

Where on Earth



“That’s the cutting edge driver of ITRF accuracy, to monitor sea level change.”

Jim Ray
National Geodetic Survey

by Jane Beitler

For as long as humans have trod the Earth, they have wanted to know just where they are along the way. Landmarks and coastlines first helped people sight their way, but mathematics made it possible to cross faceless deserts and oceans, and get home again. We have become so skilled at determining our position that we dared to explore

the vastness of space, and created technologies like Global Positioning System (GPS) devices to guide ordinary people on their rambles.

Those devices are extremely accurate because of a set of reference points, forming the International Terrestrial Reference Frame (ITRF), and an incredibly sophisticated math- and physics-based system of measurements behind it.



U.S. Navy officer Jonathan Myers explains to his colleague April Beldo how to use a marine sextant during a demonstration of celestial navigation. (Photography by T. K. Mendoza courtesy U.S. Navy)

It took a lot of knowledge to get this far, but scientists are not finished. They are still tuning their measurements to drive out the tiniest errors. But how and why?

Earth's geometry

Two thousand years ago, an Arab mariner sailed his dhow out of sight of land without GPS, compass, or sextant to judge his position. But he knew a little geometry. He measured the distance between the horizon and Polaris, the Pole Star, by holding up his thumb against the night sky. This told him his north or south position on Earth—what we call latitude. He could sail north or south until it matched the latitude of his port, then right or left as needed, keeping Polaris at the same height in the sky all the time.

While the ancient mariner was satisfied to get within sight of port, today's sailors, aviators, space agencies, engineers, and scientists require more accuracy that is not subject to clouds or pitching ship decks. Measurement technologies today may triangulate with a satellite, which in turn is calibrated against the ITRF, a set of very accurate reference points around the Earth that have been measured using lasers, satellites, and telescopes.

The Earth that your GPS sees is theoretical and needs constant syncing with the real one. On paper, latitude and longitude divide the Earth's sphere neatly into uniform minutes and seconds. But Earth is not quite round. It is slightly flattened at the poles. Like a sailor bobbing on the waves, we too are bobbing on Earth's surface. Earth rotates, wobbles, and shifts its crust, introducing a real-time element into the calculation of position.

An imaginary Earth

Earth's crust moves sometimes imperceptibly, sometimes violently during earthquakes. The crust is still slowly uncompressing itself after being squashed under the weight of thick ice sheets during the Ice Ages, a process called glacial rebound. The crust can move by meters or by a few millimeters, but enough to frustrate precision.

For all these reasons, scientists use a theoretical sphere, defined by where sea level would be if the Earth were perfectly round. In theory, gravity makes the sea level by pulling on it equally everywhere, so gravity is a good substitute for sea level. Altimeters calculate altitude as a function of gravity. But if you ran an altimeter all over Earth and plotted out all the points of equal gravity, instead of getting an ideal sphere, you would get something lumpy and irregular, like a potato. Scientists call this potato the geoid.

It turns out that gravity is not equal over the same distance from the center of the Earth. Large lakes, seas, and aquifers and certain types of rock can affect gravity. Tides and winds can push ocean waters around and change gravity. So scientists pinned measurements to Earth's rotation axis. But that turned out to be a slippery problem, too.

Earth's axis is a theoretical location, but its physical center of mass is of great importance to scientists. Like an out of balance washing machine, Earth wobbles when its crust, the atmosphere, or the ocean get slightly redistributed by plate tectonics, winds, or tsunamis, for example. National Oceanic and Atmospheric Administration researcher Jim Ray, who analyzes data for GPS satellites, said, "This is one of the weaknesses in GPS data. It's challenging to know where the center of mass for Earth is at any moment, any day."

