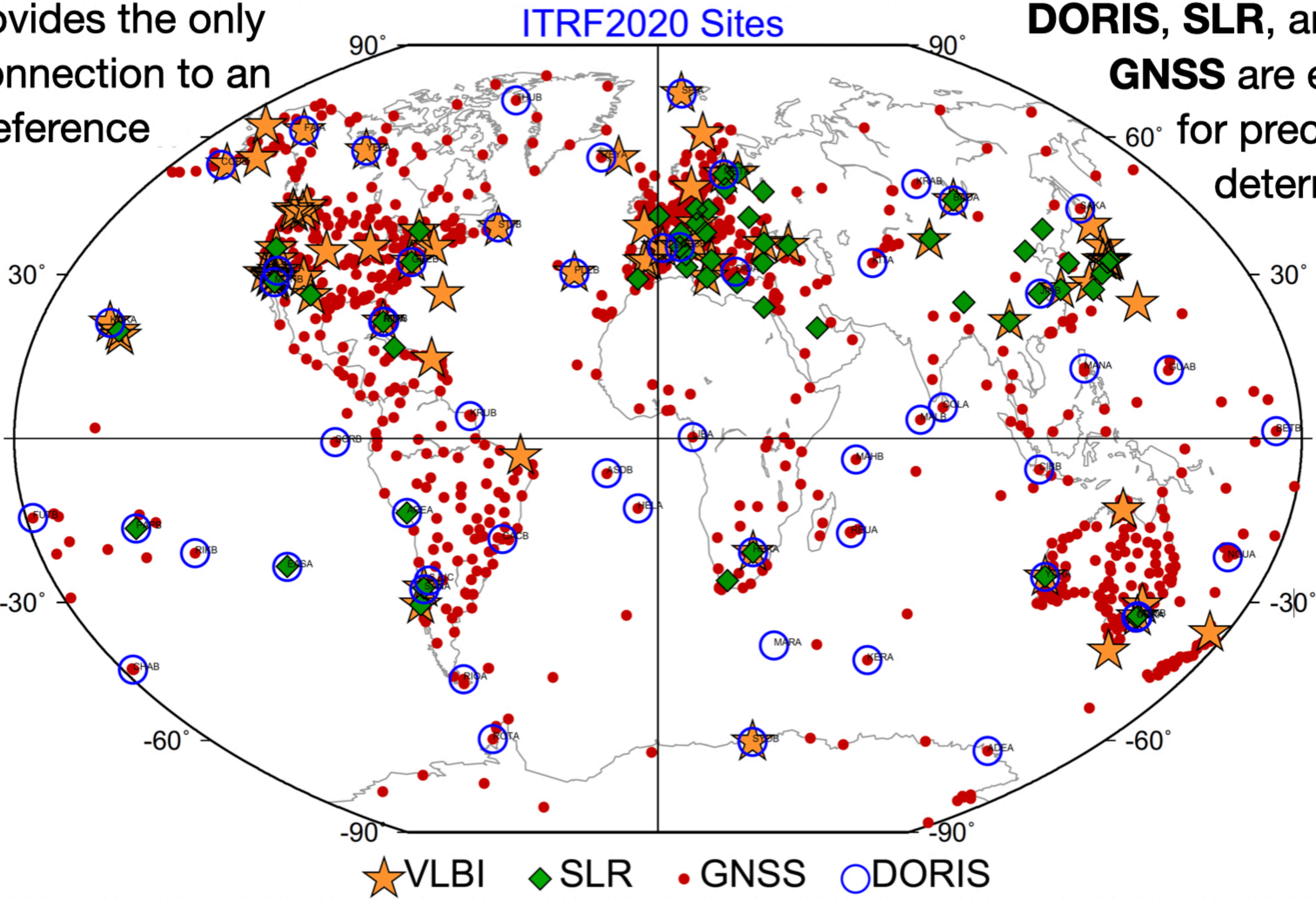
The X and Y axes are on the equatorial plane, perpendicular to the Z axis.

The Z and X axes are in the plane of the Prime Meridian (PM). The PM's location was originally defined in 1884, and redefined by the International Union of Geodesy and Geophysics (IUGG) in 1984. It is about 102 meters east of the original line through the Royal Observatory Greenwich, England.

The ITRF maintained by the International Earth Rotation and Reference Systems Service (IERS) of the International Astronomical Union.

VLBI provides the only direct connection to an inertial reference frame

DORIS, **SLR**, and **GPS/GNSS** are essential for precise orbit determination



Geographic and Cartesian coordinate systems, conversions, and coordinate transformations


North Pole
Earth
Center
Equator
Geographic
coordinates
on sphere
of unit radius
Earth-fixed
Earth-centered
reference frame

North Pole
Prime Meridian
Earth
Center
Geographic
coordinates
on sphere
of unit radius
Earth-fixed
Earth-centered
reference frame


North Pole
Prime Meridian
Equator
Geographic coordinates on sphere of unit radius
Earth-fixed Earth-centered reference frame


North Pole
P
Prime Meridian
Equator
Geographic coordinates on sphere of unit radius
Earth-fixed Earth-centered reference frame

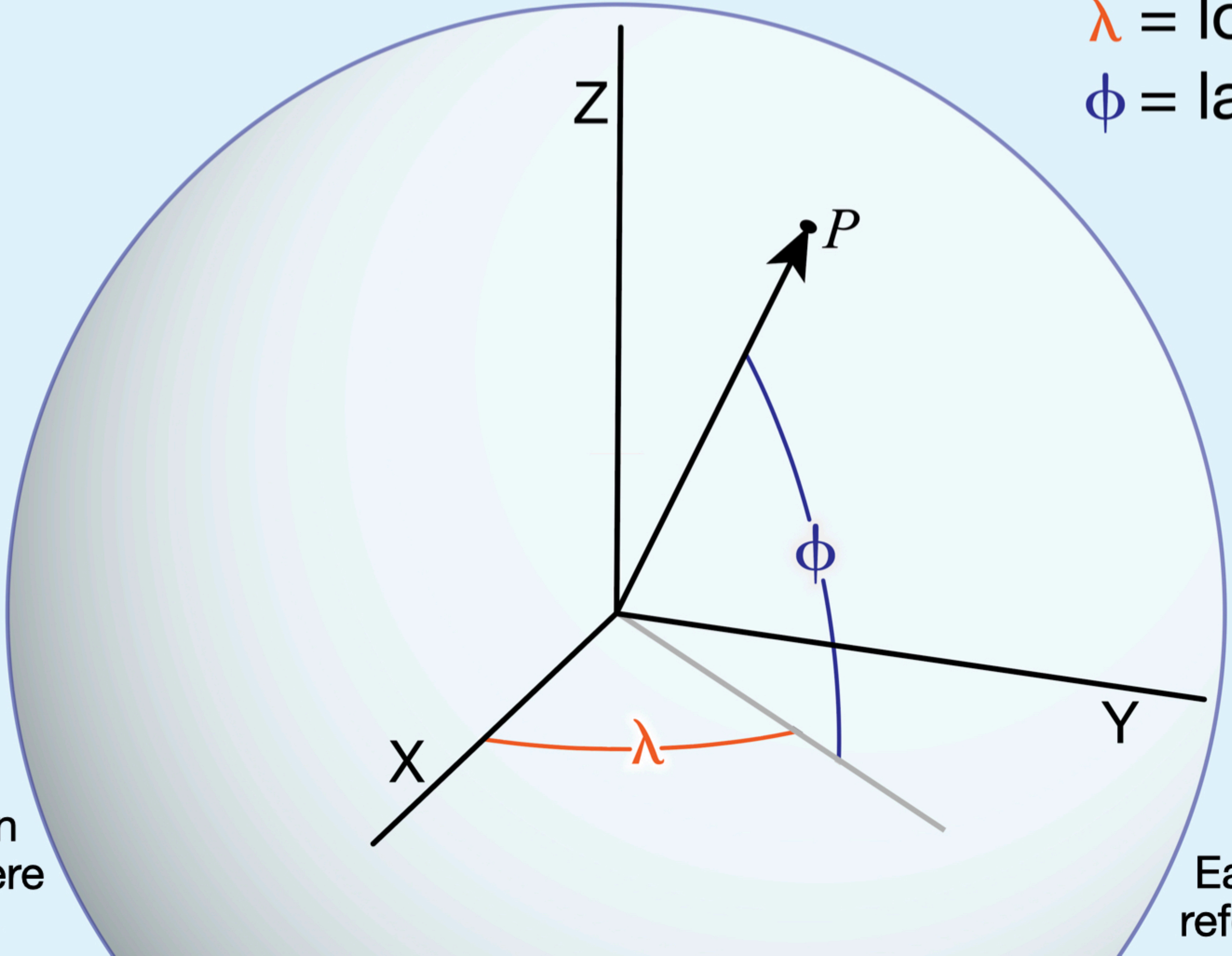

North Pole
P
Prime Meridian
Earth
Center
Equator
Geographic
coordinates
on sphere
of unit radius
Earth-fixed
Earth-centered
reference frame


North Pole
λ = longitude
φ = latitude
P
Prime Meridian
Earth Center
φ
λ
Equator
Geographic coordinates on sphere of unit radius
Earth-fixed Earth-centered reference frame


North Pole
Z
Prime Meridian
Equator
X
Y
Geographic coordinates and Cartesian axes on sphere of unit radius
Earth-fixed Earth-centered reference frame


North Pole
Z
P
Prime Meridian
Equator
X
Y
Geographic coordinates and Cartesian axes on sphere of unit radius
Earth-fixed Earth-centered reference frame

λ = longitude
ϕ = latitude



Geographic coordinates and Cartesian axes on sphere of unit radius

Earth-fixed Earth-centered reference frame

Unit vector components of position vector P given latitude and longitude

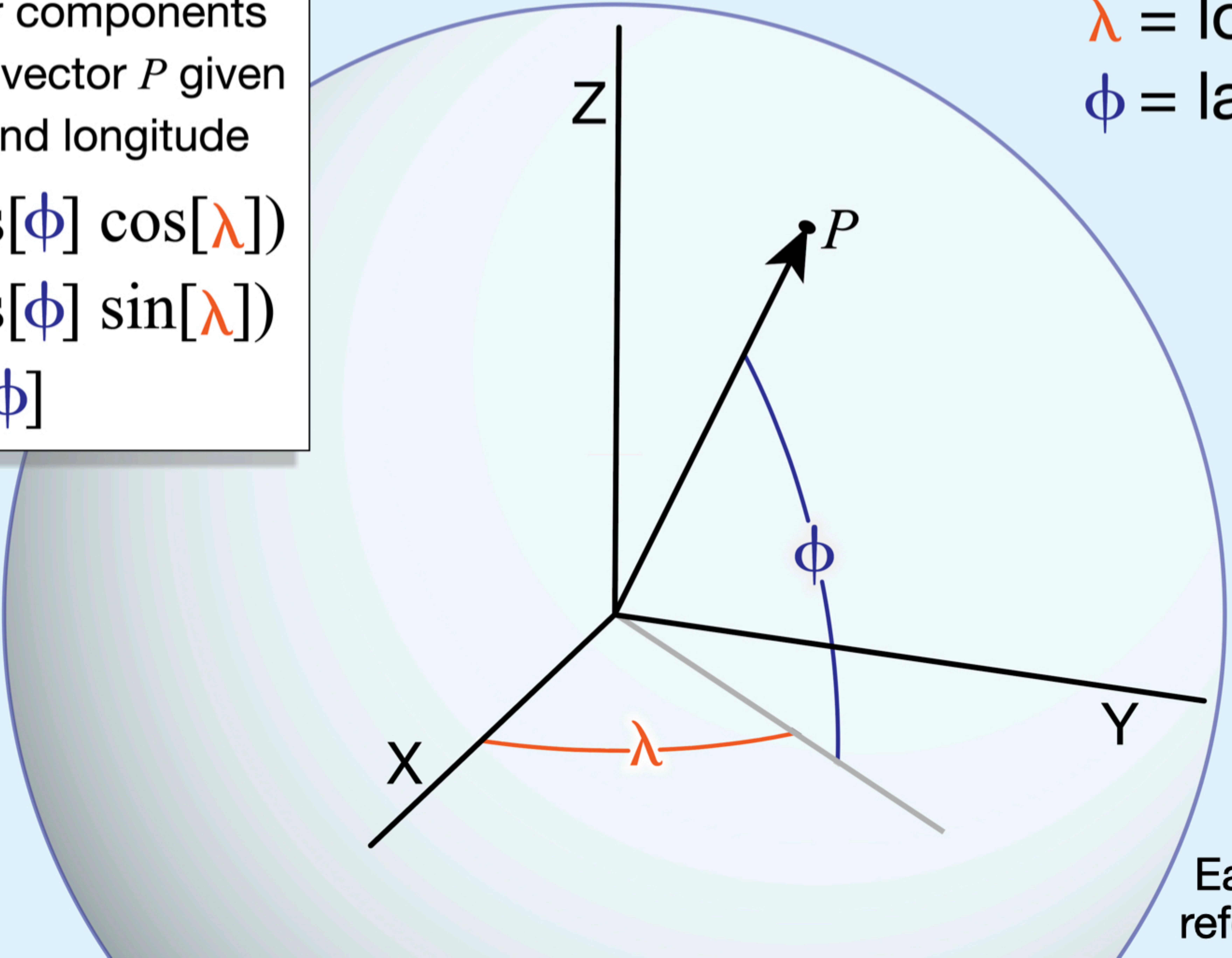
$$x_P = (\cos[\phi]\ \cos[\lambda])$$

$$y_P = (\cos[\phi]\ \sin[\lambda])$$

$$z_P = \sin[\phi]$$

λ = longitude

ϕ = latitude

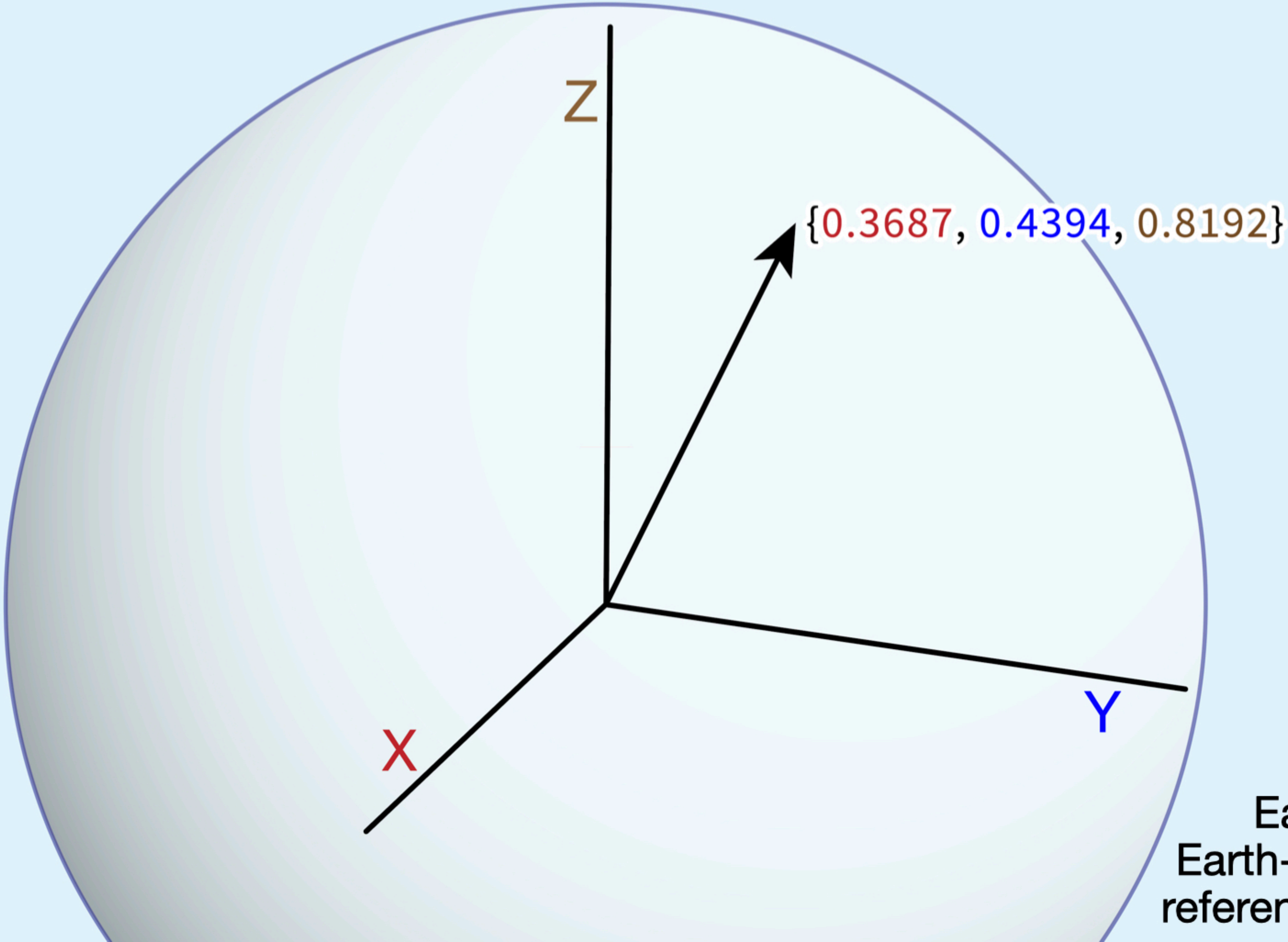


Cartesian coordinates on sphere of unit radius

Earth-fixed Earth-centered reference frame


Unit vector components of position vector P given latitude and longitude
$x_P = (\cos[\phi] \cos[\lambda])$
$y_P = (\cos[\phi] \sin[\lambda])$
$z_P = \sin[\phi]$
λ = longitude
ϕ = latitude
Z
P {0.3687, 0.4394, 0.8192}
0.8192
0.3687
0.4394
X
Y
Cartesian coordinates on sphere of unit radius
Earth-fixed Earth-centered reference frame

Cartesian coordinates on sphere of unit radius



Earth-fixed Earth-centered reference frame

Reference Frames: Overview

Local tangent-plane reference frames

Used for small areas where the curvature of Earth is not significant enough to require use of a spherical projection

(smaller than about 0.6° longitude and 0.5° latitude or about 50 km square)

Suitable for map representations of horizontal velocities for individual GPS sites or small clusters of GPS sites.


Local Cartesian reference frame on a plane that is tangent to the globe at the midpoint of the map
North Pole
Z
N
U
E
tangent plane
Prime Meridian
Equator
X
Y
+N axis: *north* directed along a meridian
+E axis: *east* directed along a parallel
+U axis: *up* directed perpendicular to the tangent plane
Earth-fixed surface-point-centered reference frame

Given these reference frames and precise orbital determination for our geophysical/geodetic satellites, we can map the world with significant locational precision

Ship Tracklines of Multibeam Bathymetric Surveys

https://sos.noaa.gov/catalog/datasets/ship-tracklines-of-multibeam-bathymetric-surveys/

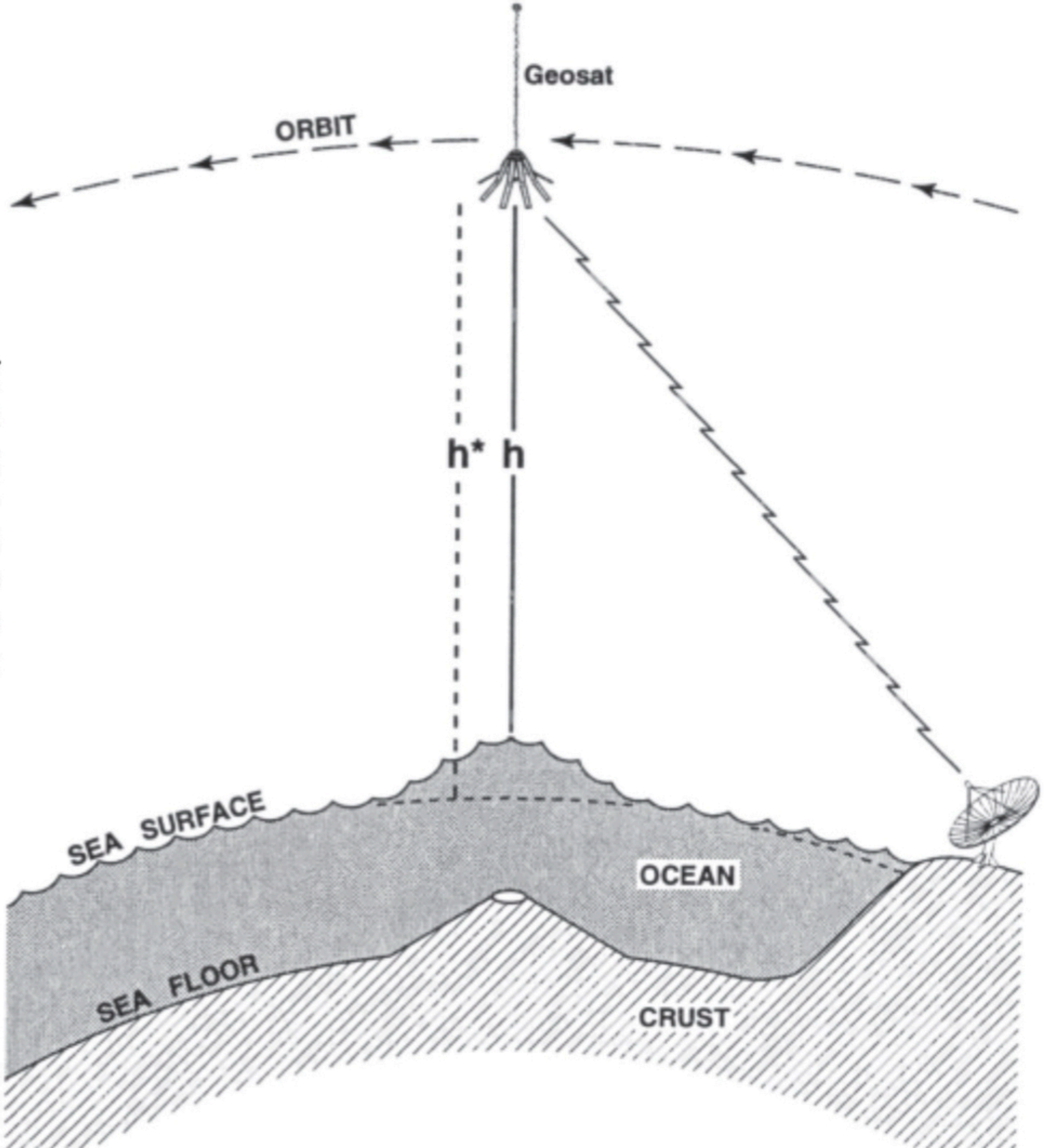
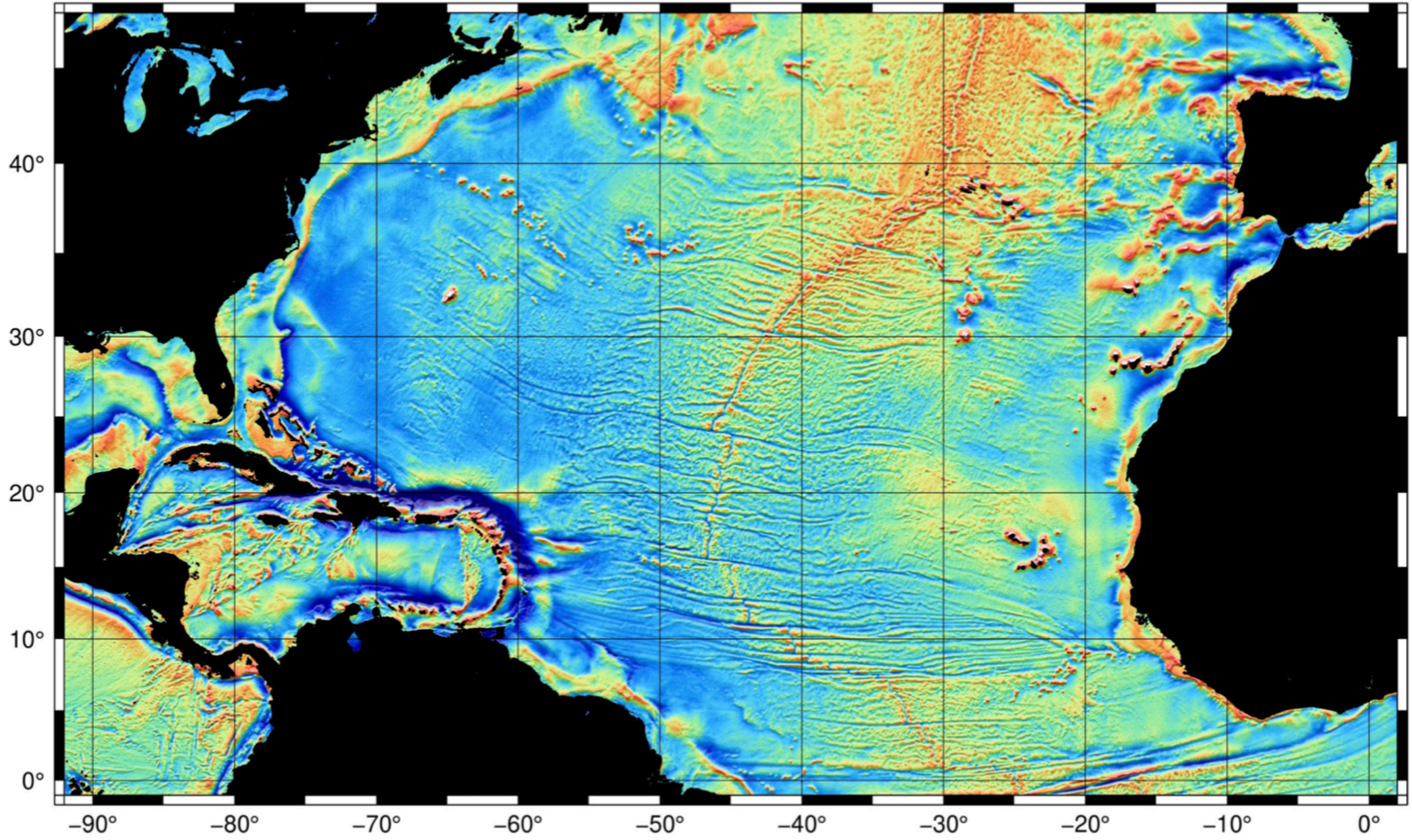


