Mapping the Earth: Radars and Topography

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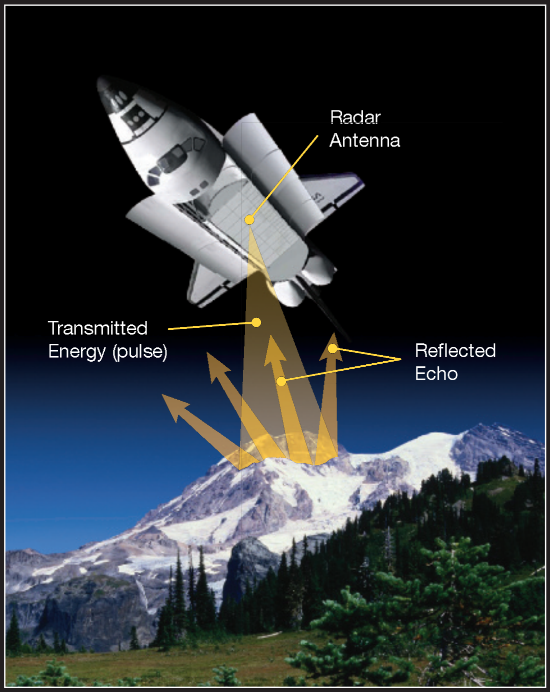
One of the Space Shuttle's enduring science legacies is the near-global topographic mapping of the Earth with innovative radar remote sensing technologies. The shuttle also served as an important engineering test bed for developing the radar-based mapping technologies that have ushered in a quiet revolution in mapping sciences. The Shuttle Radar Topography Mission data set, in particular, has had an enormous impact on countless scientific endeavors and continues to find new applications that impact lives. This mission helped create the first-ever global high-resolution data for Earth topography—a data set for the ages. On average, one Shuttle Radar Topography Mission-derived topographic data set is downloaded from the US Geological Survey's servers every second of every day—a truly impressive record. Experts believe the mission achieved what conventional human mapmaking was unable to accomplish—the ability to generate uniform resolution, uniform accuracy elevation information for most of the Earth's surface.

In all, the development of imaging radars using the shuttle demonstrated, in dramatic fashion, the synergy possible between human and robotic space operations. Radar remote sensing technology advanced by leaps and bounds, thanks to the five shuttle flights, while producing spectacular science results.

“Seeing” Through the Clouds

What Is Imaging Radar?



How does radar work? A radar transmits a pulse, then measures the reflected echo.

The term radar stands for Radio Detection and Ranging. You have seen radar images of weather patterns on television. Typical radar works like a flash camera, so it can operate day or night. But, instead of a lens and a film, radar uses an antenna to send out energy (“illumination”) and computer tapes to record the reflected “echoes” of pulses of “light” that comprise its image. Radar wavelengths are much longer than those of visible light so it can “see” through clouds, dust, haze, etc. Radar antenna alternately transmits and receives pulses at a particular microwave wavelength (range of 1 cm [0.4 in.] to several meters [feet]). Typical imaging radar systems transmit around 1,500 high-power pulses per second toward the area or surface to be imaged.