Space science

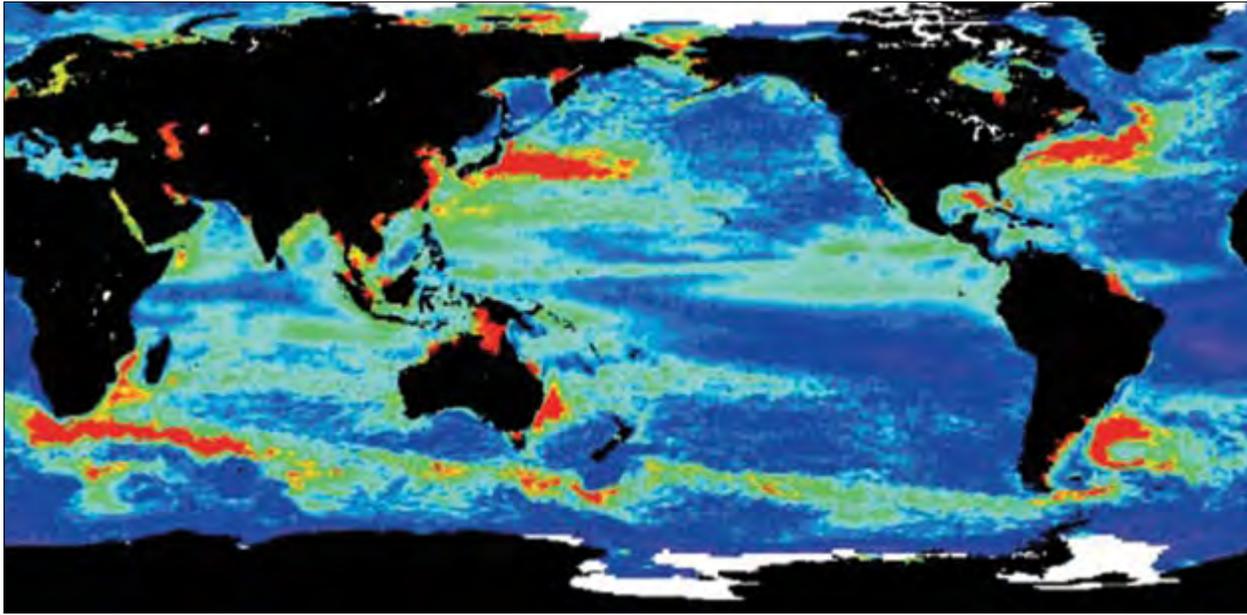
Scientists look for ways to overcome measurement problems such as these. They seek more stable points to measure against, or they measure a point several ways, and compare the measurements to help calibrate out the errors. Networks of ground stations pepper the Earth, using satellites and telescopes, radio waves and laser beams to measure position. None of the methods are perfect, but together they increase accuracy, especially when the different technologies are located side by side.

Two of these technologies make Earth-based measurements: the French Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS) network, and GPS receivers on the ground. These instruments constantly measure an Earth-based triangle using Earth's axis, a receiver or transmitter on the satellite, and a receiver or transmitter on the ground.

GPS has the advantage of being almost everywhere. Research-quality GPS receivers are also fairly inexpensive, and have many research applications besides navigation. "There are some tens of thousands of continuously operating GPS reference stations around the world," Ray said. "We use data from the best-controlled stations, about 400. GPS is the contributing technique par excellence in terms of precision."

Measure four times, cut once

GPS stations, however, get errors from being attached to Earth's crust, when the crust shifts, sinks, or bulges. Earth's imperfect rotation also introduces a miniscule distortion of time into GPS accuracy. So space-based techniques help balance out Earth-based measurements. Very Long Baseline Interferometry (VLBI) aims a



This image shows anomalies in sea level, from October 1992 to October 1997, combining data from the European Remote Sensing (ERS) satellite and the joint NASA/French Space Agency Ocean Topography Experiment (TOPEX)/Poseidon satellite. Greens, yellows, and reds indicate greater anomalies. (Courtesy European Space Agency)

radio telescope at very distant quasars. The quasars, extra-galactic objects, are so far away that their movement in space does not matter. For practical purposes, it is as if they are fixed points.

VLBI can lose some precision as radio signals sometimes get bent passing through the Earth's atmosphere. GPS calculations help adjust for those errors.

Satellite Laser Ranging (SLR), which bounces a laser beam off a small, very heavy and passive satellite, helps calibrate errors out in the other sources. Ray said, "GPS satellites are very large, unwieldy things, with large solar panels that can cause wobble. This random, minute-to-minute motion is hard to monitor. SLR satellites are very simple, like little bowling balls covered with mirrors."

No fixed position

Calibration also needs to account for how Earth's crust may be moving underneath a specific instrument site. Some crustal activity can be estimated. Zuheir Altamimi is research director at the Laboratoire de Recherche en Géodésie (LAREG) in France, which maintains the ITRF. He is one of many researchers around the world who help tune the system of reference points. He said, "We can compare the vertical and horizontal motion of instrument sites with geophysical models, such as post-glacial rebound models, and models that describe the tectonic motion of the plates." Other crustal activity may be erratic. "Many sites that are near the epicenters of earthquakes exhibit non-linear motion, which is hard to model accurately by mathematical equations," Altamimi explained.