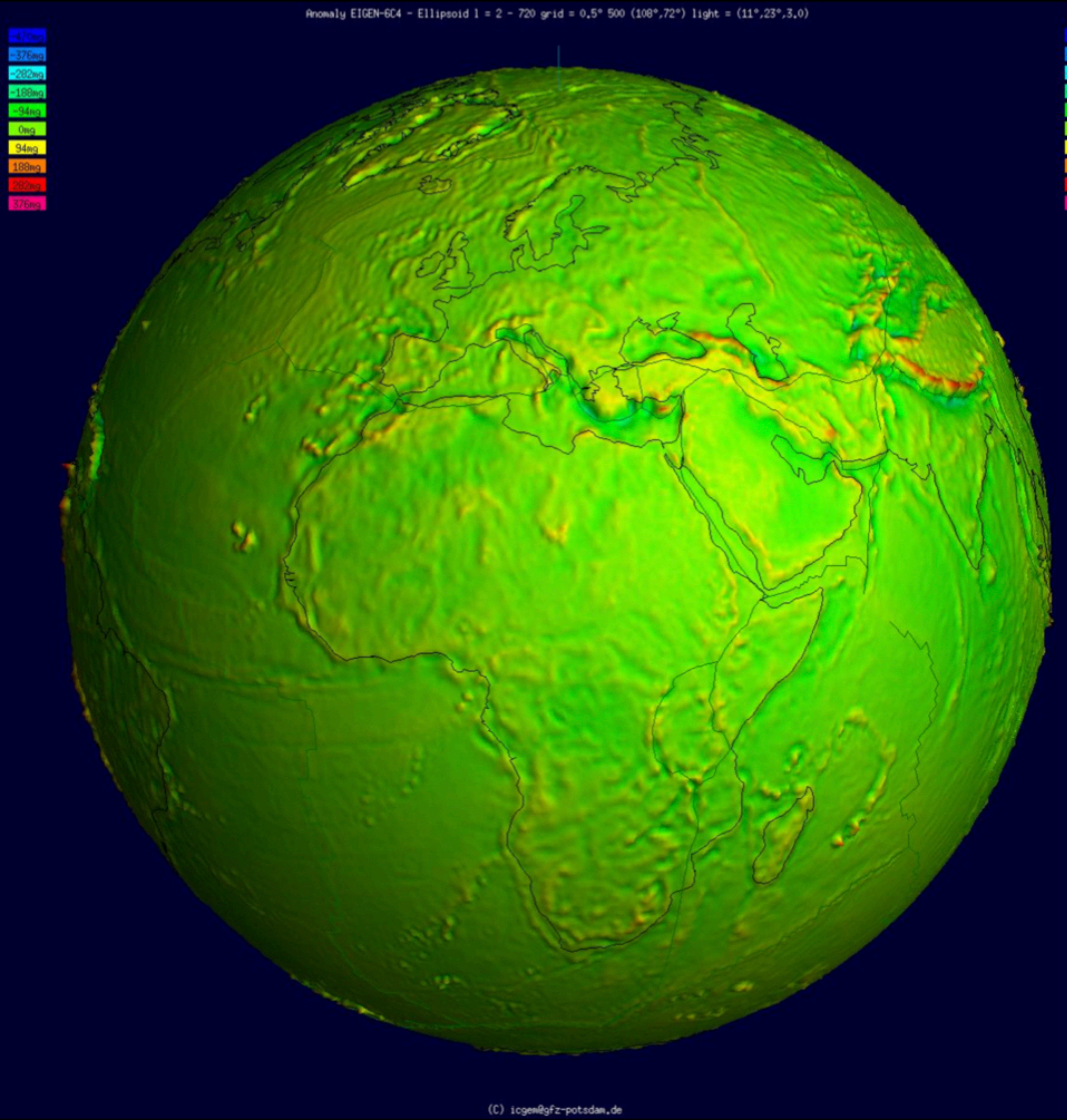
Figure 1. A pulse-limited radar altimeter orbits at an altitude of about 800 km and measures the distance to the closest ocean surface by recording the travel time of a pulse. A global tracking network along with precise orbit calculations based on the JGM-3 gravity model [*Nerem et al.*, 1994] is used to establish the height of the satellite above the reference ellipsoid (dashed curve). We assume the sea surface height above the ellipsoid is equal to the geoid height so permanent sea surface slopes associated with currents will appear as false anomalies in our gravity solution.

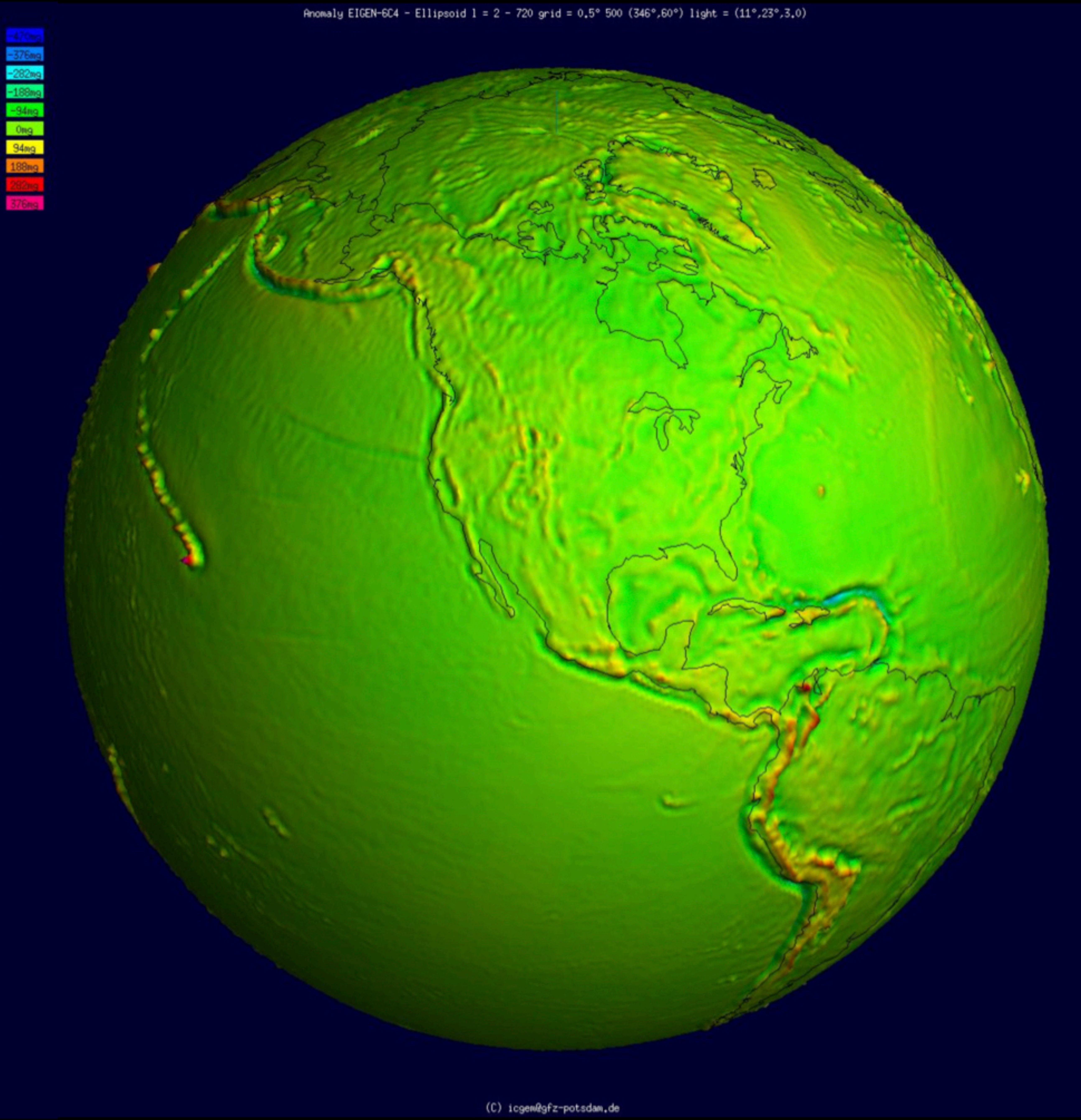
Sandwell and Smith, 1997

Marine gravity anomaly from satellite altimetry



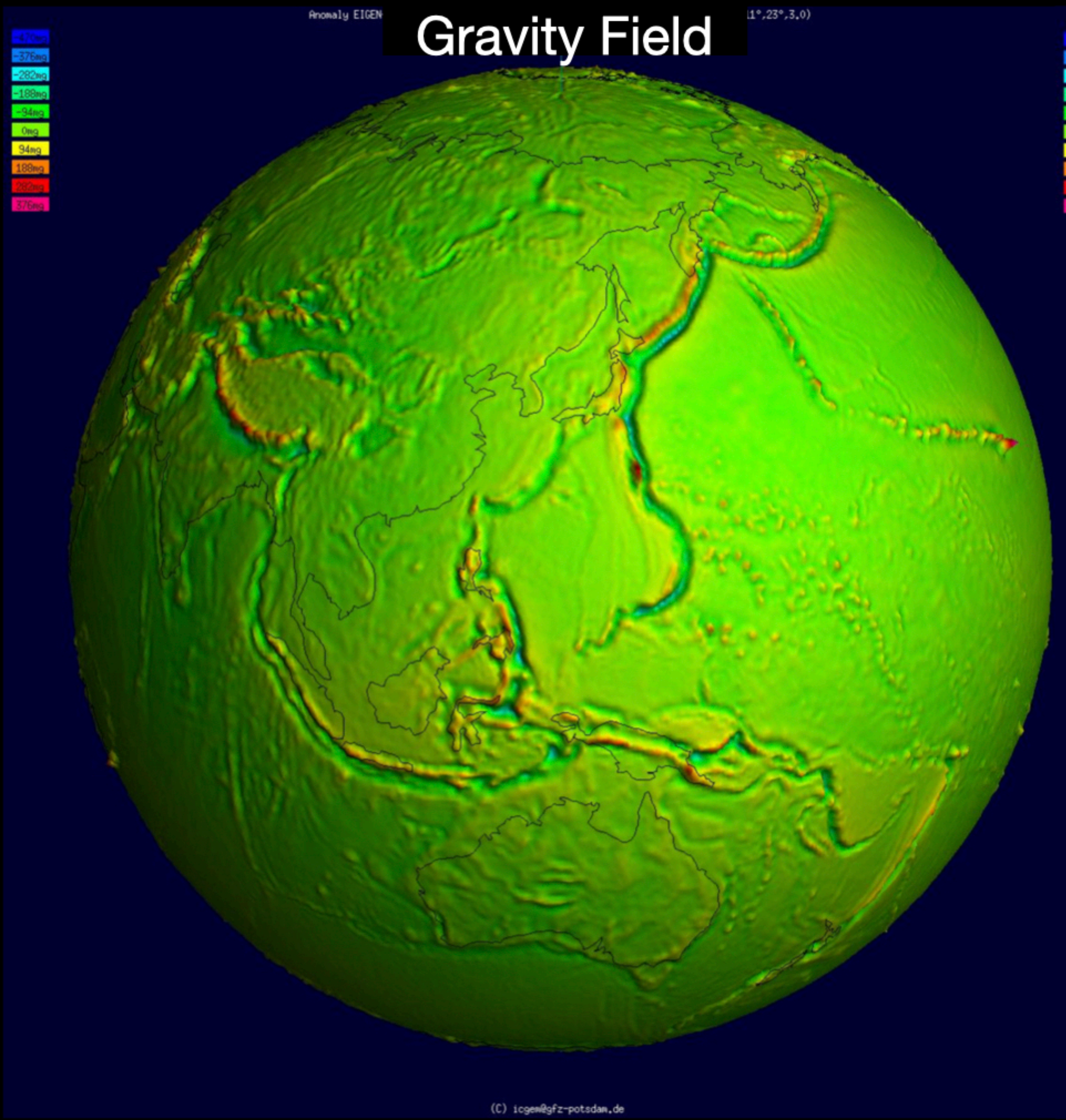
Sandwell and Smith, 1997

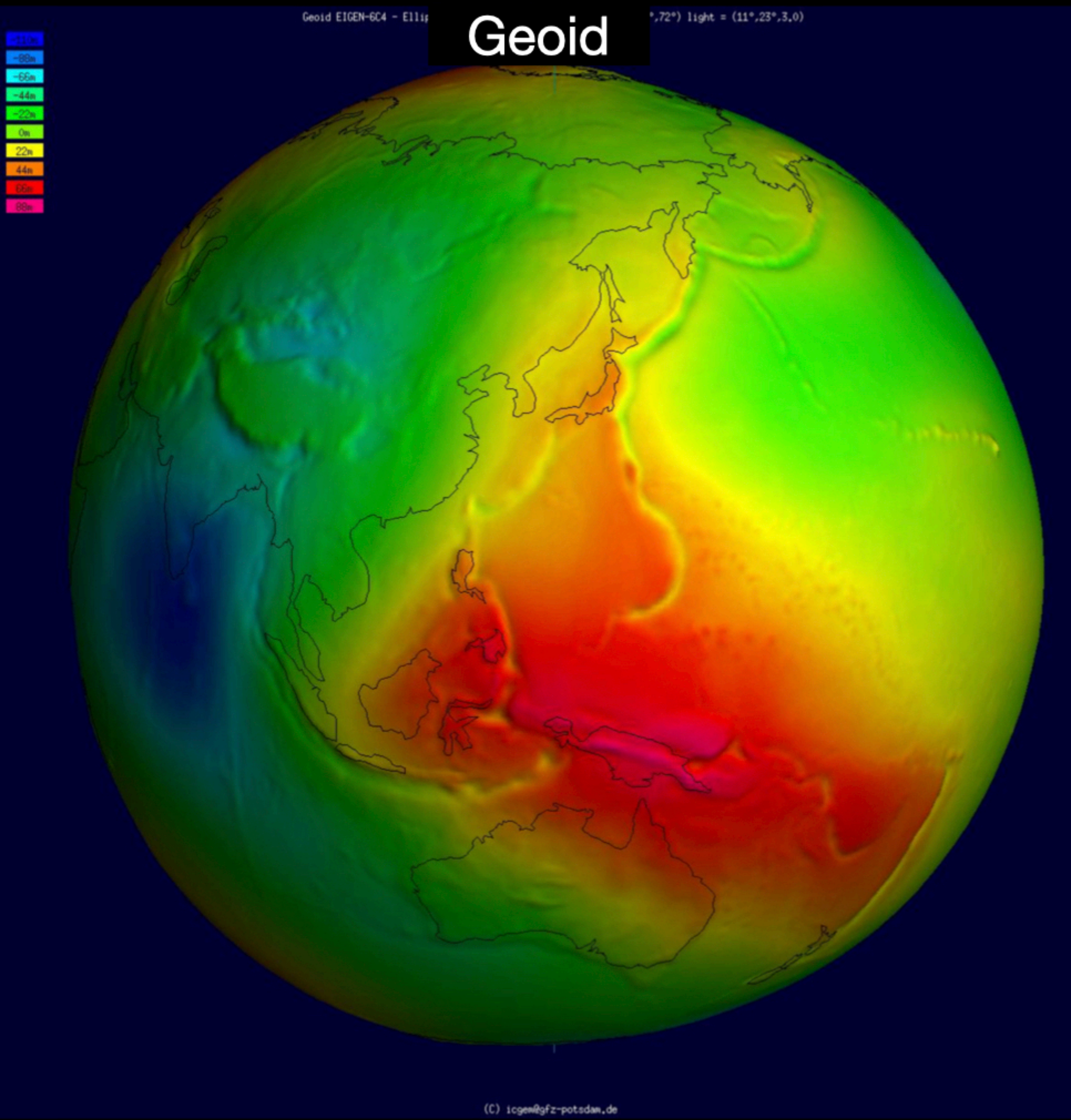




EIGEN-6C4 global gravity field model

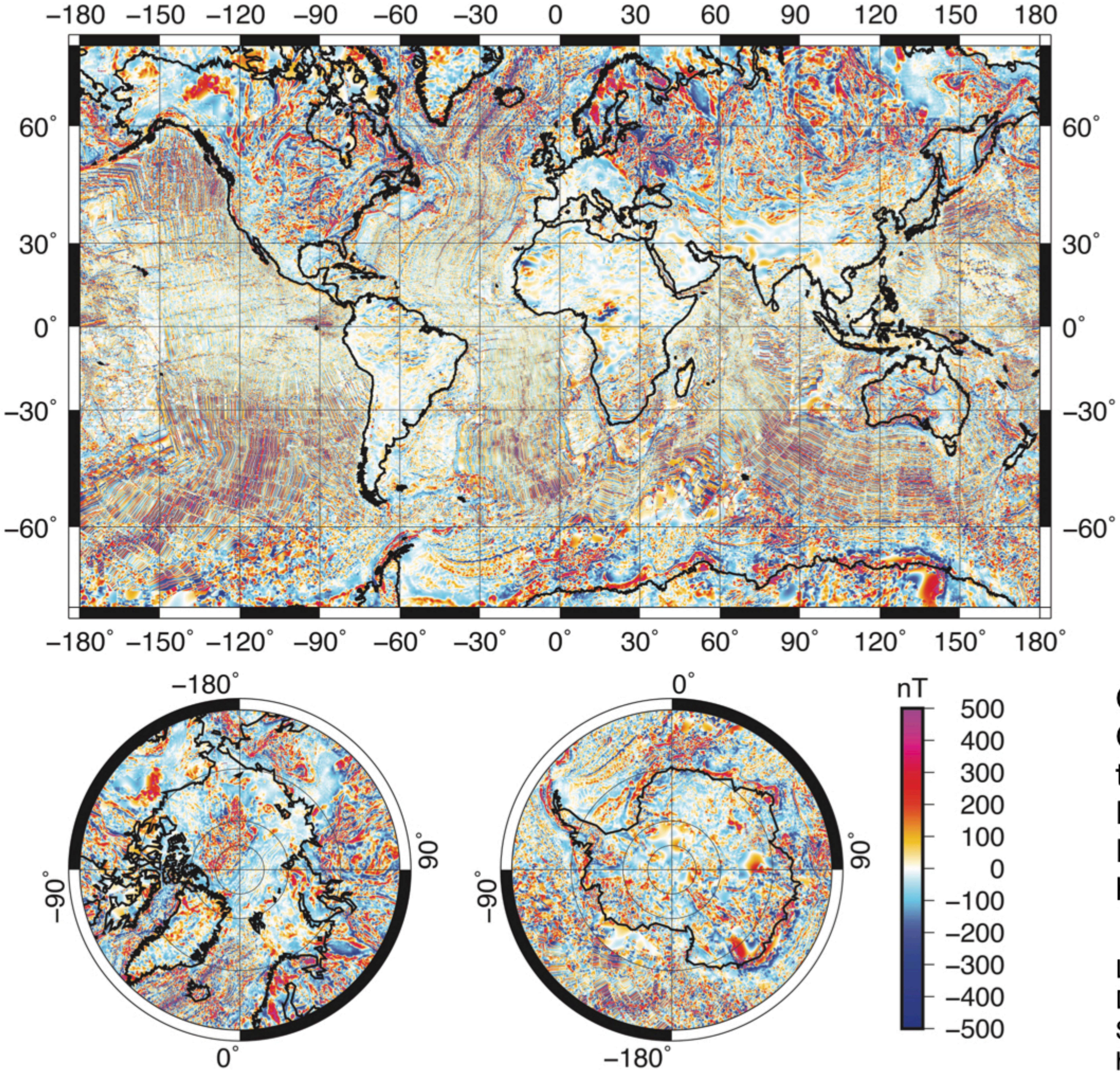
Foerste et al., 2014





EIGEN-6C4 global gravity field model Foerste et al., 2014

New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure: Science, Volume: 346, Issue: 6205, Pages: 65-67, DOI: (10.1126/science.1258213), 2014