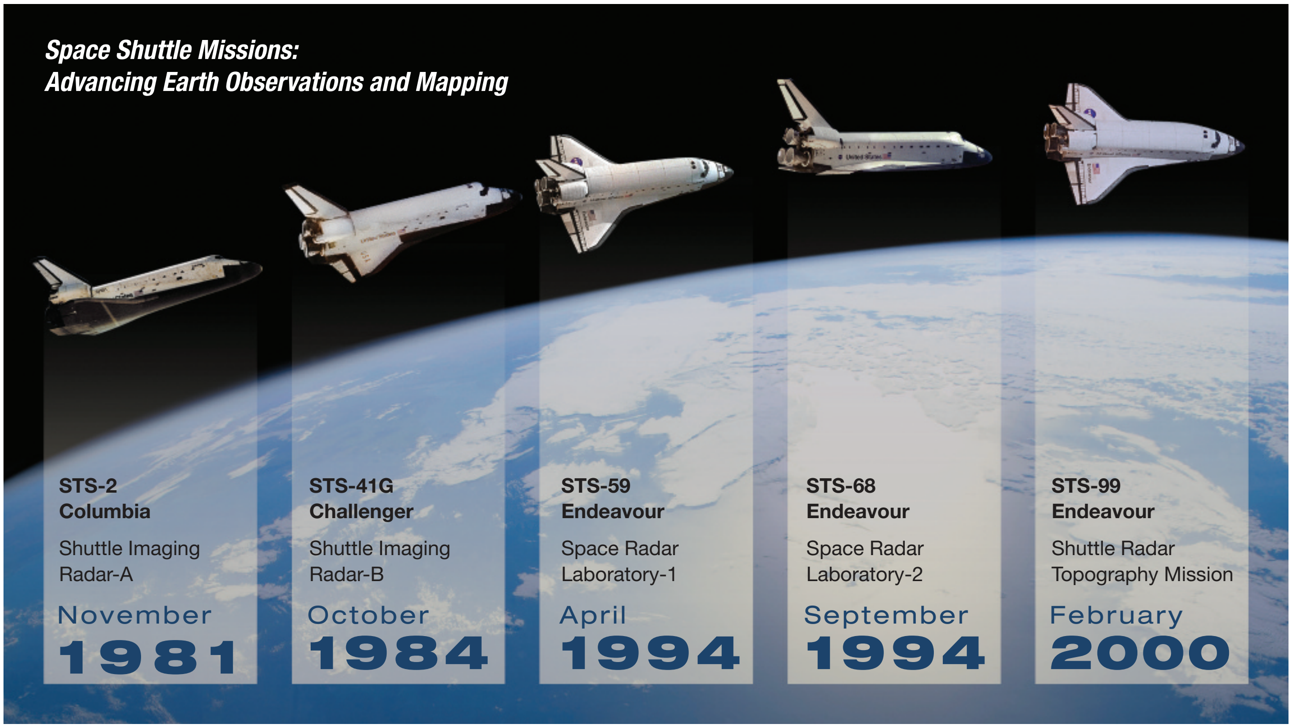
What Is Synthetic Aperture Radar?

When a radar is moving along a track, it is possible to combine the echoes received at various positions to create a sort of “radar hologram” that can be further processed into an image. The improved resolution that results would normally require a much larger antenna, or aperture, thus a “synthetic aperture” is created.

Why Do We Need Accurate Topographic Maps of the Earth?

If you have ever used a global positioning system for navigation, you know the value of accurate maps. But, have you ever wondered how accurate the height of Mount Everest is on a map or how its height was determined? One of the foundations of many science disciplines and their applications to societal issues is accurate knowledge of the Earth’s surface, including its topography. Accurate elevation maps have numerous common and easily understood civil and military applications, like locating sites for communications towers and ground collision avoidance systems for aircraft. They are also helpful in planning for floods, volcanic eruptions, and other natural disasters, and even predicting the viewscape for a planned scenic highway or trail.