As well, at a multi-instrument site, the distances between the various instruments have to be accurately known when comparing measurements, and combining them together to build the ITRF. So these sites are physically surveyed by terrestrial measurements that are then compared to measurements by space techniques.

Rising seas

Position measurements are now accurate enough for most navigation uses. More accuracy is interesting mainly to scientists studying the Earth. For example, the ITRF can help track the exact rate of global sea level rise, which is increasing because of glacier and ice sheet melting. "This question is hard to answer, because there are so many error sources in the measurements," said Altamimi.

Ray said, "That's the cutting-edge driver of ITRF accuracy, to monitor sea level change. ITRF does not actually allow you to measure sea level change, but it is the underlying structure that allows measurement systems like altimetry to do the job." Altimeters bounce radar signals off the ocean surface, but those altimetry measurements depend on a measurement frame centered at Earth's center of mass. "That only makes sense if you have a really high accuracy ITRF," Ray said.

Sea level rise will be a hard-felt impact of climate warming. The changes each year are small, but over time rising seas can inundate low-lying areas where millions of people work and live. Tide gauge records over the last century estimate an average of 1.7 millimeters of sea level rise per year, while satellite altimetry data, which have a more global coverage but cover only the most recent decades, estimate 3.4 millimeters. So scientists ask if sea level rise is accelerating and

About the remote sensing data used				
Techniques	Global Navigation Satellite System (GNSS)	Satellite Laser Ranging (SLR)	Very Long Baseline Interferometry (VLBI)	Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS)
Satellites	Global Positioning System (GPS) and other Global Navigation Satellite Systems	LAGEOS-1 and 2, Etalon-1 and -2		TOPEX/Poseidon, Jason-1 and -2, Envisat, Cryosat-2, HY-2A, and SPOT-2, -3, -4, and -5
Ground Instruments	~400 GNSS reference receivers	~40 Laser Ranging systems	~40 radiotelescopes	~60 radio beacons
DAACs	NASA Crustal Dynamics Data Information System (CDDIS)			

if that can be reliably measured. “For this problem, we need a really high accuracy ITRF, one that is stable over decades,” Ray said.

The ITRF 2014

Researchers are busy on the next version of the ITRF, planned for release in 2014. Detailed surveys of the ITRF instrument sites are high on the list of ways to drive errors out of the measurements. The ITRF researchers can test their methods with an archive of data from the four measurement methods at the NASA Crustal Dynamics Data Information System (CDDIS). These archived data help them model the effects of various improvements to the instruments, the sites, or the data analyses.

Altamimi said, “When we started to construct the first reference frame that combined different techniques, in 1985, at that time the precision was at the decimeter level. Now it is reaching a few millimeters.” The goal for the next version of the ITRF is an accuracy approaching the science requirement: 1 millimeter of average error, and 0.1 millimeter per year of instability. “It is a small number, but it has an impact,” Altamimi said.

About the scientists



Zuheir Altamimi is research director at the Laboratoire de Recherche en Géodésie (LAREG) in France. His work focuses on geodesy, and theories and applications of terrestrial reference systems. The Institut National de L’Information Géographique et Forestiere supports his research. (Photograph courtesy LAREG)



Jim Ray is a geodesist in the Geosciences Research Division of the National Geodetic Survey, where he works on GPS data analysis. He was previously the Analysis Center coordinator for the International GNSS Service (IGS) and the head of the Earth Orientation Department at the U.S. Naval Observatory. The National Oceanic and Atmospheric Administration supports his research. (Photograph courtesy J. Ray)

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Reference

Altamimi, Z., X. Collilieux, and L. Métivier. 2011. ITRF 2008: an improved solution of the International Terrestrial Reference Frame. *Journal of Geodesy* 85: 457–473, doi:10.1007/s00190-011-0444-4.

For more information

NASA Crustal Dynamics Data Information System (CDDIS)
<http://cddis.nasa.gov>
 The International Terrestrial Reference Frame (ITRF)
<http://itrf.ensg.ign.fr>
 Laboratoire de Recherche en Géodésie (LAREG)
<http://recherche.ign.fr/labs/lareg/page.php>
 Sea Level Rise and Coastal Flooding Impacts Viewer
<http://csc.noaa.gov/digitalcoast/tools/slrviewer>