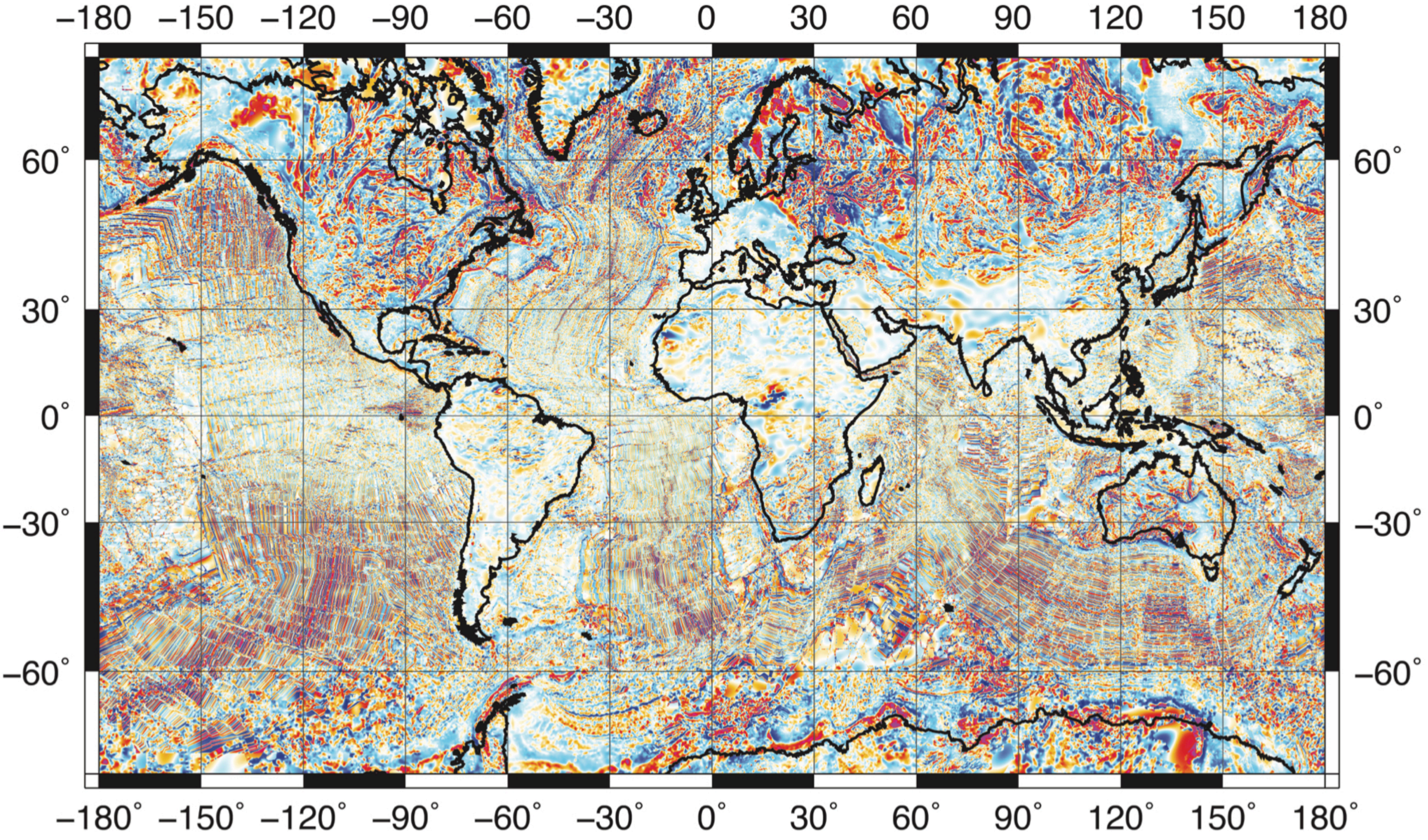


World Digital Magnetic Anomaly Map (WDMAM) version 2.1

Magnetic field at 5 km elevation above mean sea level, combining satellite and other observations

Choi, Y., Dyment, J., Lesur, V., Garcia Reyes, Catalan, M., Ishihara, T., Litvinova, T., Hamoudi, M., the WDMAM Task Force*, and the WDMAM Data Providers**, 2023, World Digital Magnetic Anomaly Map version 2.1, map available at http://www.wdmam.org.

Lesur et al., 2016, Building the second version of the World Digital Magnetic Anomaly Map (WDMAM): Earth, Planets and Space, v. **68**, article 27, https://doi.org/10.1186/s40623-016-0404-6


–180
–150
–120
–90
–60
–30
0
30
60
90
120
150
180
60°
30°
0°
–30°
–60°
–180°
–150°
–120°
–90°
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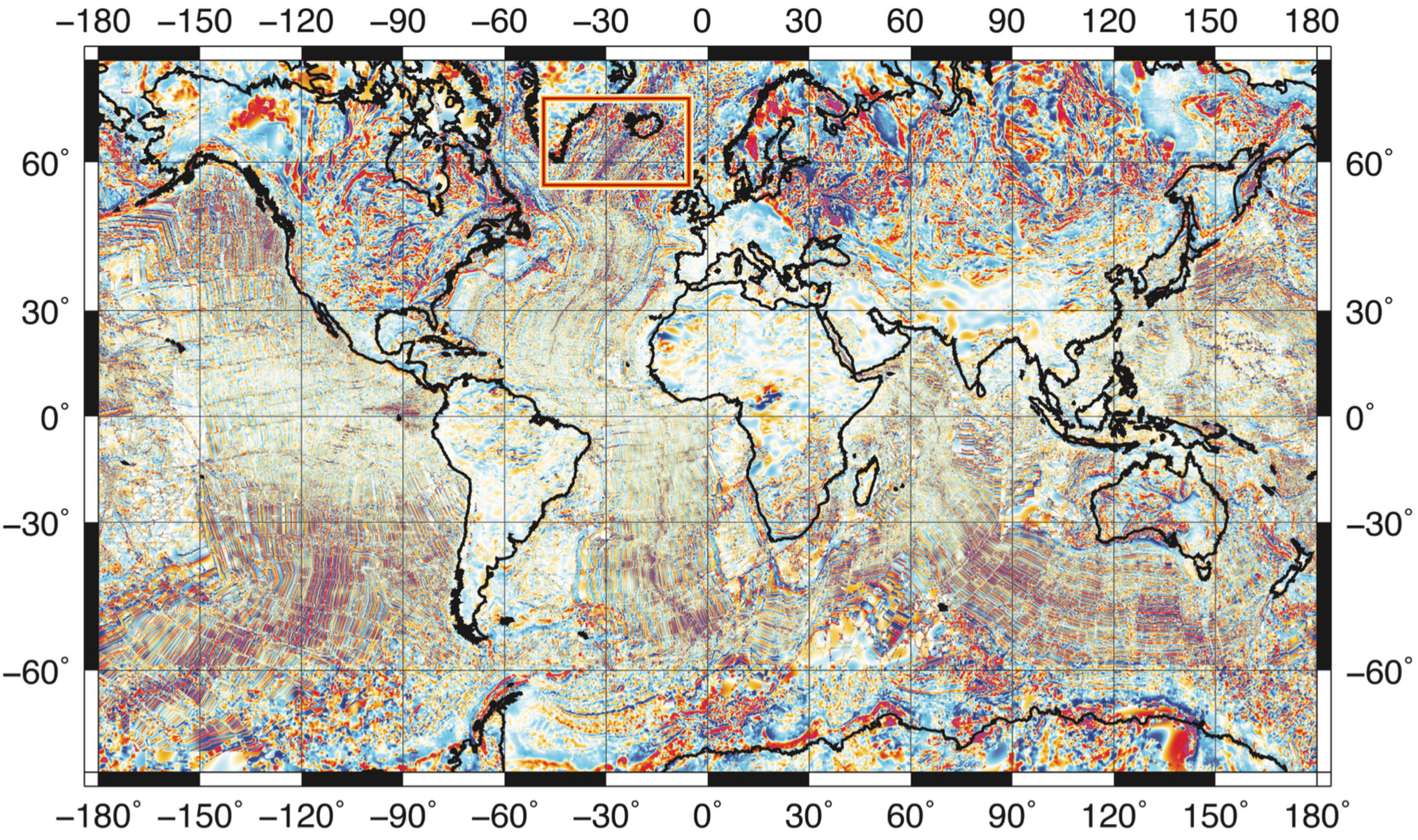
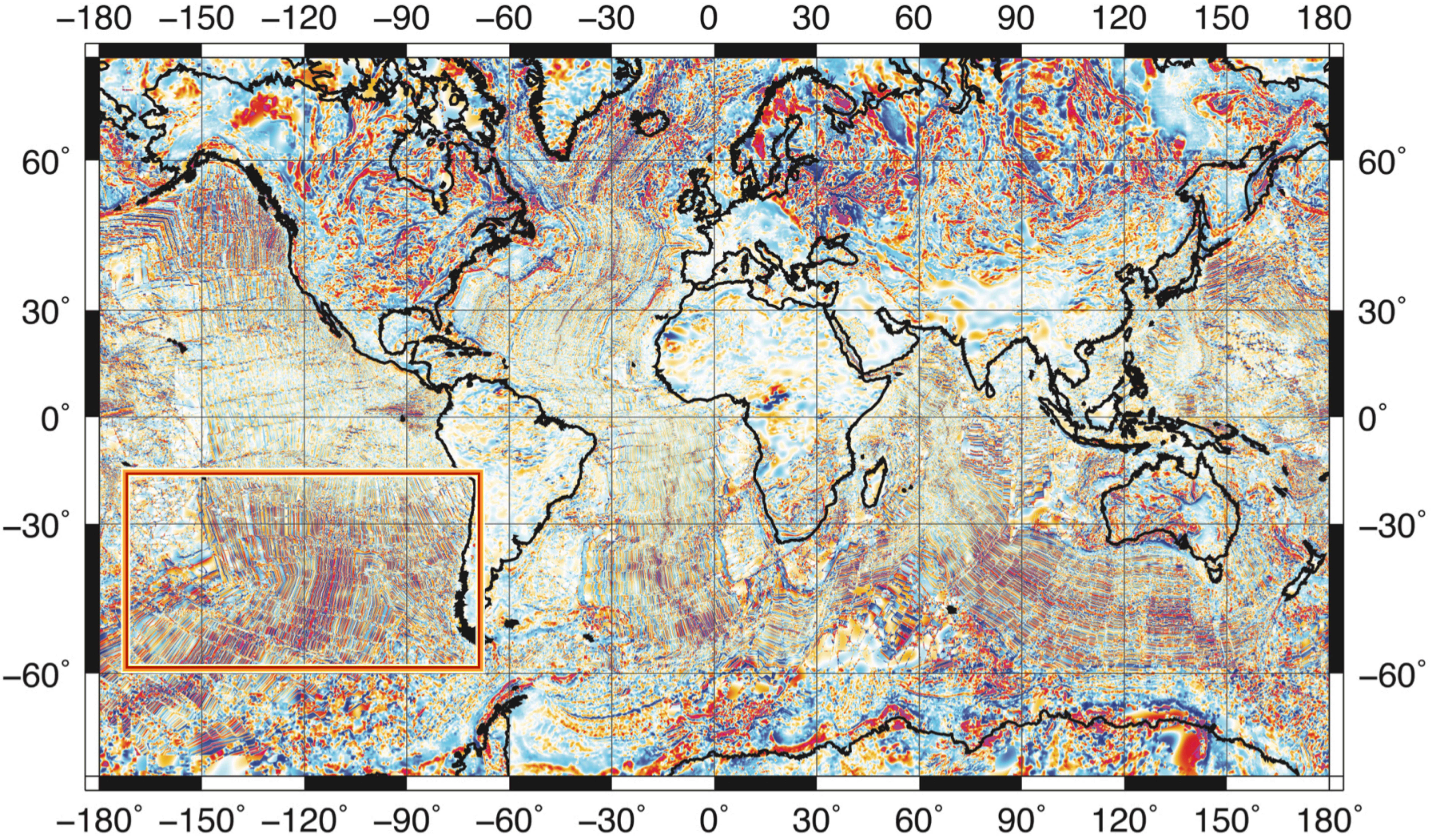
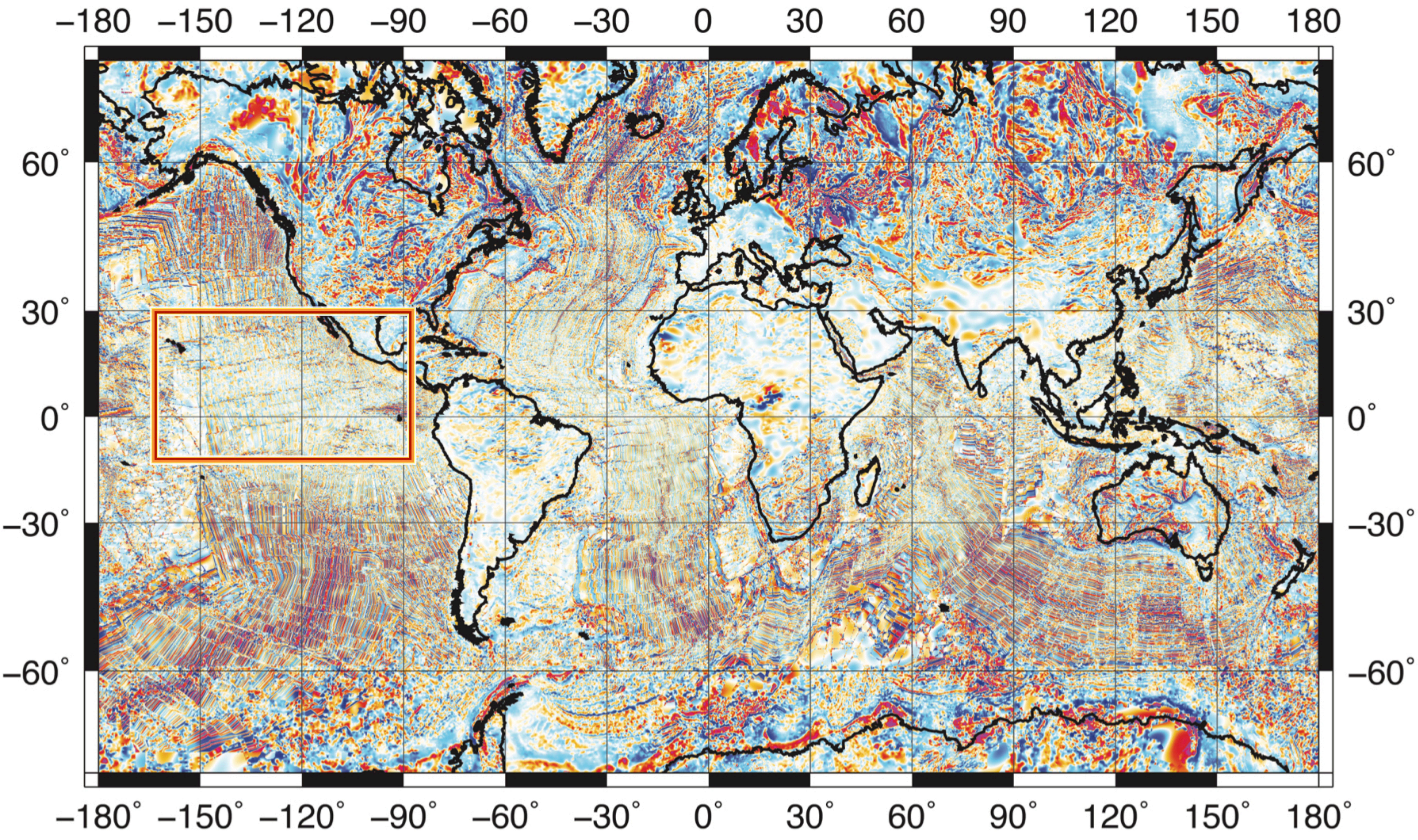
60°
90°
120°
150°
180°



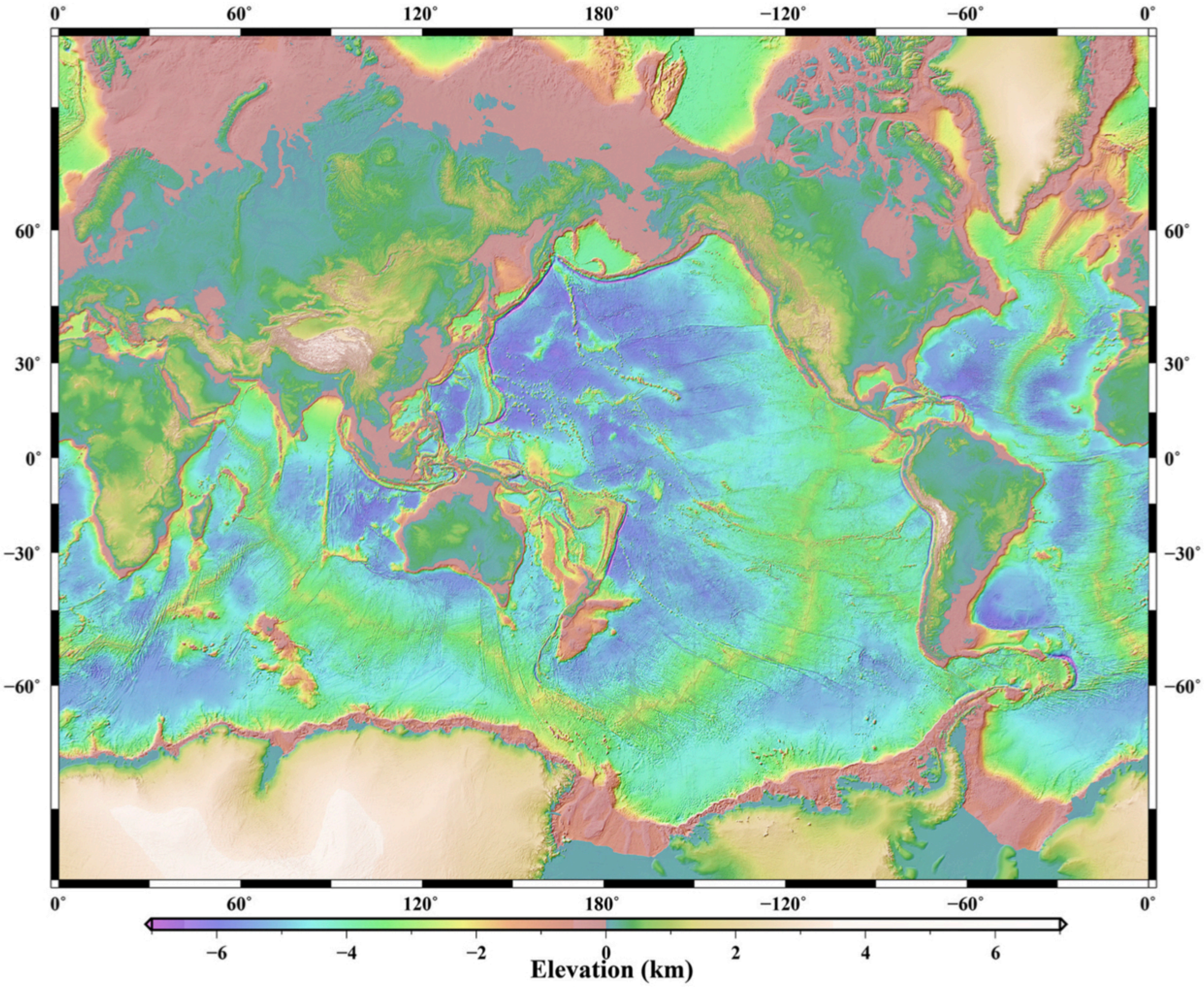
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
60° 30° 0° −30° −60°
−180° −150° −120° −90° −60° −30° 0° 30° 60° 90° 120° 150° 180°



−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
60° 30° 0° −30° −60°
−180° −150° −120° −90° −60° −30° 0° 30° 60° 90° 120° 150° 180°



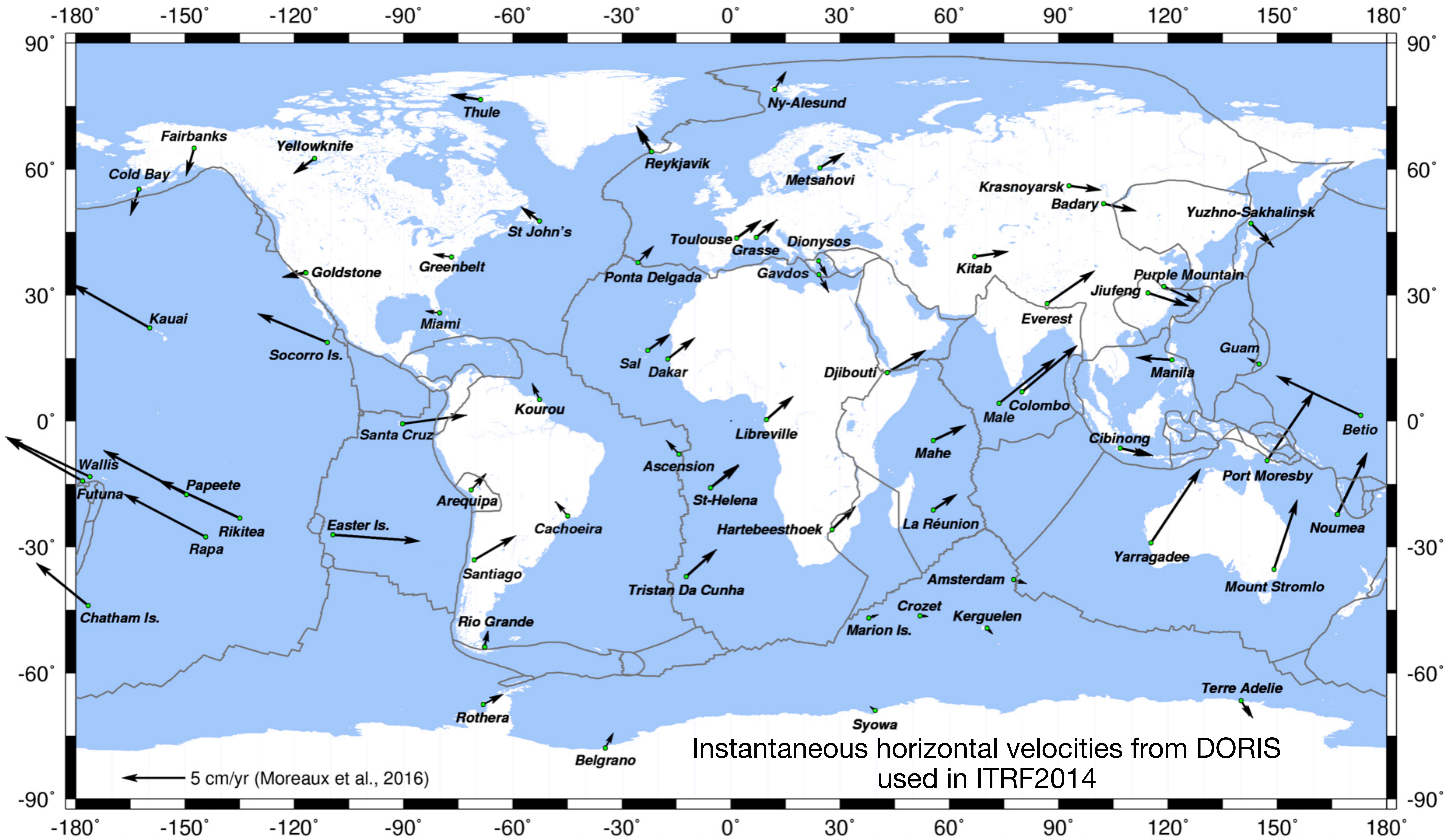
−180 −150 −120 −90 −60 −30 0 30 60 90 120 150 180
60° 30° 0° −30° −60°
60° 30° 0° −30° −60°
−180° −150° −120° −90° −60° −30° 0° 30° 60° 90° 120° 150° 180°