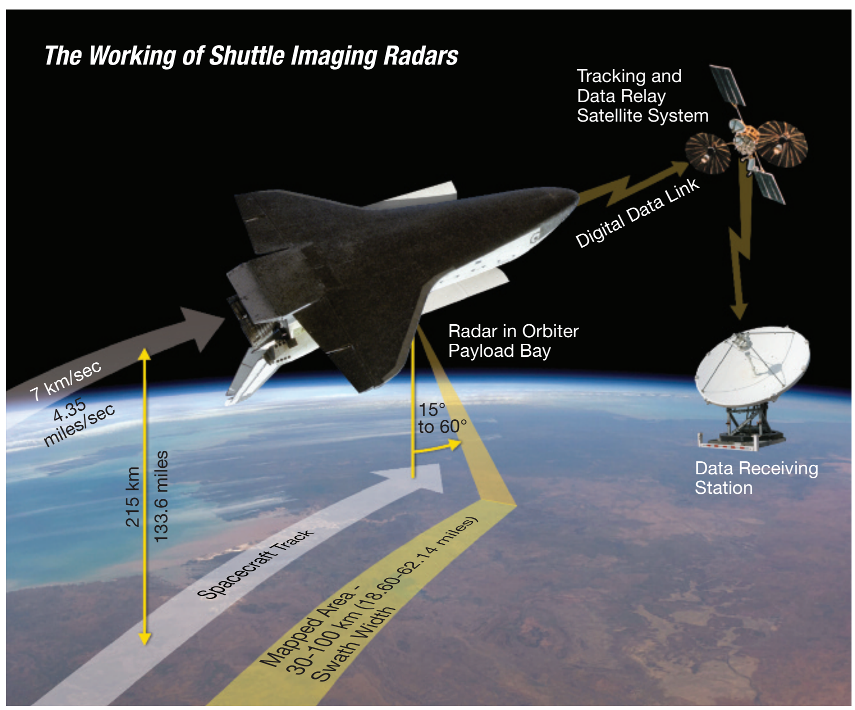
It is hard to imagine that the global topographic data sets through the end of the 20th century were quite limited. Many countries created and maintained national mapping databases, but these databases varied in quality, resolution, and accuracy. Most did not even use a common elevation reference so they could not be easily combined into a more global map. Space Shuttle radar missions significantly advanced the science of Earth mapping.



Shuttle and Imaging Radars—A Quiet Revolution in Earth Mapping

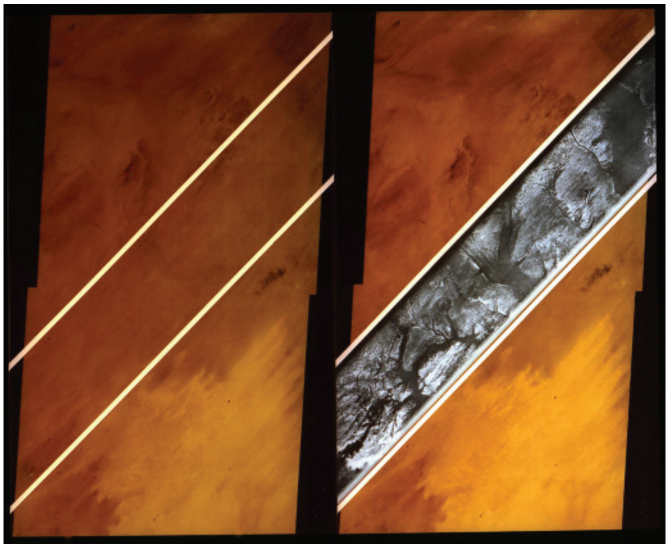
The First Mission

The Shuttle Imaging Radar-A flew on Space Shuttle Columbia (Space Transportation System [STS]-2) in November 1981. This radar was comprised of a single-frequency, single-polarization (L-band wavelength, approximately 24-cm [9-in.]) system with an antenna capable of acquiring imagery at a fixed angle and a data recorder that used optical film. Shuttle Imaging Radar-A worked perfectly, and the radar acquired images covering approximately 10 million km² (4 million miles²) from regions with surface covers ranging from tropical



Space Shuttle's track at the altitude of 215 km (134 miles) with changing radar antenna look angle allowed the mapping of swaths up to 100 km (62 miles) wide.

forests in the Amazon and Indonesia to the completely arid deserts of North Africa and Saudi Arabia. Analysts found the data to be particularly useful in geologic structure mapping, revealing features like lineaments, faults, fractures, domes, layered rocks, and outcrops. There were even land-use applications since radar is sensitive to changes in small-scale roughness, surface vegetation, and human-made structures. Urban regions backscatter strongly, either because the walls of buildings form corner reflectors with the surface or because of the abundance of metallic structures—or both.