SRTM15Plus map of Earth's topography and bathymetry

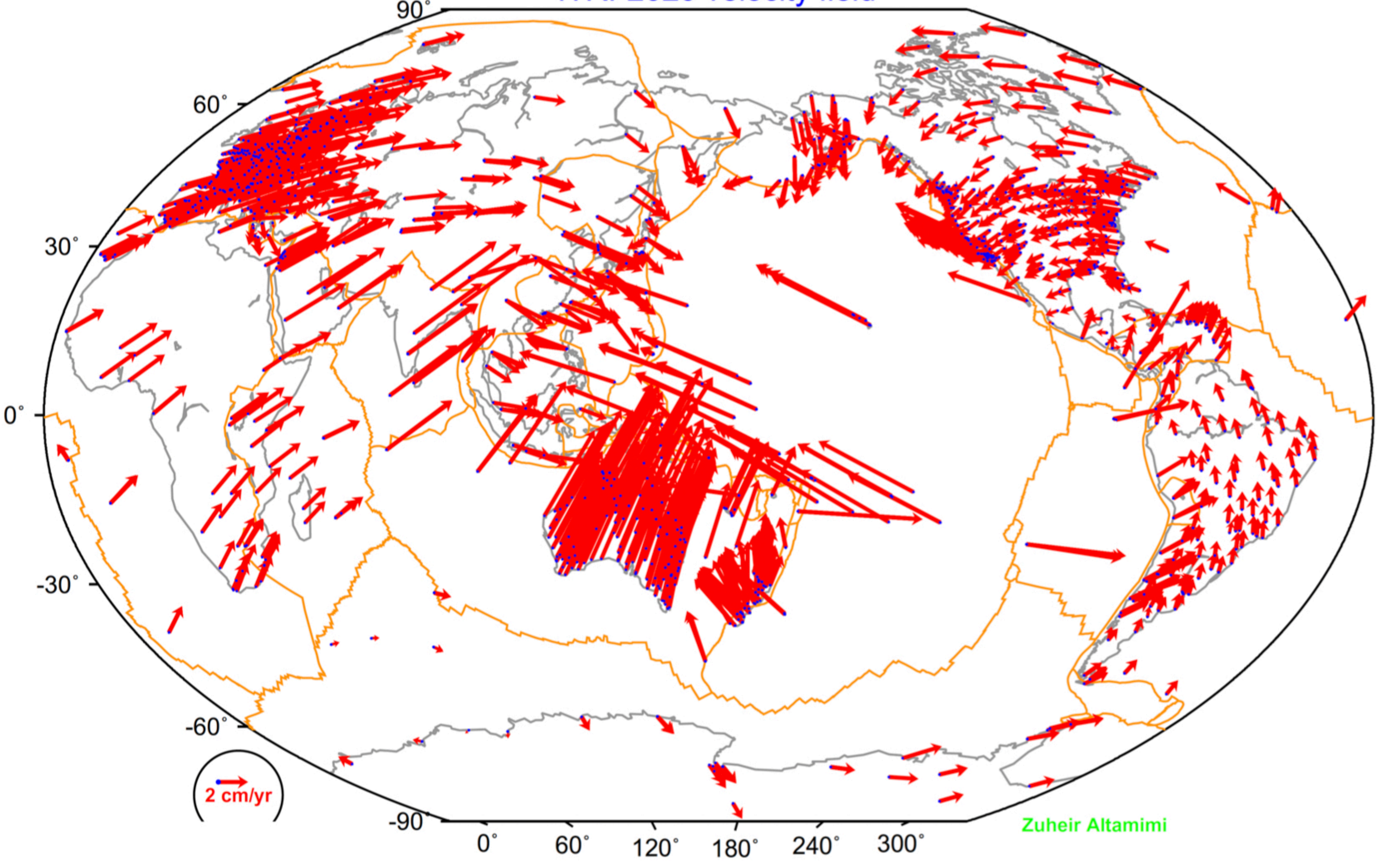
Incorporates results from Shuttle Radar Altimetry, satellite laser altimetry, shipborne sonar and multibeam surveys, and land surveys.

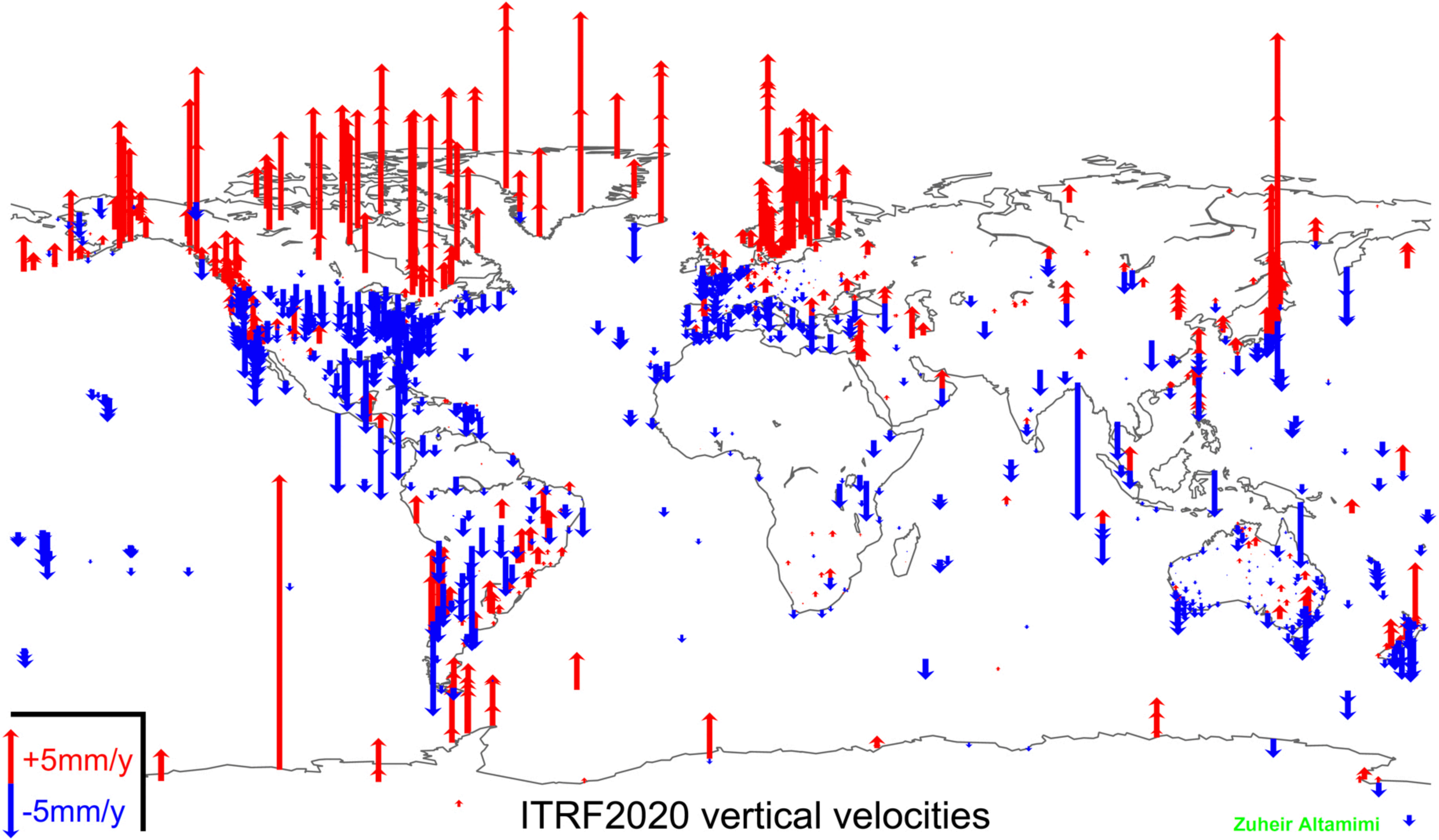
Tozer et al., 2019, Fig. 4



Thule
Ny-Alesund
Fairbanks
Yellowknife
Cold Bay
Reykjavik
Metsahovi
Krasnoyarsk
Badary
Yuzhno-Sakhalinsk
St John's
Toulouse
Grasse
Dionysos
Ponta Delgada
Gavdos
Greenbelt
Goldstone
Kitab
Purple Mountain
Jiufeng
Kauai
Miami
Everest
Socorro Is.
Sal
Dakar
Djibouti
Guam
Manila
Kourou
Colombo
Male
Betio
Santa Cruz
Libreville
Cibinong
Mahe
Wallis
Ascension
Port Moresby
Papeete
Futuna
Arequipa
St-Helena
La Réunion
Noumea
Rikitea
Easter Is.
Cachoeira
Hartebeesthoek
Rapa
Santiago
Yarragadee
Amsterdam
Tristan Da Cunha
Mount Stromlo
Chatham Is.
Crozet
Kerguelen
Rio Grande
Marion Is.
Terre Adelie
Rothera
Syowa
Belgrano
5 cm/yr (Moreaux et al., 2016)
Instantaneous horizontal velocities from DORIS used in ITRF2014

ITRF2020 velocity field




+5mm/y
-5mm/y
ITRF2020 vertical velocities
Zuheir Altamimi

Precise position determination enables precise mapping in geology, geophysics, oceanography, and geodesy

| Home | People | Contact | About us | Vacancies | News Archive | MAGNET | Acknowledgements |

Recent Research
- Great Basin Strain
- Basin and Range Dynamics
- Aquifer Deformation
- Geothermal Energy
- Global Tectonics
- Reference Frames
- Global Strain Rate Map
- Yucca Mountain GPS
- Vertical Land Motion
- Publications

MAGNET GPS Network
- Network Information and Data

People
- Geoff Blewitt
- Bill Hammond
- Corné Kreemer
- Bret Pecoraro
- Aren Crandall-Bear
- Nina Miller

Past Members
- Justine Overacker
- Zack Young
- Meredith Kraner
- Hans-Peter Plag
- Elliot Klein
- Jayne Bormann
- Jay Goldfarb
- Yang Zhang
- Sumant Jha
- Emma Hill

University of Nevada, Reno

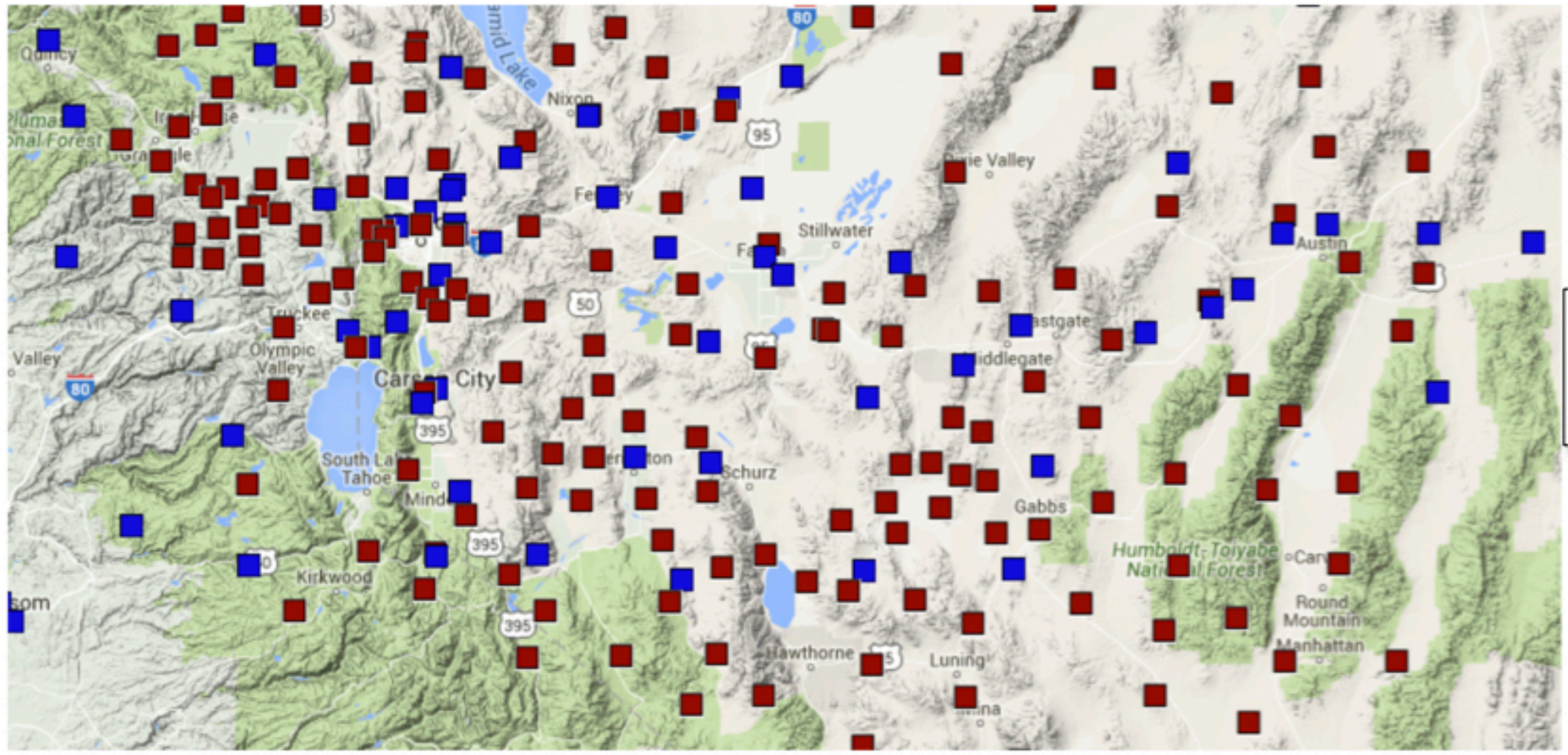
Nevada Bureau of Mines and Geology

The MAGNET GPS Network

Network Information

Table 1. Station Location and DOI Information	Table 2. Instrumentation and Monumentation Information	Table 3. Station MIDAS Velocities	Link to MAGNET RINEX Data	Link to MAGNET IGS Style log files

Click Image for Interactive Google Map



MAGNET RINEX data can be accessed directly from us via our web server. These data are updated daily as soon as they are ingested into our own data processing system. They are also available via UNAVCO's GPS/GNSS Data Archive Interface.

MAGNET geodetic network operations are currently supported by the NSF and USGS NEHRP program through:

- **Cooperative agreement G20AC00046, "Western Great Basin Geodetic Network Operations: MAGNET 2020-2025", to Hammond and Blewitt**
- **NSF Project 1615253, "Collaborative Research: Using GPS to Unravel the Long-Term Kinematics and Dynamics of the American Southwest from an Ever-Changing Deformation Field", to Kreemer and Blewitt**

In the past, many other projects have supported MAGNET. See our Acknowledgements page for a complete list of grants that have supported MAGNET field opertaions.

http://geodesy.unr.edu/magnet.php

Welcome to the Nevada Geodetic Laboratory GPS Networks Map

Click on sites for station information.

http://geodesy.unr.edu/NGLStationPages/gpsnetmap/GPSNetMap_MAG.html

https://earthquake.usgs.gov/monitoring/gps/Pacific_Northwest/p150

http://geodesy.unr.edu/NGLStationPages/stations/P150.sta

Cronin photo

GPS/GNSS station P150

USGS Earthquake Hazards Program, Pacific Northwest Network

Martis Peak, California

Lat 39.173257°N

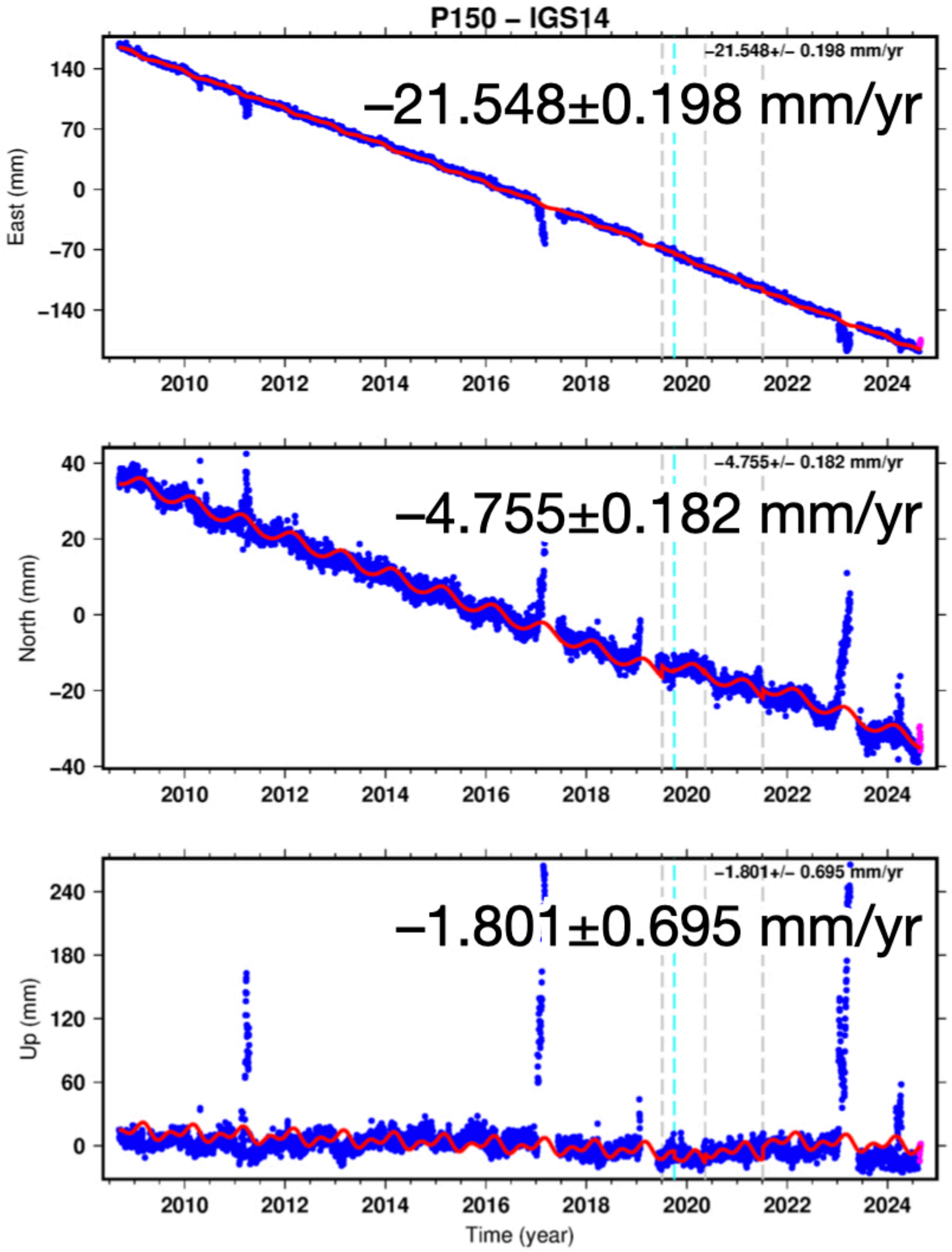
Long 120.020188°W


Digital Surface Model (DSM)
Fire Lookout
P150
ray dome
P150 solar panels
& instrument package
0
100 m
2014 USFS Tahoe National Forest Lidar.
Distributed by OpenTopography.
https://doi.org/10.5069/G9V122Q1 .
Accessed: 2024-09-07


Digital Surface Model (DSM)
0
100 m
2014 USFS Tahoe National Forest Lidar.
Distributed by OpenTopography.
https://doi.org/10.5069/G9V122Q1 .
Accessed: 2024-09-07


Digital Terrain Model (DTM)
0
100 m
2014 USFS Tahoe National Forest Lidar.
Distributed by OpenTopography.
https://doi.org/10.5069/G9V122Q1 .
Accessed: 2024-09-07

Repeated precise position determination over time — instantaneous velocity



Time Series of Daily Positions Relative to IGS14 (ITRF)

GPS station P150 on Martis Peak, California, from 9/11/2008 to 8/29/2024.

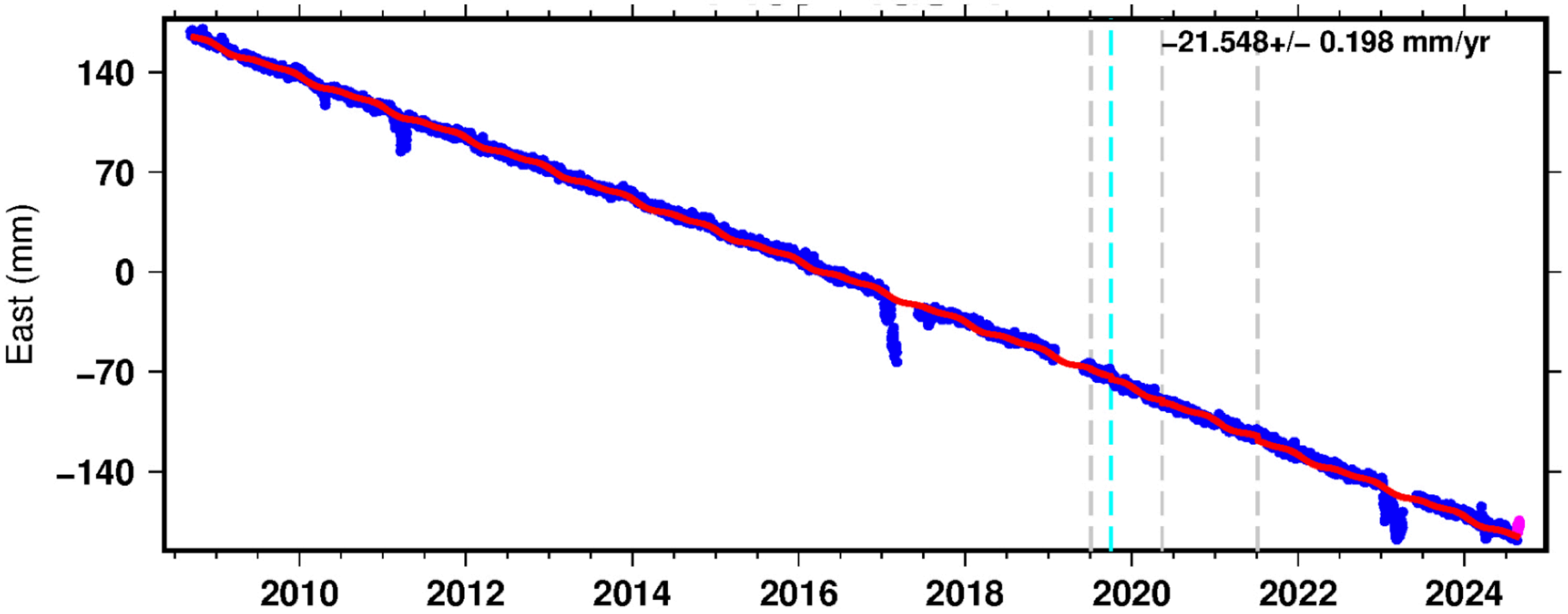
The slope of each time series is the mean velocity in that direction.

Positive slopes are toward north, east, or up.

Nevada Geodetic Laboratory

http://geodesy.unr.edu/NGLStationPages/stations/P150.sta

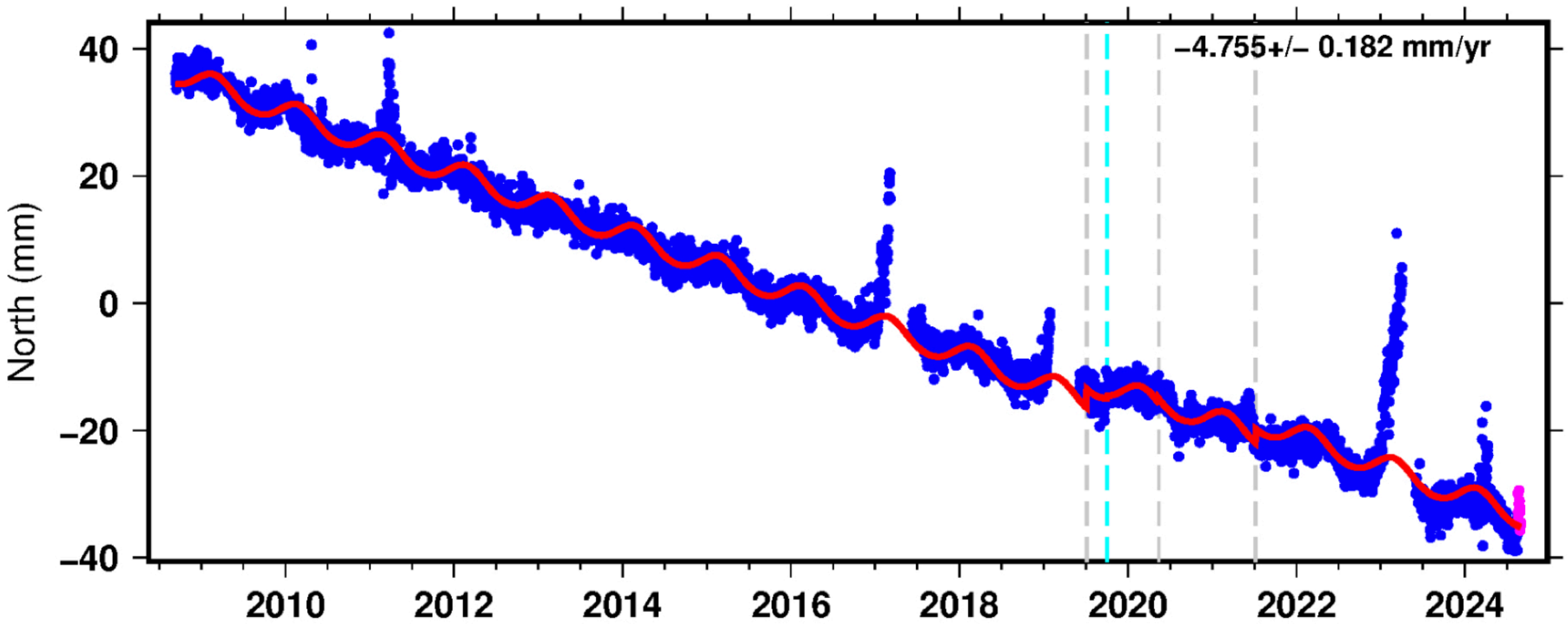
Time Series of Daily Positions of P150 Relative to IGS14 (ITRF)



Nevada Geodetic Laboratory

http://geodesy.unr.edu/NGLStationPages/stations/P150.sta

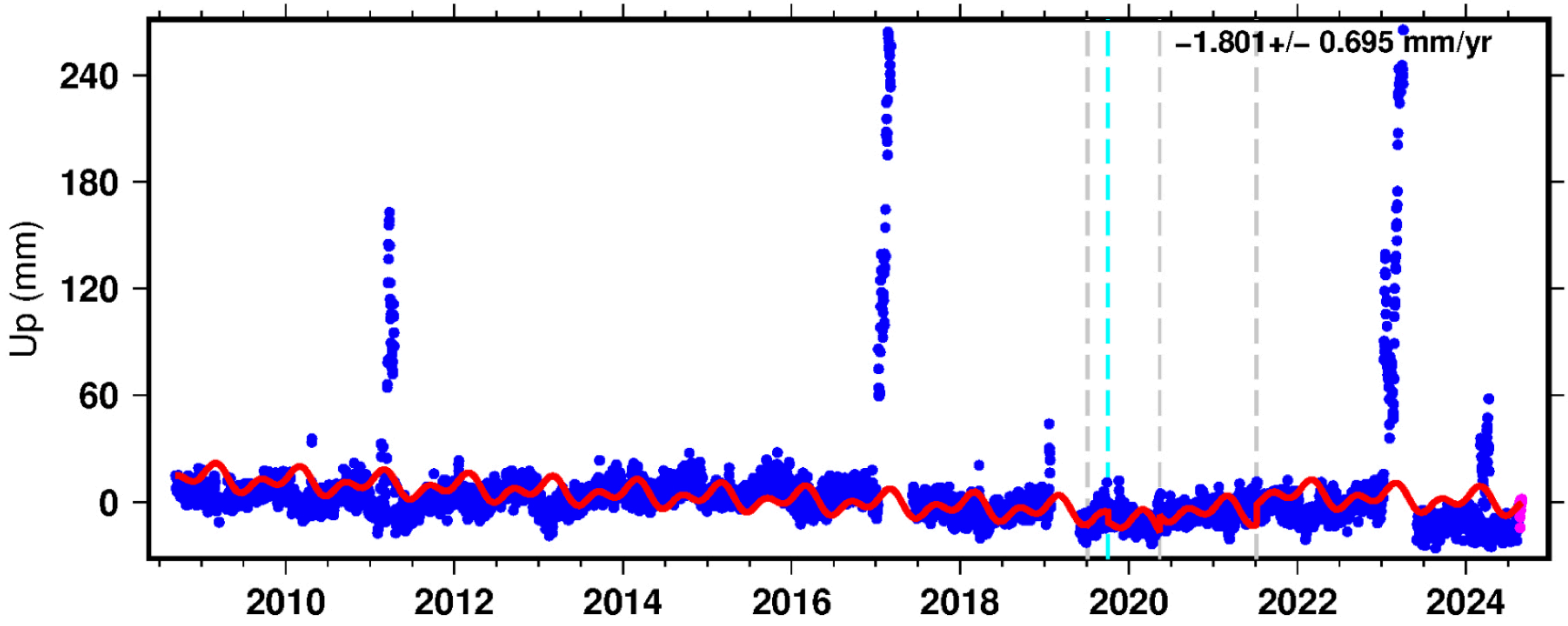
Time Series of Daily Positions of P150 Relative to IGS14 (ITRF)



Nevada Geodetic Laboratory

http://geodesy.unr.edu/NGLStationPages/stations/P150.sta

Time Series of Daily Positions of P150 Relative to IGS14 (ITRF)



Nevada Geodetic Laboratory

http://geodesy.unr.edu/NGLStationPages/stations/P150.sta

Welcome to the Nevada Geodetic Laboratory GPS Networks Map

Click on sites for station information.

http://geodesy.unr.edu/NGLStationPages/gpsnetmap/GPSNetMap_MAG.html

Welcome to the Nevada Geodetic Laboratory GPS Networks Map

Click on sites for station information.

http://geodesy.unr.edu/NGLStationPages/gpsnetmap/GPSNetMap_MAG.html

MAGNET GPS Network
All Other GPS Stations

Welcome to the Nevada Geodetic Laboratory GPS Networks Map

Click on sites for station information.

Welcome to the Nevada Geodetic Laboratory GPS Networks Map

Click on sites for station information.

MAGNET GPS Network
All Other GPS Stations

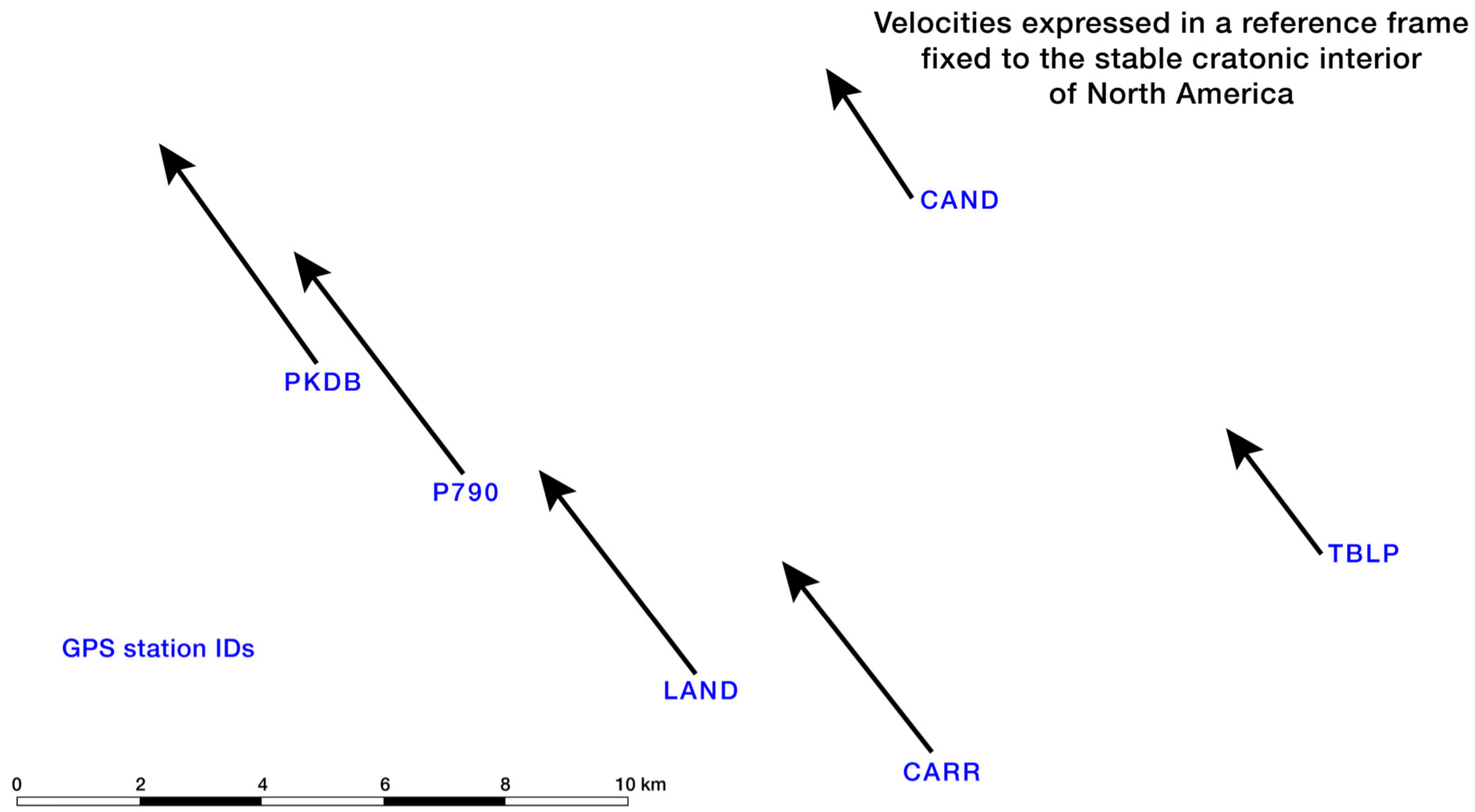
https://earthquake.usgs.gov/monitoring/gps/Pacific_Northwest_ITRF2014/p695

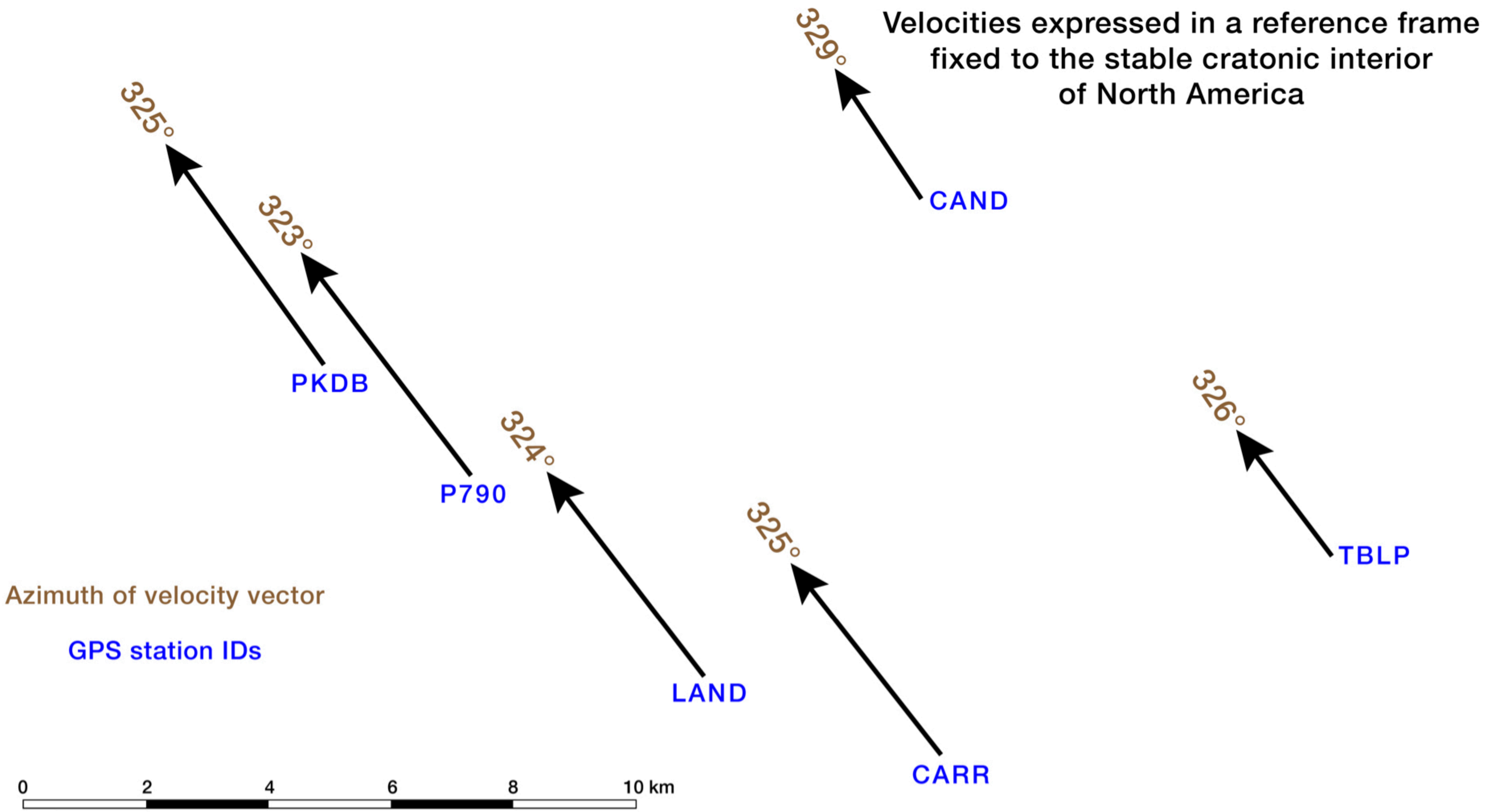
GPS/GNSS station P695, being installed on the north ridge of Mt. St. Helens, Washington, 2004

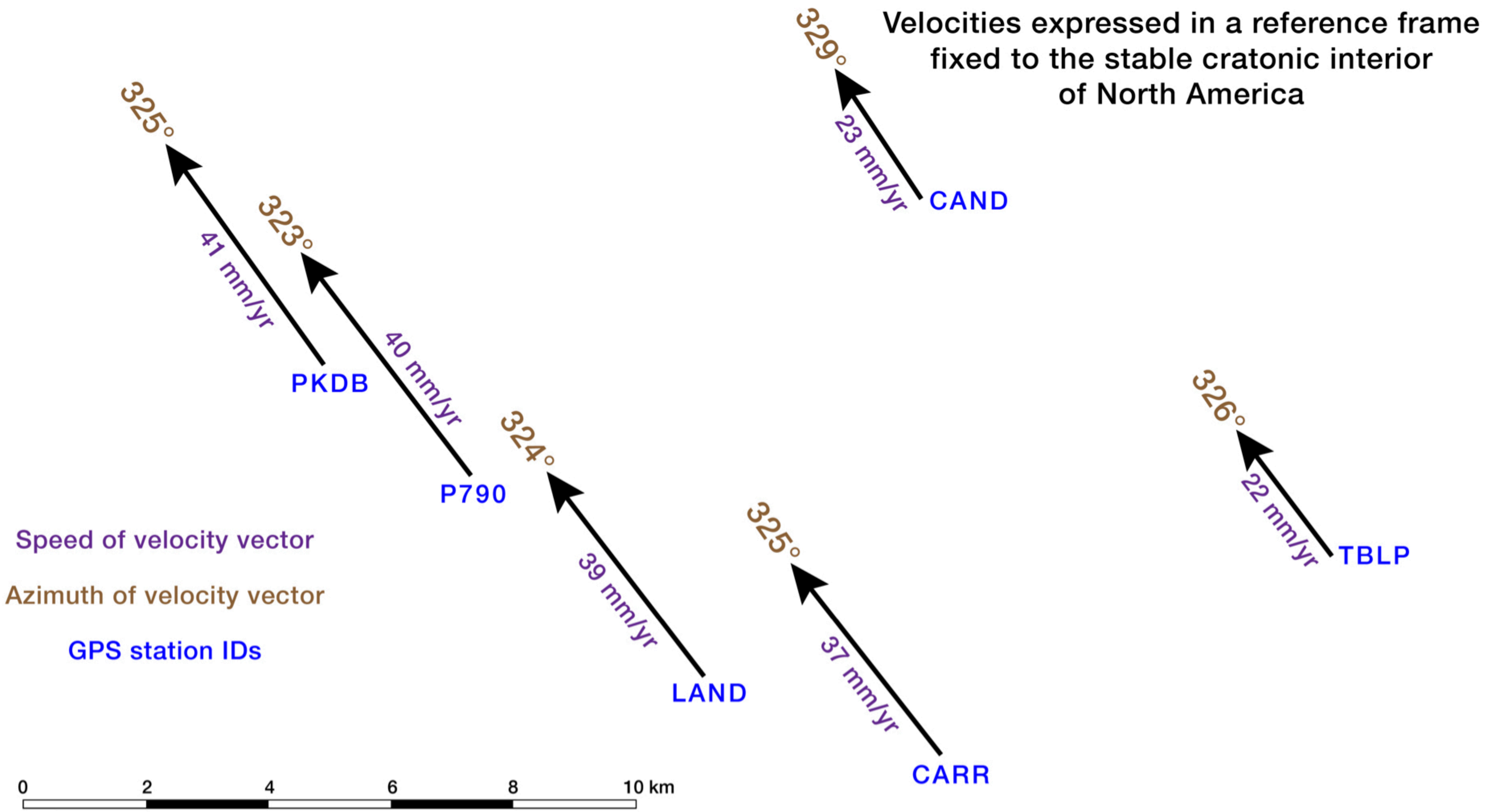
Welcome to the Nevada Geodetic Laboratory GPS Networks Map

Click on sites for station information.

http://geodesy.unr.edu/NGLStationPages/gpsnetmap/GPSNetMap_MAG.html

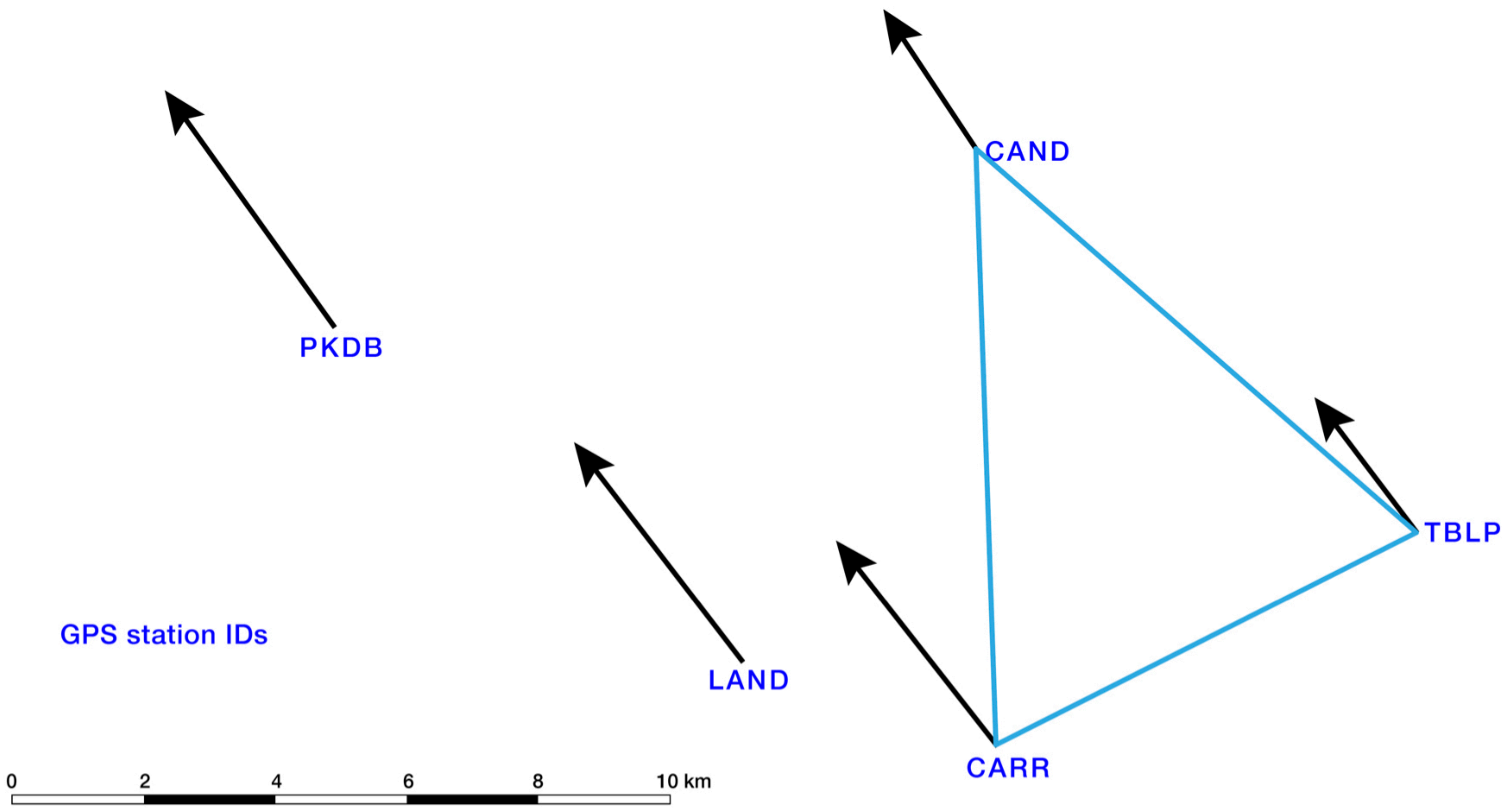

Velocities expressed in a reference frame
fixed to the stable cratonic interior
of North America
CAND
PKDB
P790
TBLP
GPS station IDs
LAND
CARR
0
2
4
6
8
10 km