Left: *Optical view of the Sahara region (Africa) showing the vast, featureless expanse of sand. The white lines depict the radar flight path.*

Right: *Radar imagery over the same region, taken during STS-2 (1981), reveals the network of channels and dried-up rivers (radar rivers) beneath the sand sheets, thereby illustrating the power of radar for archeological mapping.*

The Shuttle Imaging Radar-A's most important discovery, however, resulted from a malfunction. STS-2 was planned as a 5-day excursion and the payload operators generated an imaging schedule to optimize use of the radar's 8-hour supply of film. But early on, one of the three Orbiter fuel cells failed, which by mission rules dictated a minimum-duration flight—in this case, a bit over 2 days. So, the operators quickly retooled the plan to use the film in that time frame and ended up running the system whenever the Orbiter was over land. The result was a number of additional unplanned image passes over Northern Africa, including the hyper-arid regions of the Eastern Sahara.

"Radar Rivers" Uncovered

This Sahara region, particularly the Selima Sand Sheet straddling the Egypt/Sudan border, is one of the driest places on our planet. Photographs from orbit show nothing but vast, featureless expanses of sand, and with good reason. The area gets rain no more than two or three times per century, and rates a 200 on the geological aridity index. For comparison, California's Death Valley—the driest place in the United States—rates no more than a 7 on the geological aridity index.

But when scientists got their first look at the Shuttle Imaging Radar-A images, they said "Hey, where's the sand sheet?" Instead of the expected dark, featureless plain, they saw what looked like a network of rivers and channels that covered virtually all the imaged area and might extend for thousands of kilometers (miles). To everyone's surprise, the radar waves had penetrated 5 or more meters (16 or more feet) of loose, porous sand to reveal the denser rock, gravel, and alluvium marking riverbeds that had dried up and been covered over tens of thousands of years ago.

Scientists knew the Sahara had not always been dry because some 50 million years ago, large mammals roamed its lush savannahs, swamps, and grasslands. Since then, the region has fluctuated between wet and dry, with periods during which rivers carved a complex drainage pattern across the entire Northern part of the continent. The existence of wadis (dry valleys) carved in Egypt's nearby Gilf Kebir Plateau, as well as other geologic evidence, supports this idea.

Subsequent field expeditions and excavations verified the existence of what came to be called the "radar rivers" and even found evidence of human habitation in the somewhat wetter Neolithic period, about 10,000 years ago. This discovery of an evolving environment was a harbinger of current concerns about global climate change, evoking historian Will Durant's statement, "Civilization exists by geological consent, subject to change without notice."

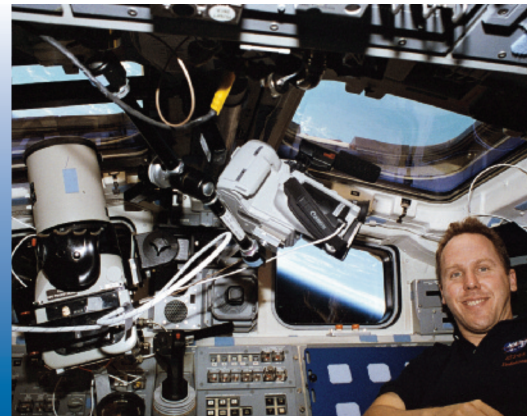
The Second Mission

The Shuttle Imaging Radar-B mission launched October 5, 1984, aboard the Space Shuttle Challenger (STS-41G) for an 8-day mission. This radar, again L-band, was a significant improvement, allowing multi-angle imaging—a capability achieved by using an antenna that could be mechanically tilted. It was also designed as a digital system, recording echo data to a tape recorder on the flight deck for subsequent downlink to the ground but with Shuttle Imaging Radar-A's optical recorder included as a backup. The results, deemed successful, included the cartography and stereo mapping effort that produced early digital-elevation data.

Next Generation of Space Radar Laboratory Missions

The Shuttle Imaging Radar instrument expanded to include both L-band (24 cm [9 in.]) and C-band (6 cm [2 in.]) and, with the inclusion of the German/Italian X-band (3 cm [1 in.]), radar. For the first time, an orbiting radar system not only included three wavelengths, the instrument was also fully polarimetric, capable of acquiring data at both horizontal and vertical polarizations or anything in between. It also used the first "phased-array" antenna, which meant it could be electronically steered to point at any spot on the ground without any motion of the antenna or platform. The resulting multiparameter images could be combined and enhanced to produce some of the most spectacular and information-rich radar images ever seen.