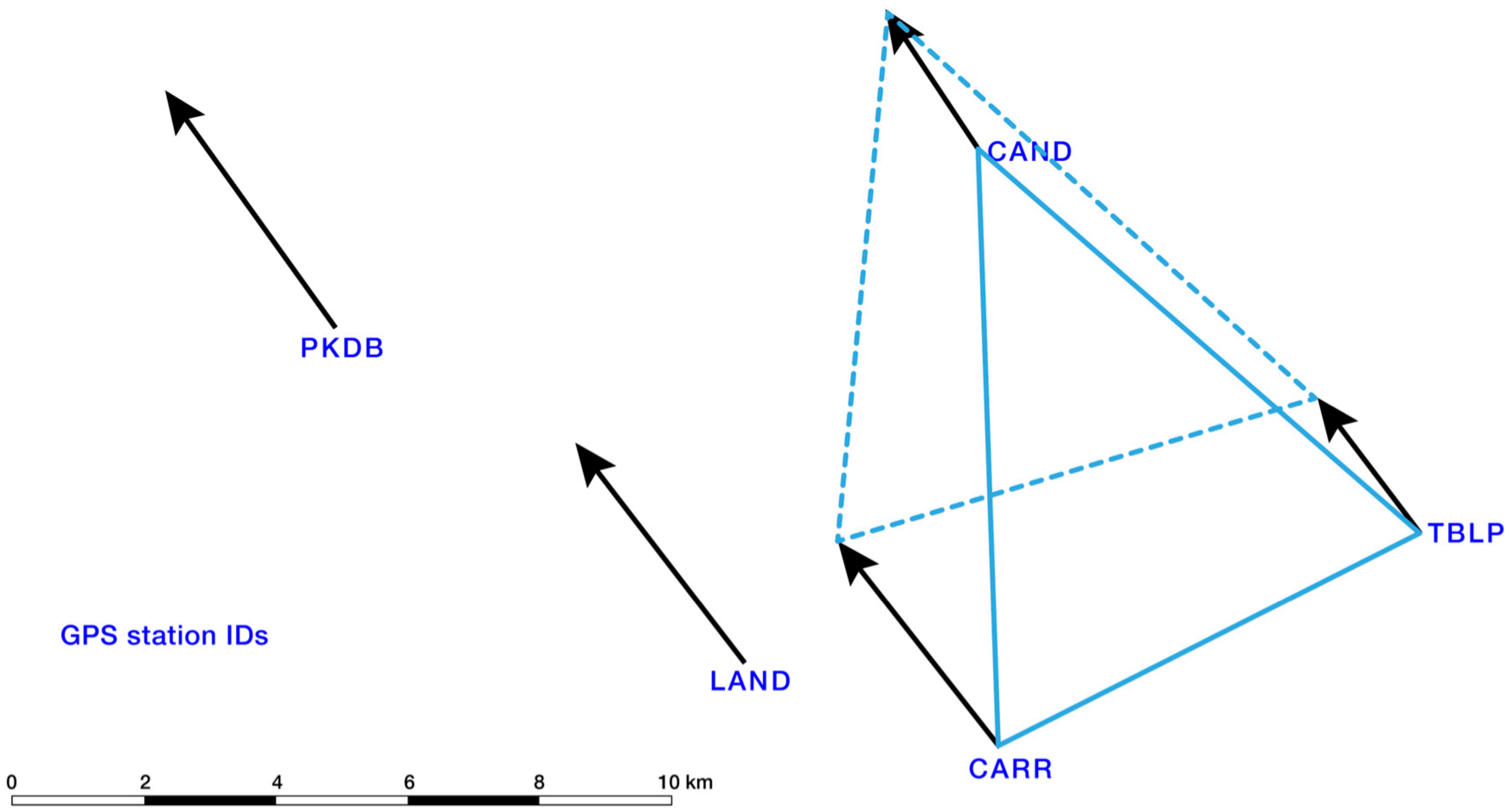

Velocities expressed in a reference frame fixed to the stable cratonic interior of North America
329°
CAND
325°
323°
PKDB
P790
324°
326°
TBLP
325°
LAND
CARR
Azimuth of velocity vector
GPS station IDs
0
2
4
6
8
10 km


Velocities expressed in a reference frame fixed to the stable cratonic interior of North America
329°
23 mm/yr
CAND
325°
41 mm/yr
PKDB
323°
40 mm/yr
P790
324°
39 mm/yr
LAND
325°
37 mm/yr
CARR
326°
22 mm/yr
TBLP
Speed of velocity vector
Azimuth of velocity vector
GPS station IDs
0
2
4
6
8
10 km

Velocities expressed in a reference frame fixed to the stable cratonic interior of North America
San Andreas fault zone
325°
41 mm/yr
PKDB
323°
40 mm/yr
P790
324°
39 mm/yr
LAND
325°
37 mm/yr
CARR
329°
23 mm/yr
CAND
326°
22 mm/yr
TBLP
Speed of velocity vector
Azimuth of velocity vector
GPS station IDs
Gateway to Heaven
Saint John the Baptist...
Parkfield
0
2
4
6
8
10 km

How else can we use these velocity vectors?


CAND
PKDB
TBLP
LAND
CARR
GPS station IDs
0
2
4
6
8
10 km



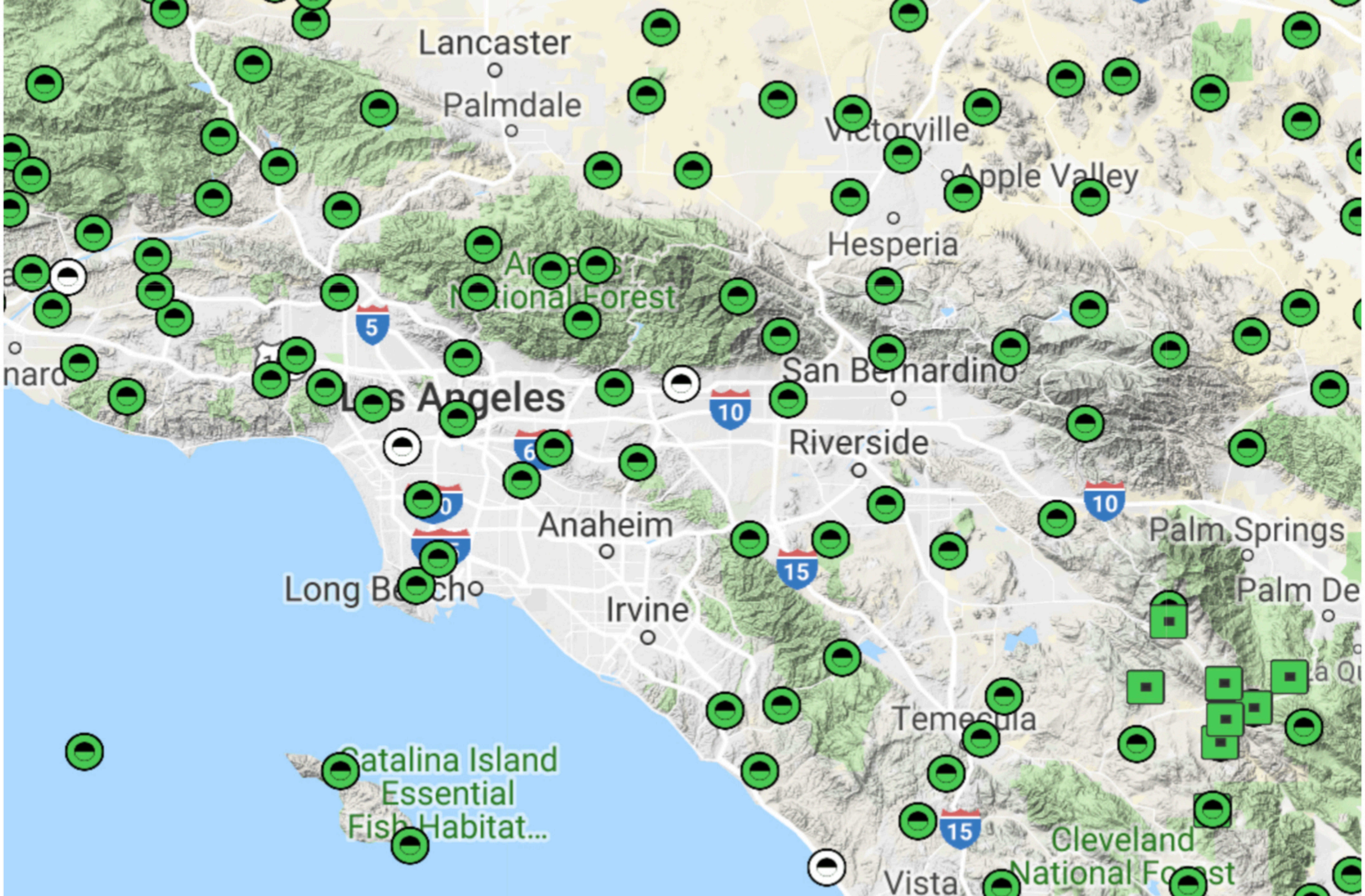
CAND
PKDB
TBLP
LAND
GPS station IDs
CARR
0
2
4
6
8
10 km

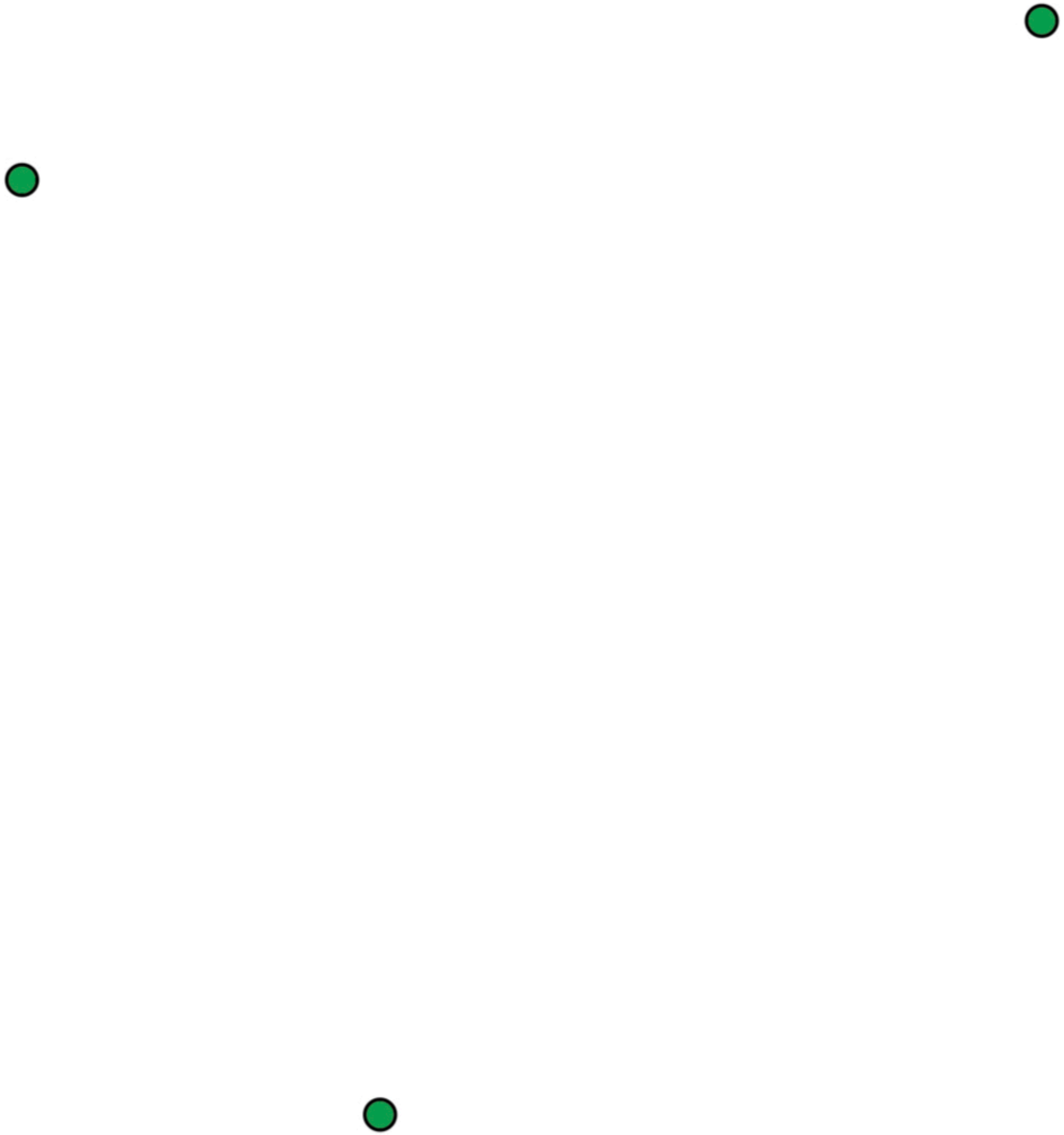
How can we describe this strained triangle in a way that a geoscientist, geodesist, or engineer might understand?

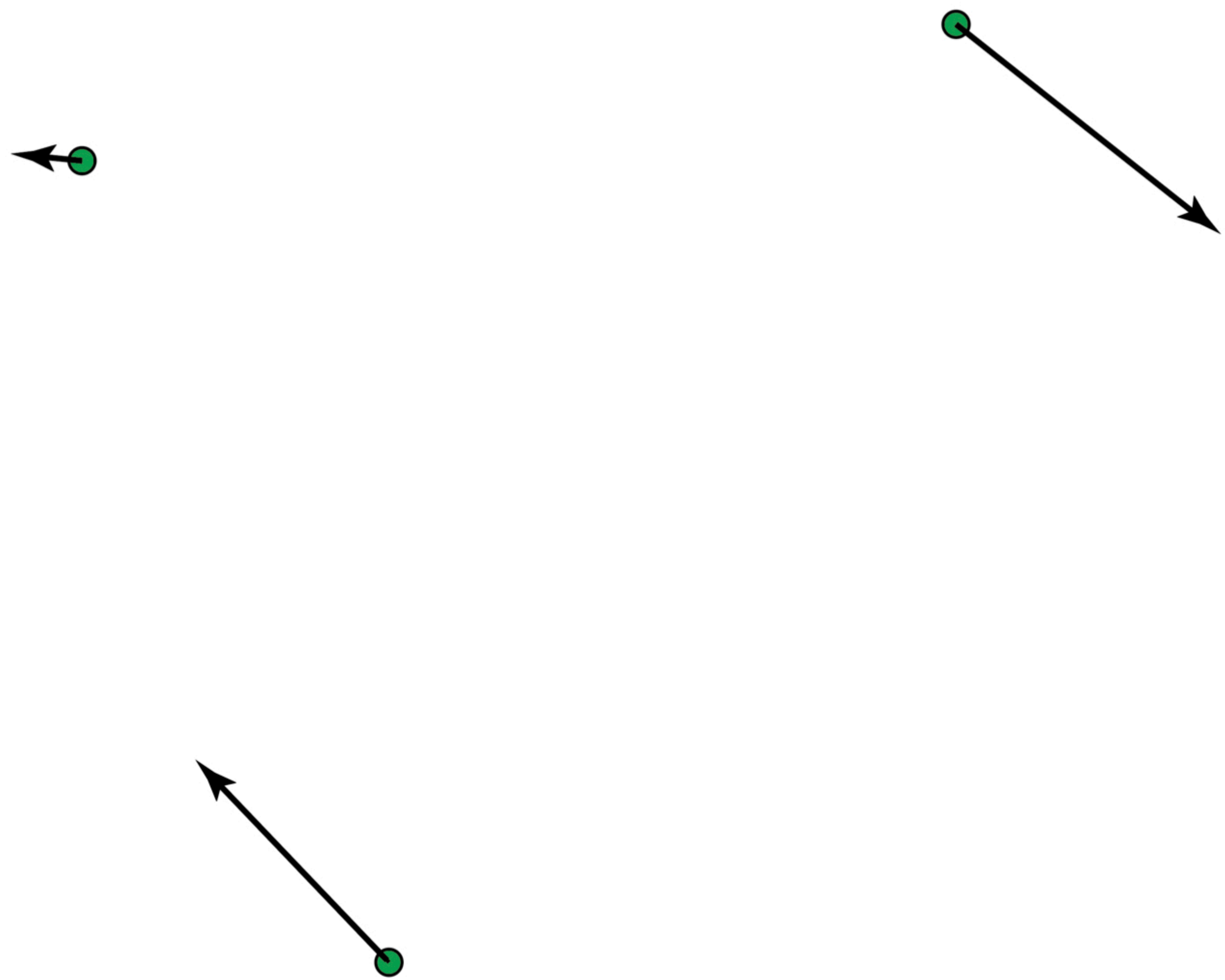
Using Velocities from a Triangle of GPS Sites to Investigate Crustal Strain

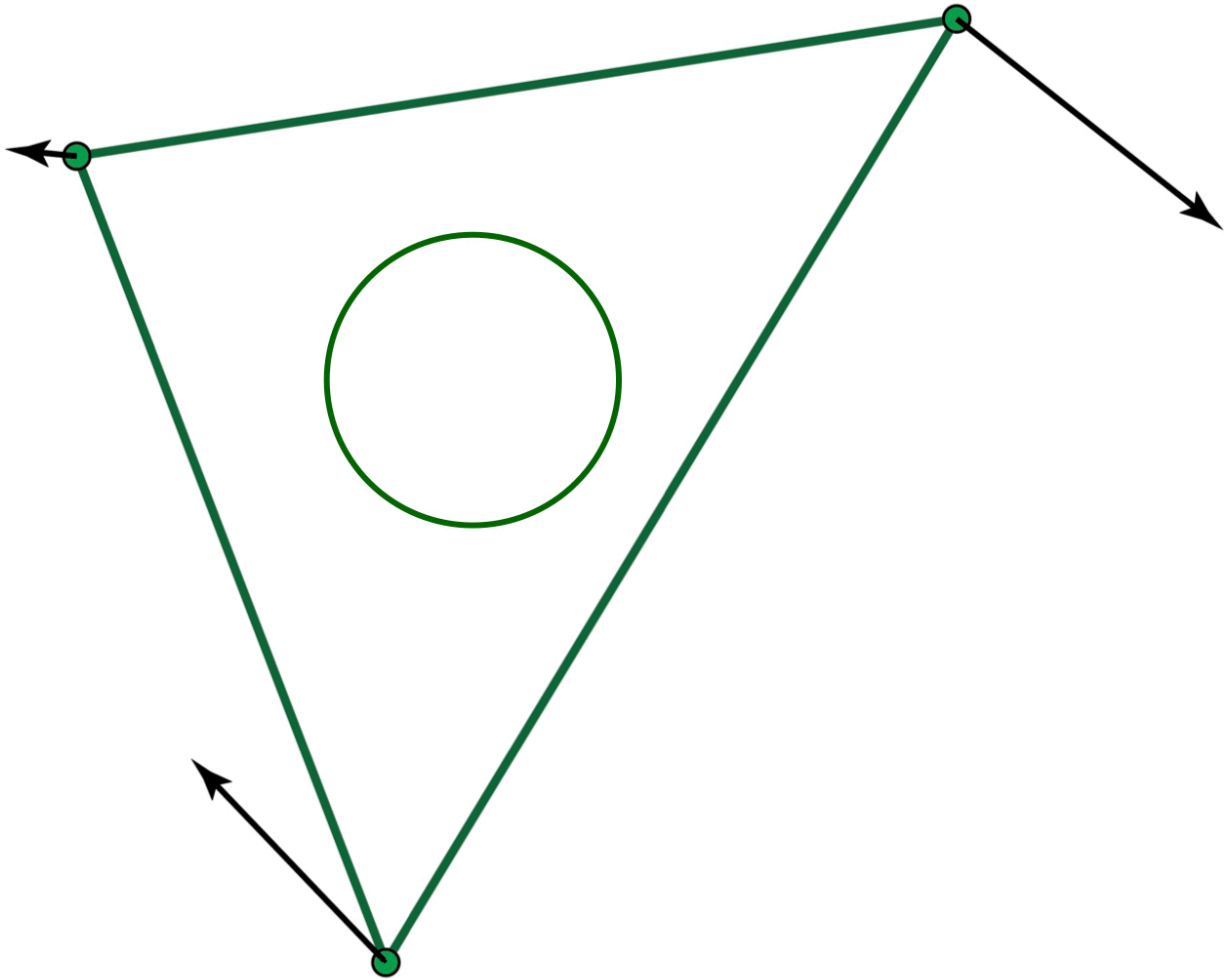
UNAVCO GPS Crustal Strain Curriculum Team