The Space Radar Laboratory missions (1 and 2) in 1994 were an international collaboration among NASA, the Jet Propulsion Laboratory, the German Space Agency, and the Italian Space Agency and constituted a real quantum leap in radar design, capability, and performance.



Tom Jones, PhD
Astronaut on STS-59 (1994), STS-68 (1994), STS-80 (1996), and STS-98 (2001).

"Space Radar Laboratory-1 and -2 orbited a state-of-the-art multifrequency radar observatory to examine the changing state of Earth's surface. Our STS-59 and STS-68 crews were integral members of the science team. Both missions returned, in total, more than 100 terabytes of digital imagery and about 25,000 frames of detailed Earth photography targeted on more than 400 science sites around the globe.

"For our crews, the missions provided a glorious view of Earth from a low-altitude, high-inclination orbit. Earth spun slowly by our flight deck windows, and we took advantage of the panorama with our 14 still and TV cameras. On September 30, 1994, on Space Radar Laboratory-2, we were treated to the awesome sight of Kliuchevskoi volcano in full eruption, sending a jet-like plume of ash and steam 18,288 m (60,000 ft) over Kamchatka. Raging wildfires in Australia, calving glaciers in Patagonia, plankton blooms in the Caribbean, and biomass burning in Brazil showed us yet other faces of our dynamic Earth. These two missions integrated our crews into the science team as orbital observers, providing 'ground truth' from our superb vantage point. Flight plan duties notwithstanding, I found it hard to tear myself away from the windows and that breathtaking view.

"Both missions set records for numbers of individual Orbiter maneuvers (~470 each) to point the radars, and required careful management of power resources and space-to-ground payload communications. The demonstration of precise orbit adjustment burns, enabling repeat-pass interferometry with the radar, led to successful global terrain mapping by the Shuttle Radar Topography Mission (STS-99) in 2000."

The Shuttle Radar Topography Mission—A Quantum Leap in Earth Mapping

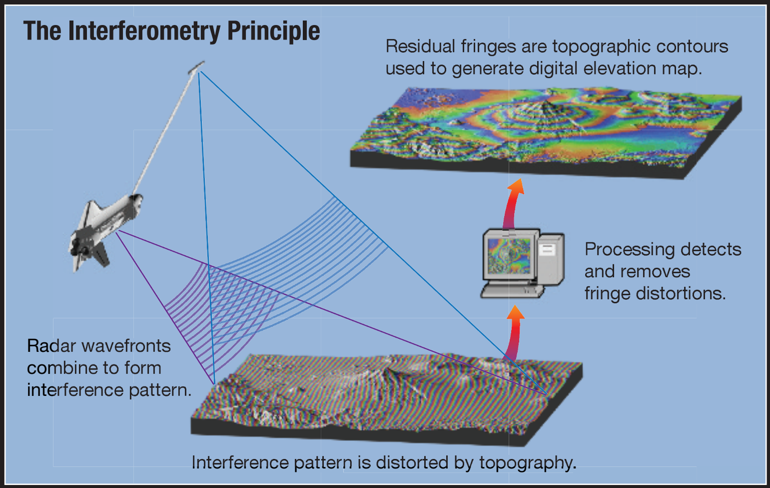
The Shuttle Radar Topography Mission was major a breakthrough in the science of Earth mapping and remote sensing—a unique event. NASA, the Jet Propulsion Laboratory, the National Geospatial-Intelligence Agency (formerly the Defense Mapping Agency Department of Defense), and the German and Italian Space Agencies all collaborated to accomplish the goals of this mission. The 11-day flight of the Space Shuttle Endeavour for the Shuttle Radar Topography Mission acquired a high-resolution topographic map of the Earth's landmass (between 60°N and 56°S) and tested new technologies for deployment of large, rigid structures and measurement of their distortions to extremely high precision.

How Did the Shuttle Radar Topography Mission Work?

The heart of this mission was the deployable mast—a real engineering marvel. At launch, it was folded up inside a canister about 3 m (10 ft) long. The mast had 76 bays made of plastic struts reinforced with carbon fiber, with stainless-steel joints at the corners and titanium wires held taut by 227 kg (500 pounds) of tension. The strict requirements of interferometry dictated that the mast be incredibly rigid and not flex by more than a few centimeters (inches) in response to the firing of the Orbiter's attitude control vernier jets. It didn't. Once in orbit, a helical screw mechanism pulled the mast open and unfurled it one "bay" at a time to the mast's full length of 60 m (197 ft).

A crucial aspect of the mapping technique was determination of the interferometric baseline. The Shuttle Radar Topography Mission was designed to produce elevations such that 90% of the measured points had absolute errors smaller than 16 m (52 ft), consistent with National Mapping Accuracy Standards, and to do so without using ground truth—information collected "on location." Almost all conventional mapping techniques fit the results to ground truth, consisting of arrays of points

Generating Three-dimensional Images

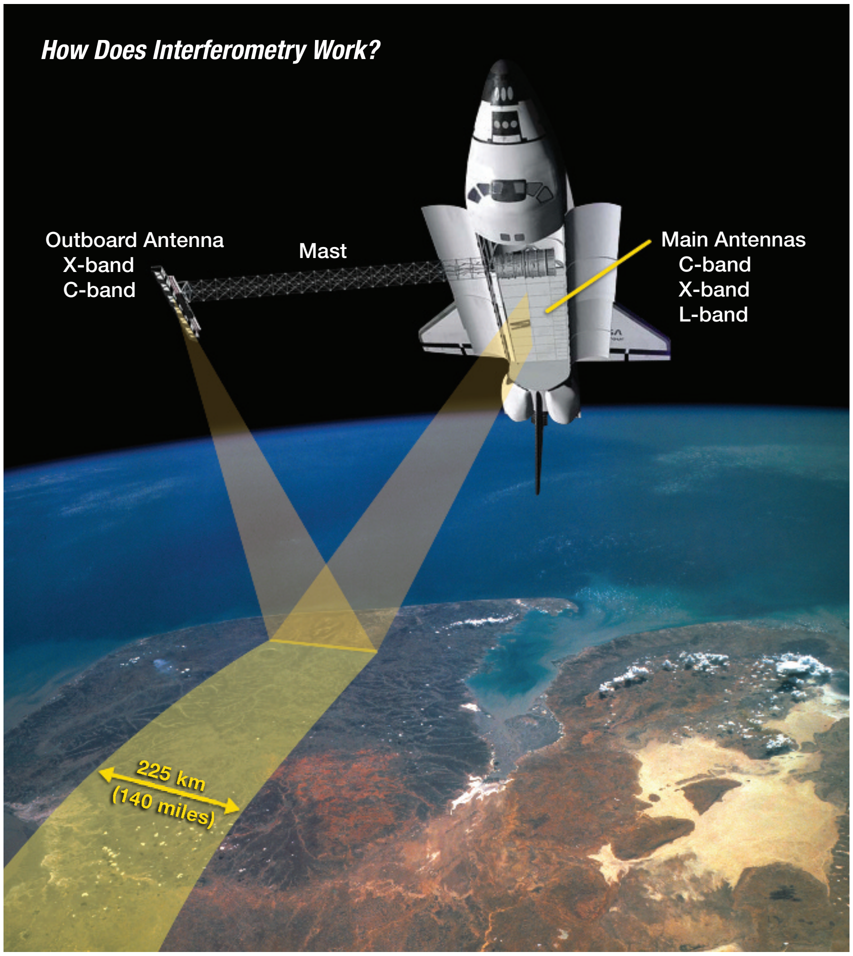


What Is Radar Interferometry?

When two sets of radar signals are combined, they create interference patterns. The measurement of this interference is called interferometry.