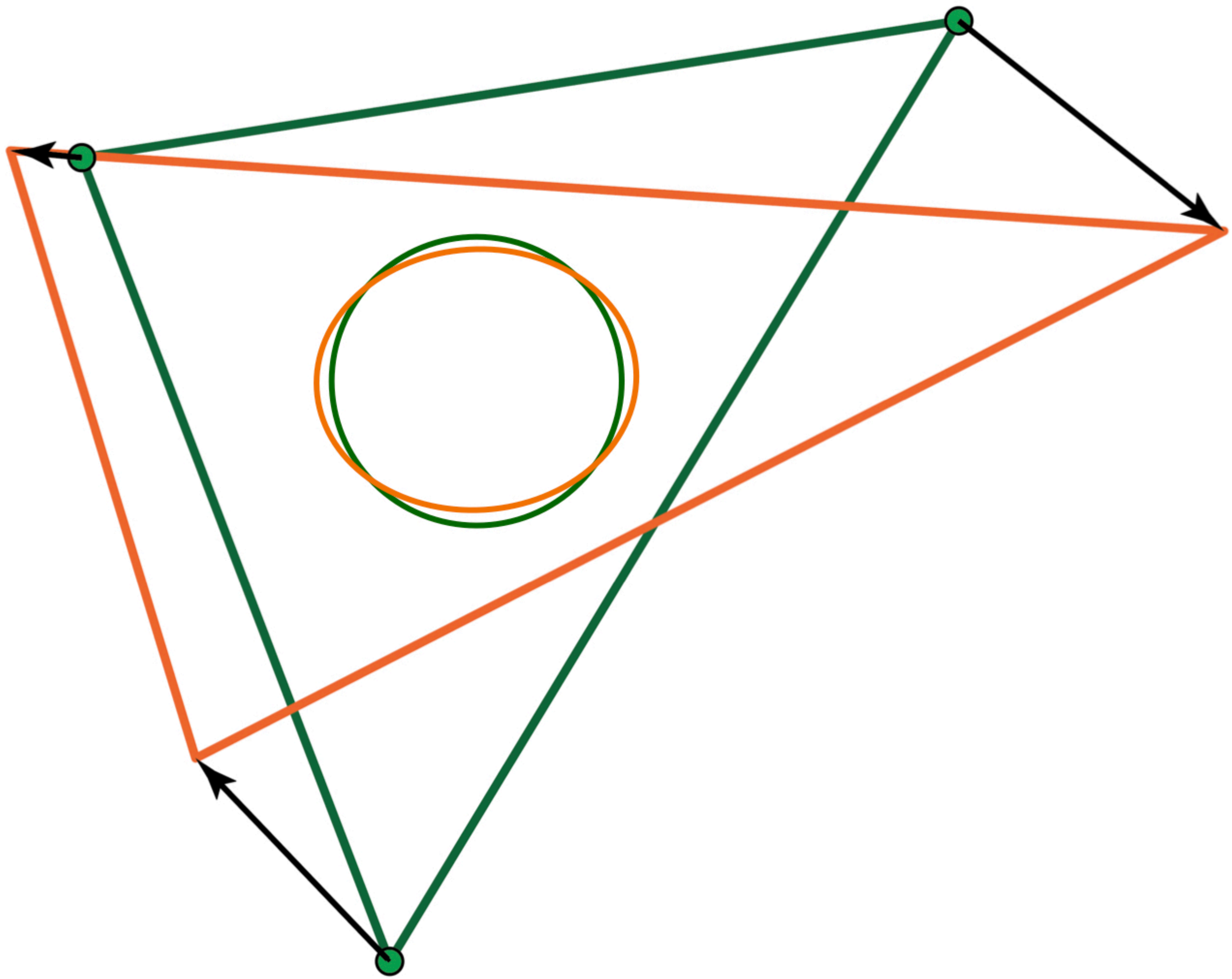
September 9, 2012

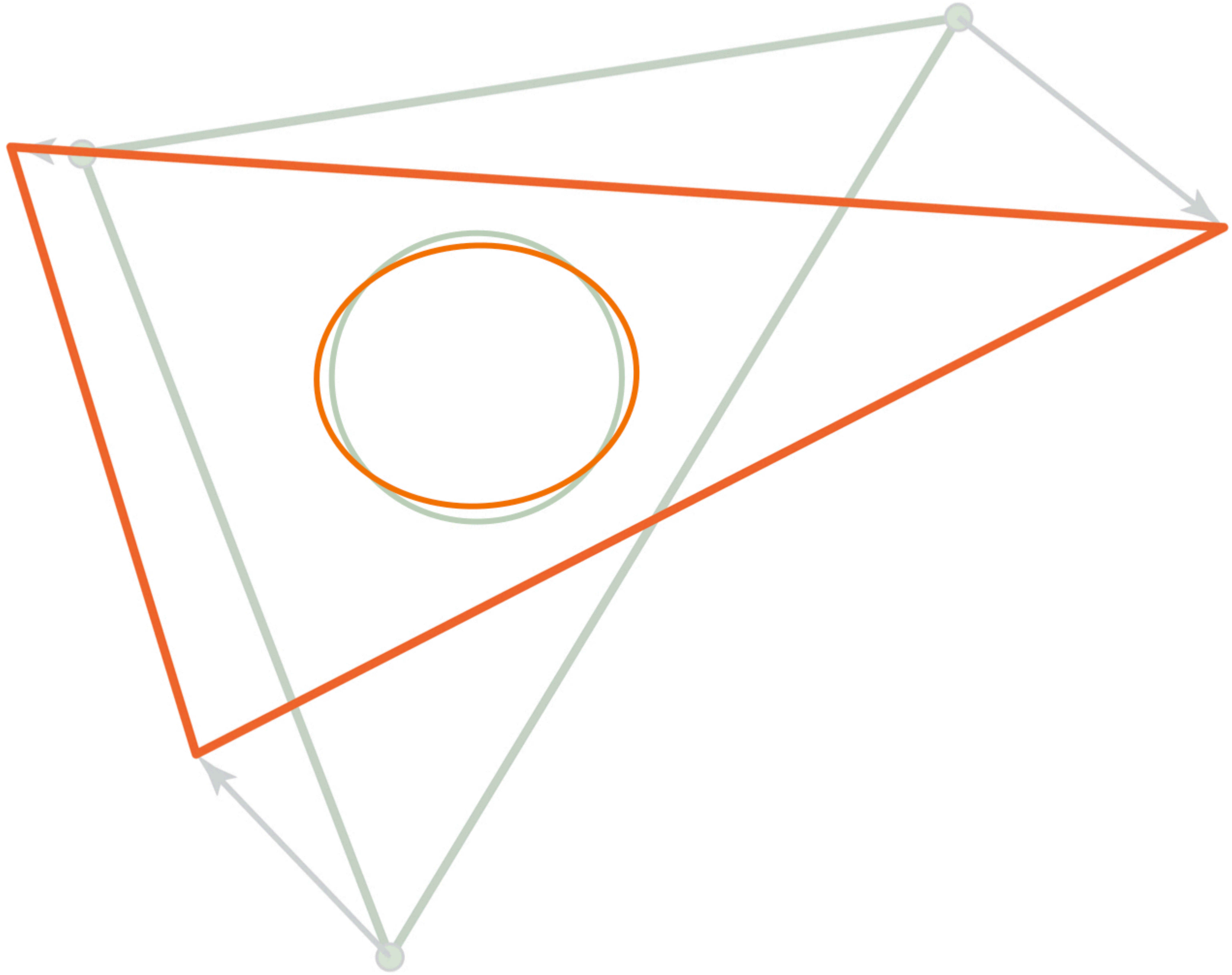

Lancaster
Palmdale
Victorville
Apple Valley
Hesperia
Angeles National Forest
5
San Bernardino
10
Los Angeles
Riverside
10
Anaheim
15
Palm Springs
Long Beach
Irvine
Palm De
Temecula
Catalina Island Essential Fish Habitat...
15
Cleveland National Forest
Vista

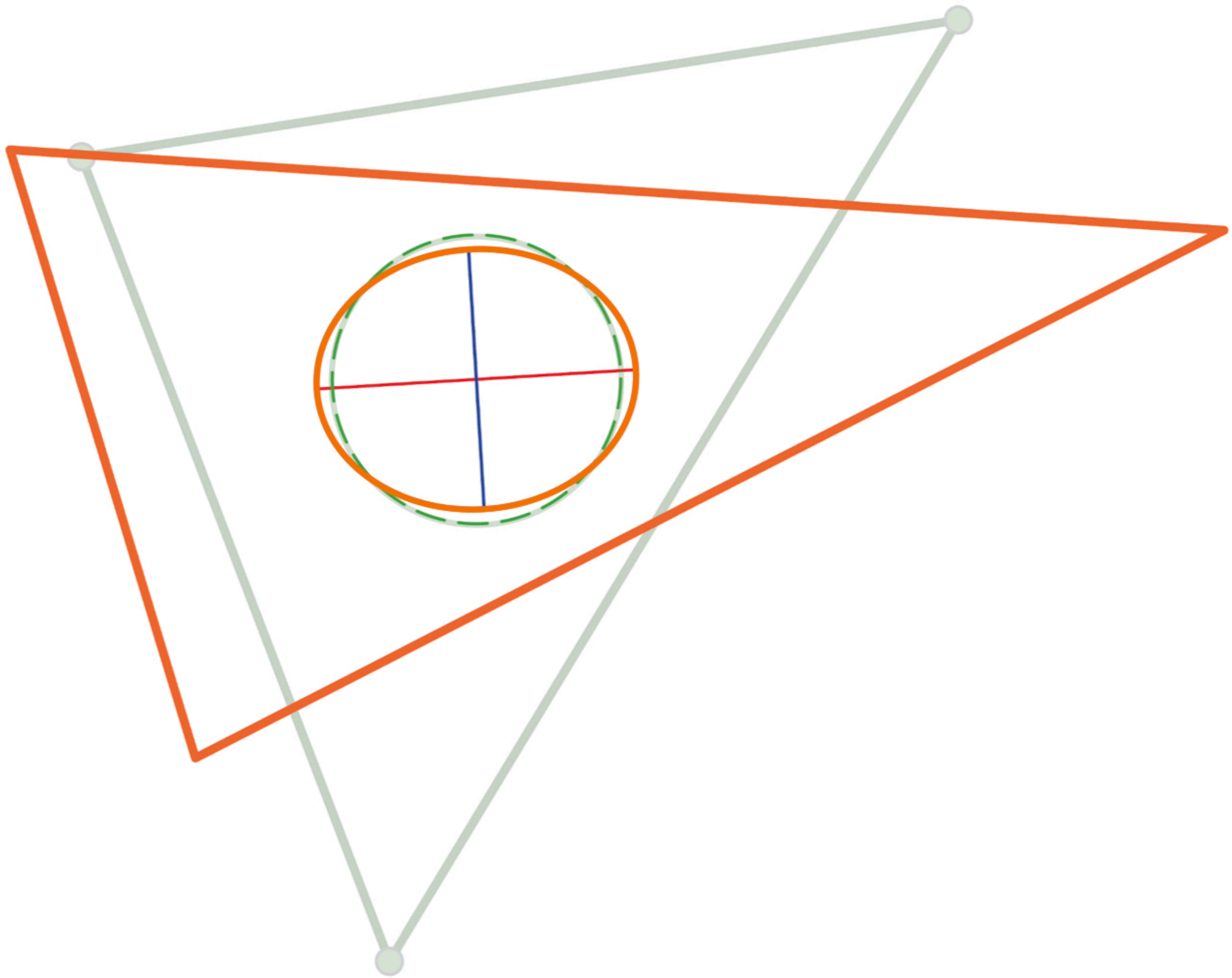


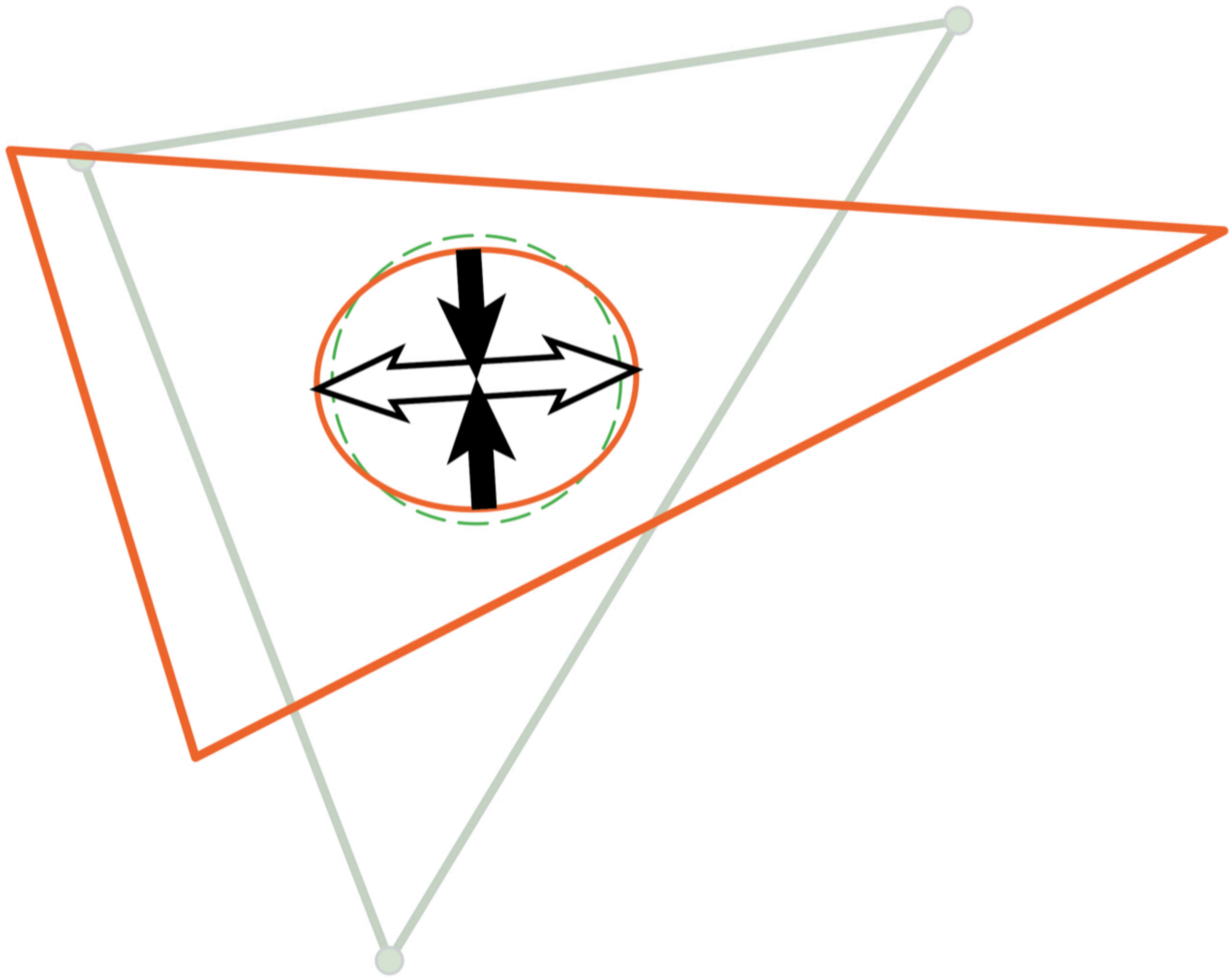


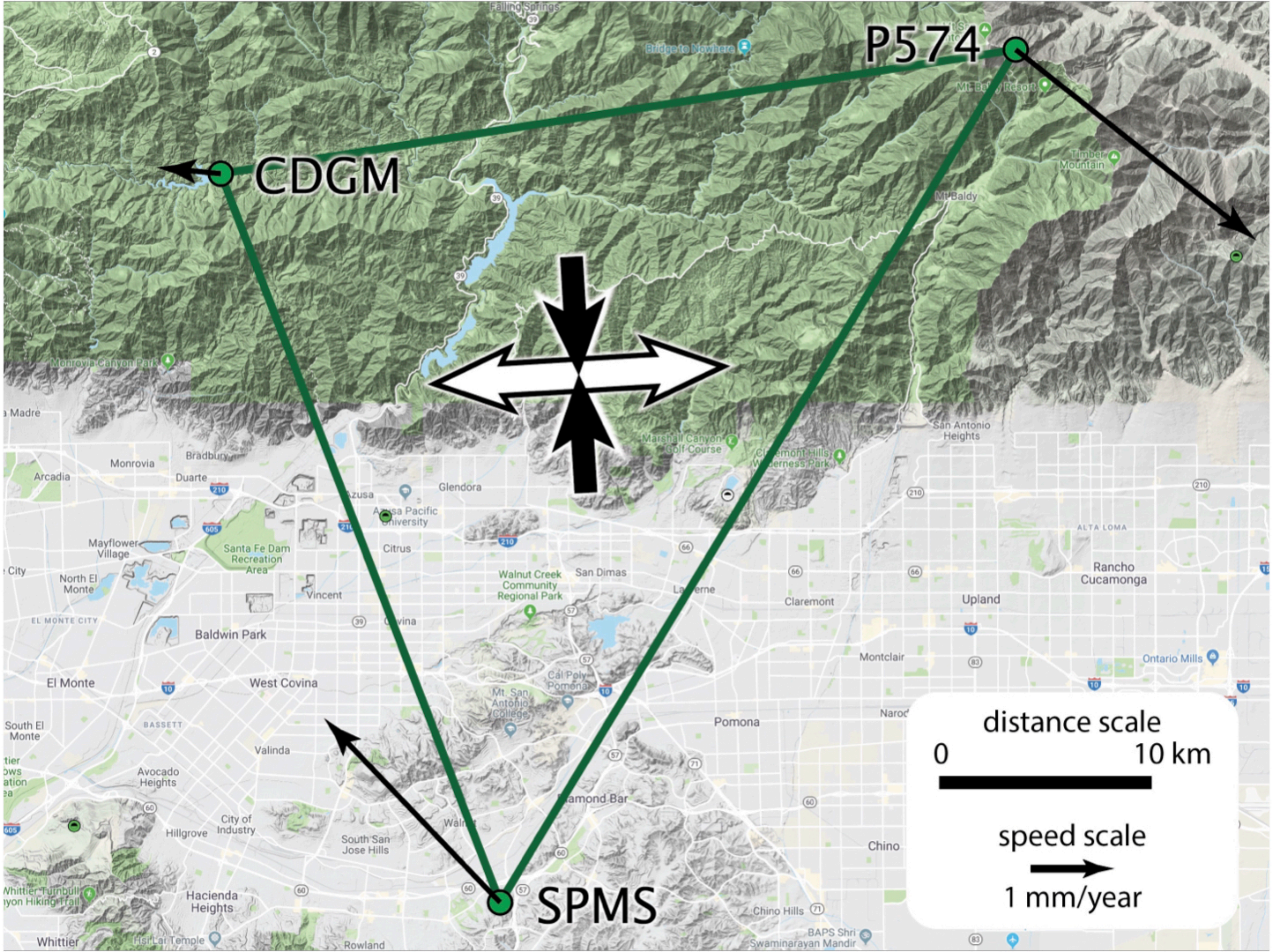


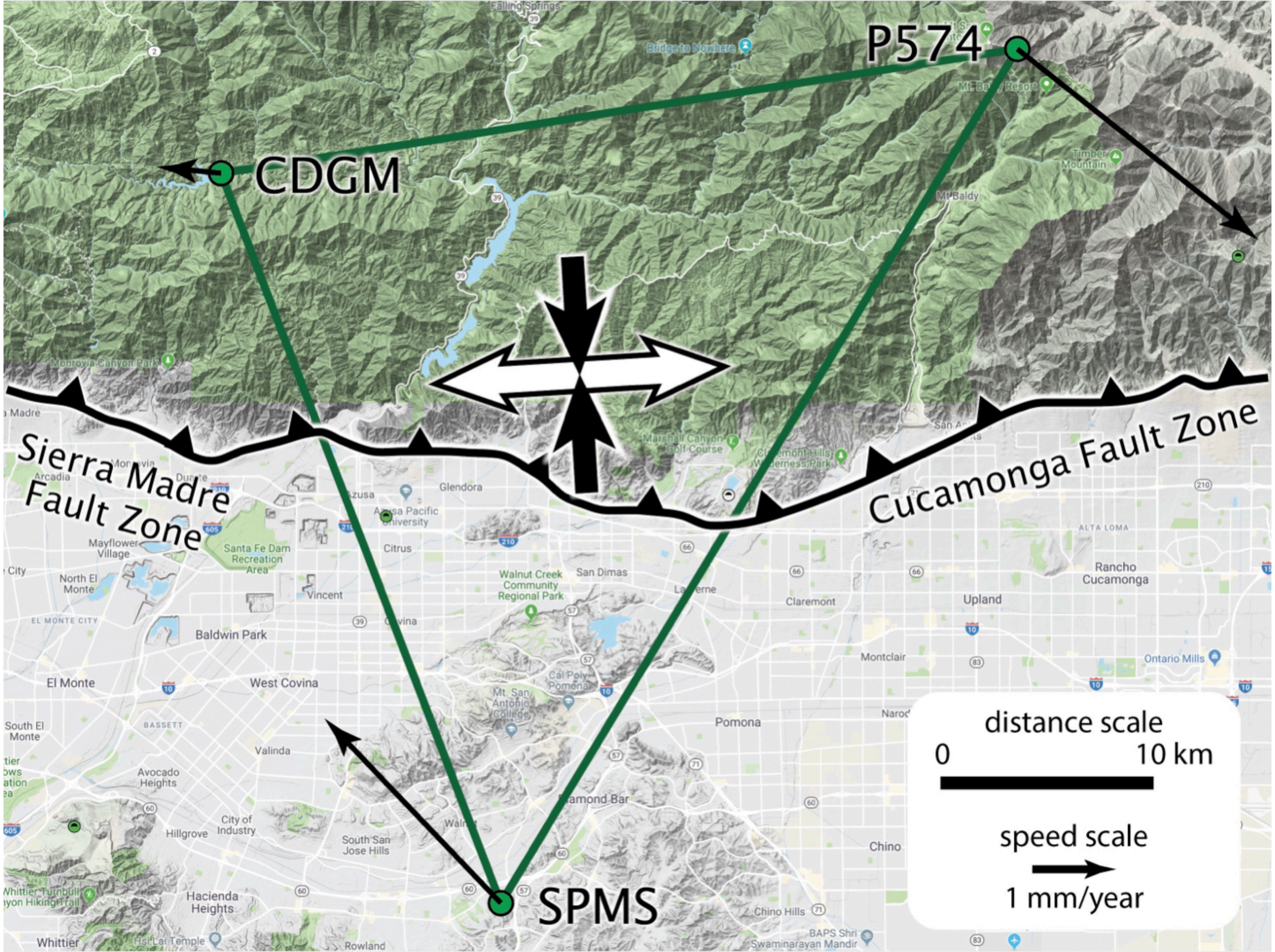


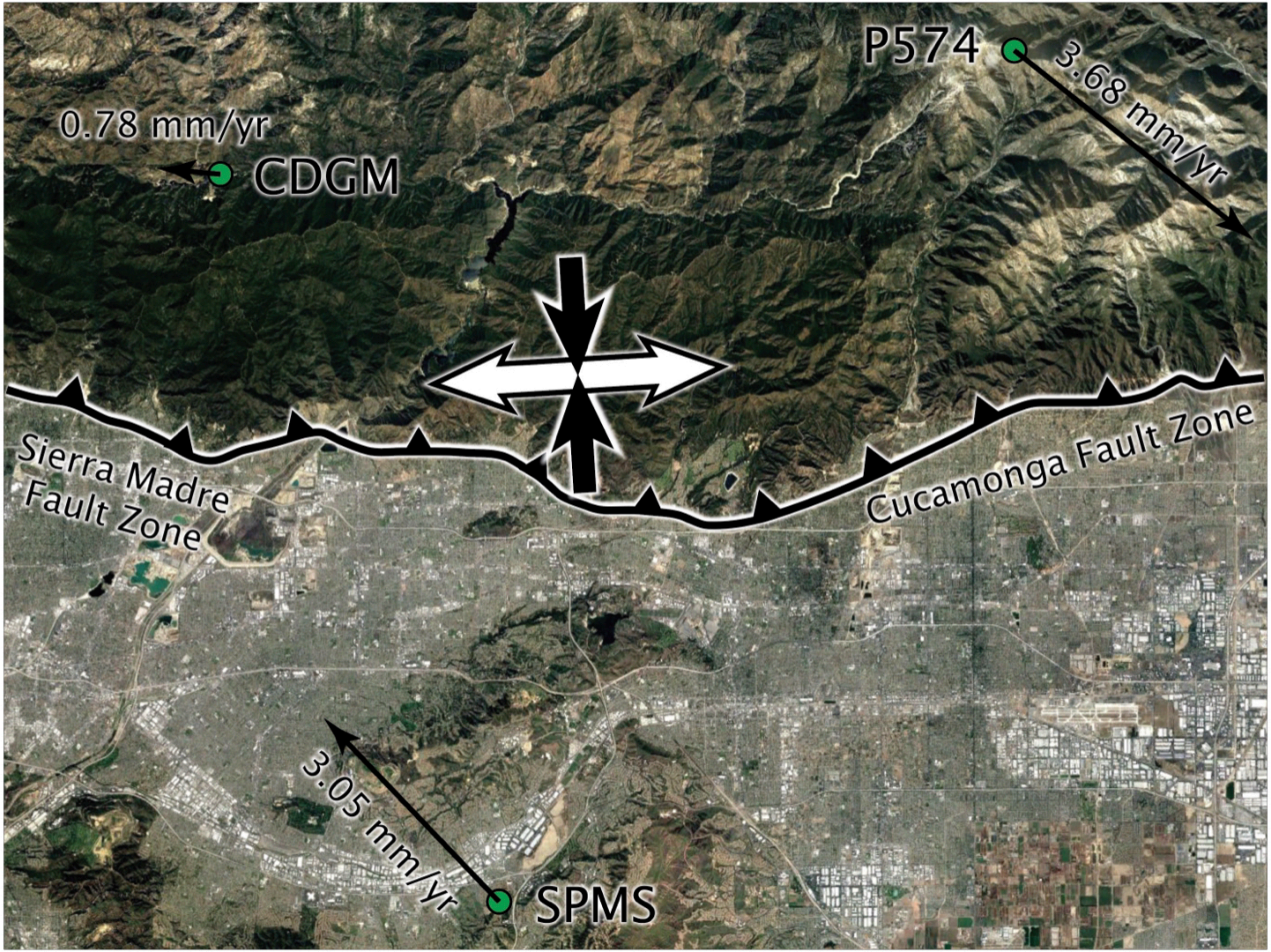






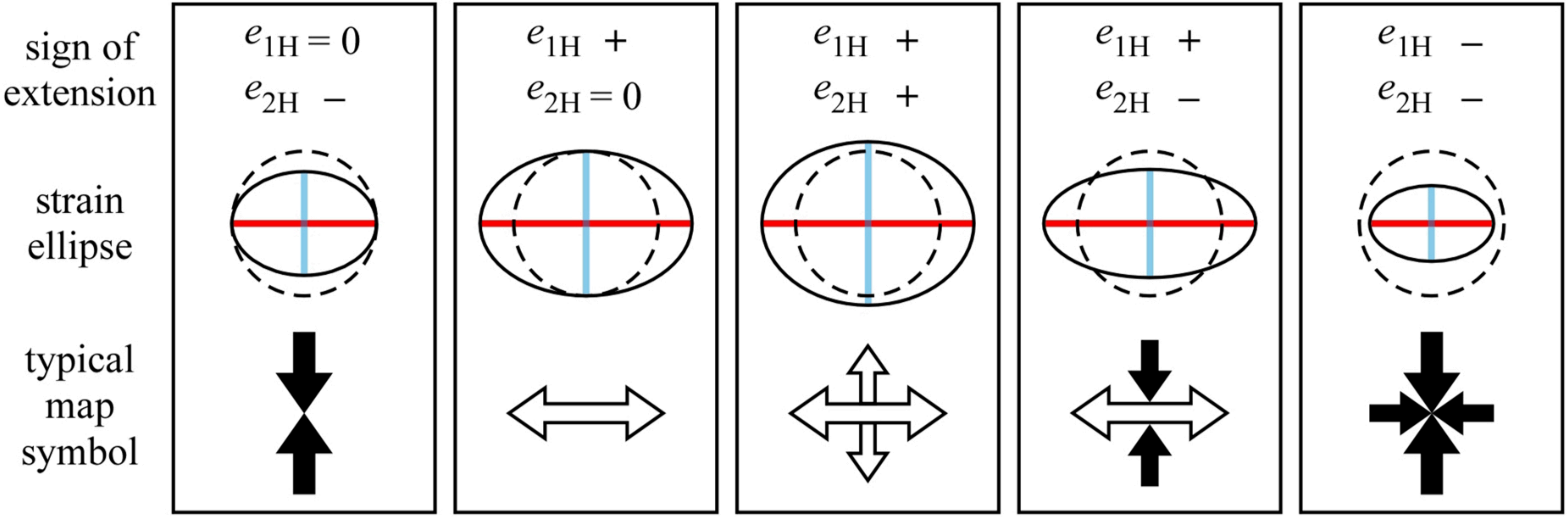

P574
CDGM
SPMS
distance scale
0
10 km
speed scale
1 mm/year

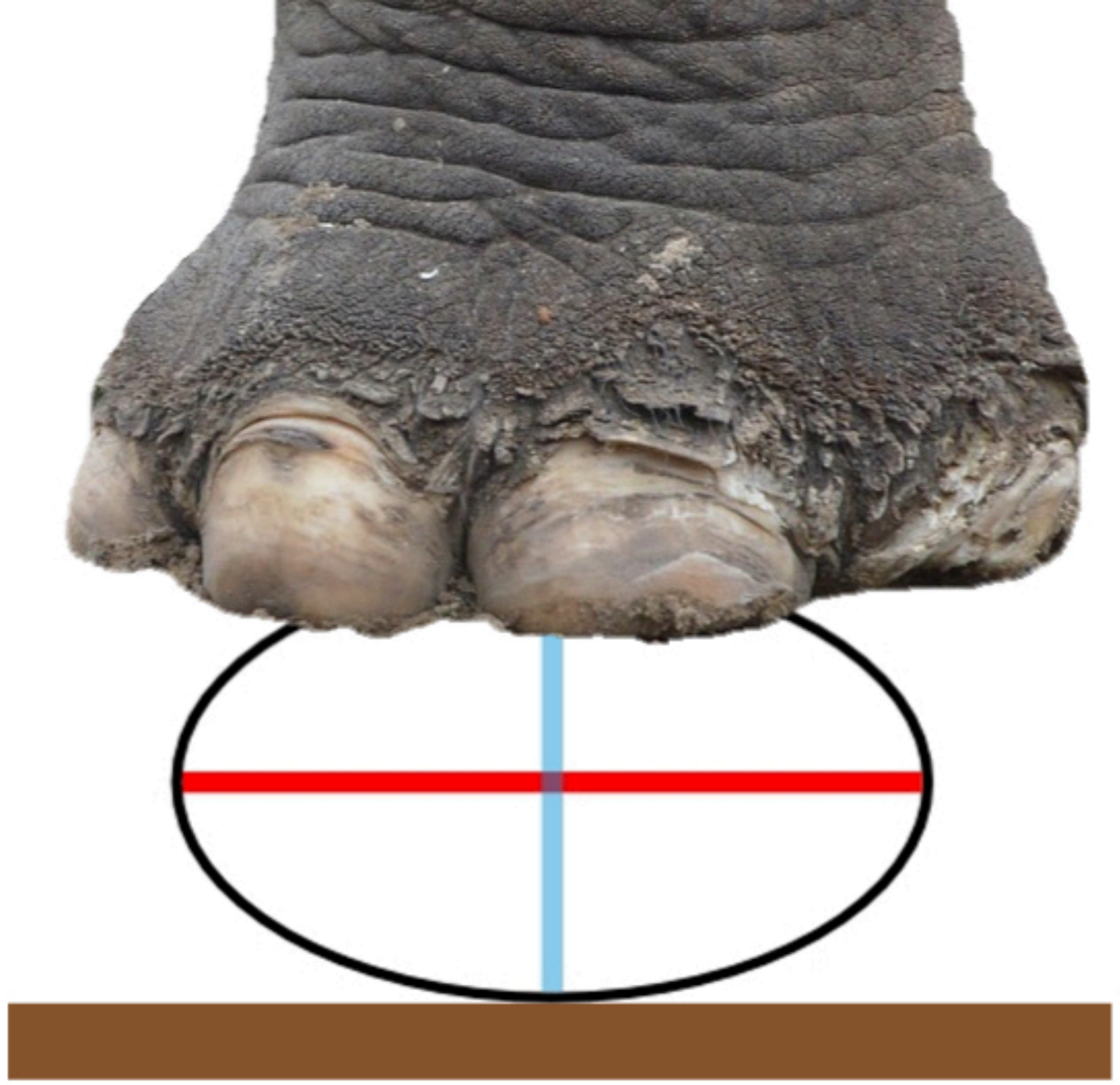

P574
CDGM
SPMS
Sierra Madre
Fault Zone
Cucamonga Fault Zone
distance scale
0
10 km
speed scale
1 mm/year

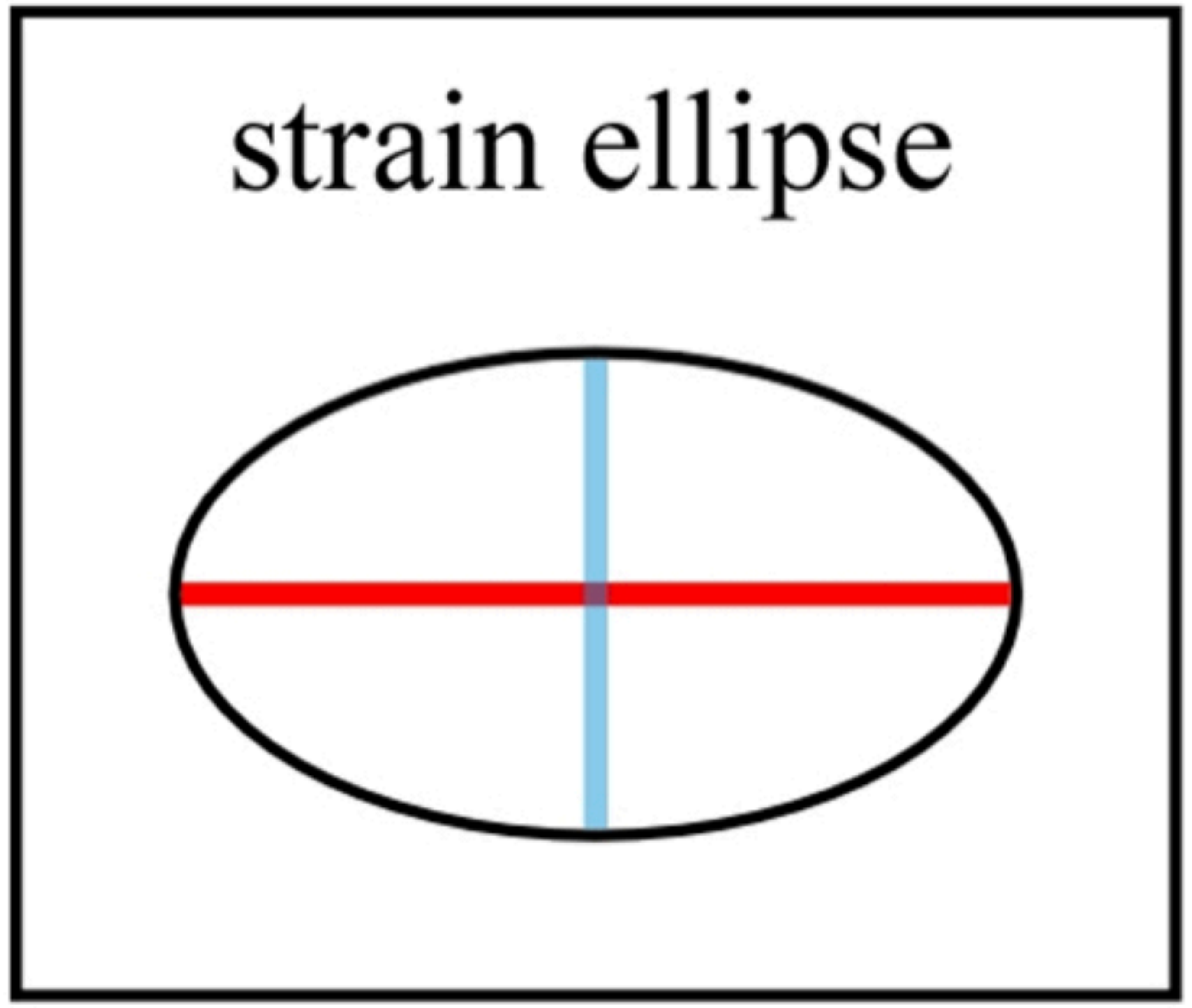

P574
3.68 mm/yr
0.78 mm/yr
CDGM
Sierra Madre
Fault Zone
Cucamonga Fault Zone
3.05 mm/yr
SPMS

How to visualize a strain ellipse (more or less)

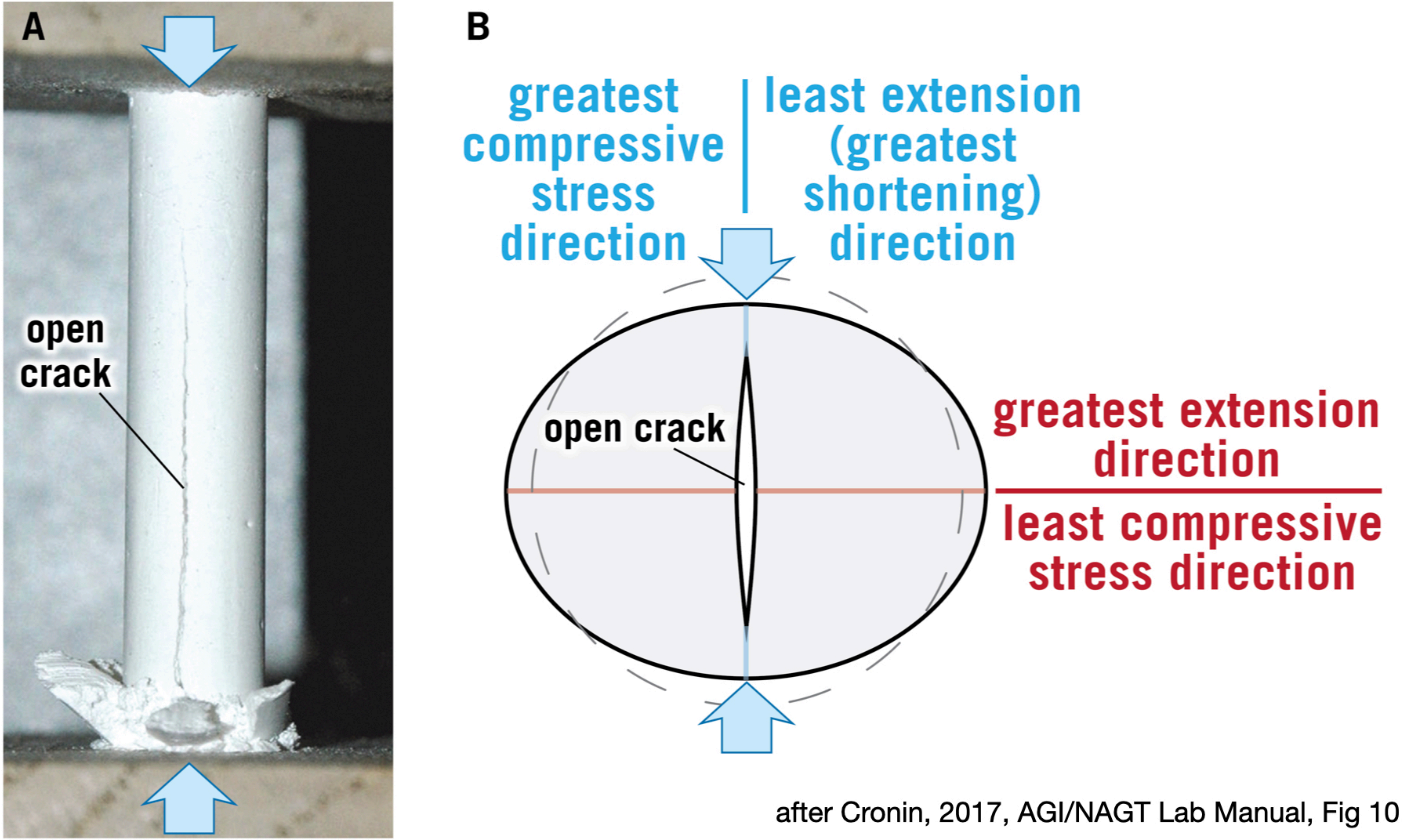
The dashed circle in the illustrations below is the unstrained shape. The extension (e) is zero along an axis if that axis is the same length as the unstrained circle's radius. If the strain axis is longer than the circle's radius, e is positive.







Map views of fault trends that might be associated with this horizontal strain ellipse

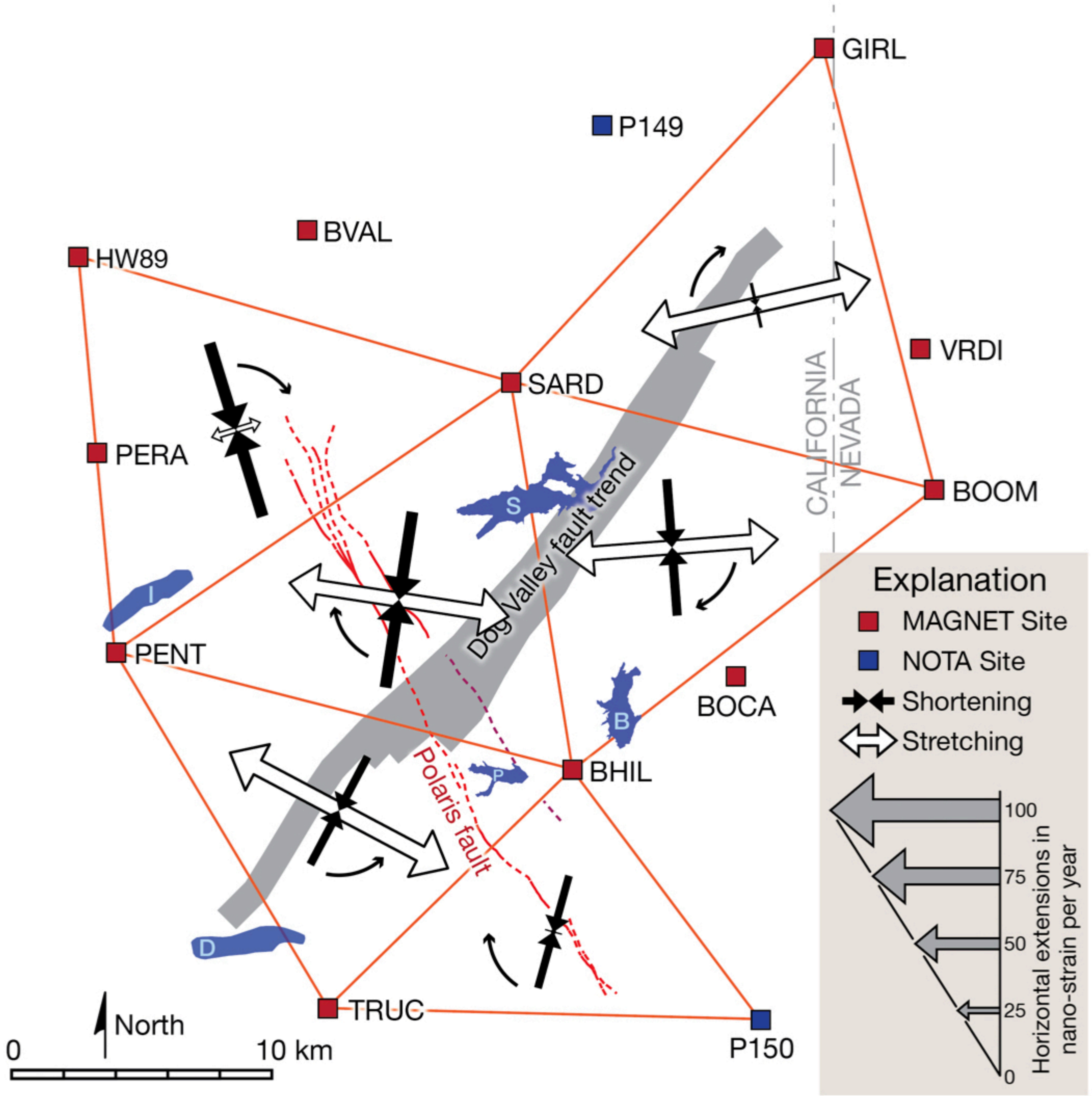


after Cronin, 2017, AGI/NAGT Lab Manual, Fig 10.7

Regional joint set at Zion National Park, Utah.

NASA Landsat 8 Operational Land Imager scene

https://earthobservatory.nasa.gov/IOTD/view.php?id=88228



Graphic depiction of crustal strain computed from GNSS/ GPS site velocity data near the Dog Valley fault zone, Truckee area, California

Hobart, C., 2021, Selecting Locations for Future Geophysical Surveys in Search of the Dog Valley Fault Using Earthquake, LiDAR, and GPS Data: M.S. Thesis, Baylor University, 89 p.

Geodetic Station Used in Model
Tensor Style
Contractional
Strike-Slip
Extensional
RL
Likely N.L.C. Orient.
Other N.L.C. Orient.
LL
Principal Strain Rate Axes
(normalized to largest abs. value)
Black = Contractional
White = Extentional
2nd Invariant ($10^{-9}yr^{-1}$)
0
4
16
64
256
1024
41°
40°
39°
38°
37°
Tahoe
San Francisco
Kreemer, Blewitt, and Elliot, 2014


Tahoe