For example, if someone imagines a person standing with both arms extended to his or her sides and that person is holding a pebble (representing one radar each) in each hand but then drops the pebbles into a pond, two rippling concentric circles (representing radar signals) would emanate from the splash. As the two waves travel outward, they will eventually combine with each other causing "interference" patterns.

Similar patterns are generated when signals from two radar antennas are combined. Elevation differences on the surface cause distortions in the fringes that can be measured to determine the elevations. This was the concept used in the Shuttle Radar Topographic Mapping mission.



This interferometry concept was used in the Shuttle Radar Topography Mapping mission. Radars on the mast (not to scale) and in the shuttle payload bay were used to map a swath of 225 km (140 miles), thus covering over 80% of the Earth's landmass.

with known locations and elevations, to remove any residual inaccuracies. But, because the Shuttle Radar Topography Mission would be mapping large regions with no such known points, the system had to be designed to achieve that accuracy using only internal measurements.

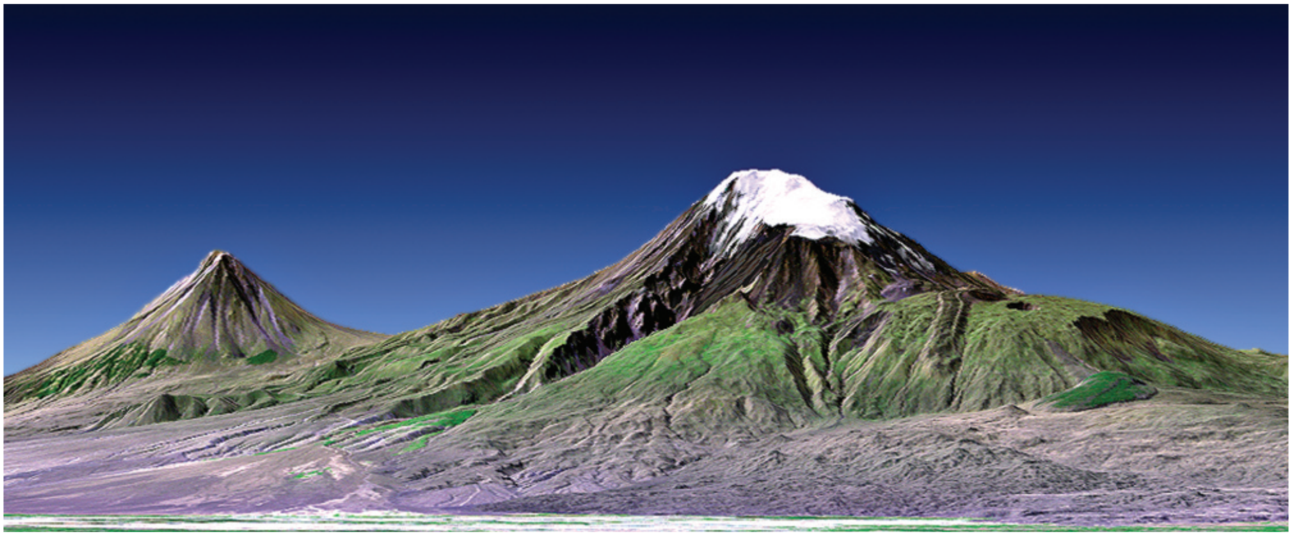
This was a major challenge since analysis showed that a mere 1-arc-second error in our knowledge of the absolute orientation of the mast would result in a 1-m (3-ft) error in the elevation measurements. A 1-arc-second angle over the 60-m (197-ft) baseline is only 0.3 mm (0.1 in.)—less than the thickness of a penny.

This problem was solved by determining the Orbiter's attitude with an inertial reference unit borrowed from another astronomy payload, augmented with a new star tracker. To measure any possible bending of the mast, the borrowed star tracker was mounted on the main antenna to stare at a small array of light-emitting diodes mounted on the other antenna at the end of the mast. By tracking the diodes as if they were stars, all mast flexures could be measured and their effects removed during the data processing.

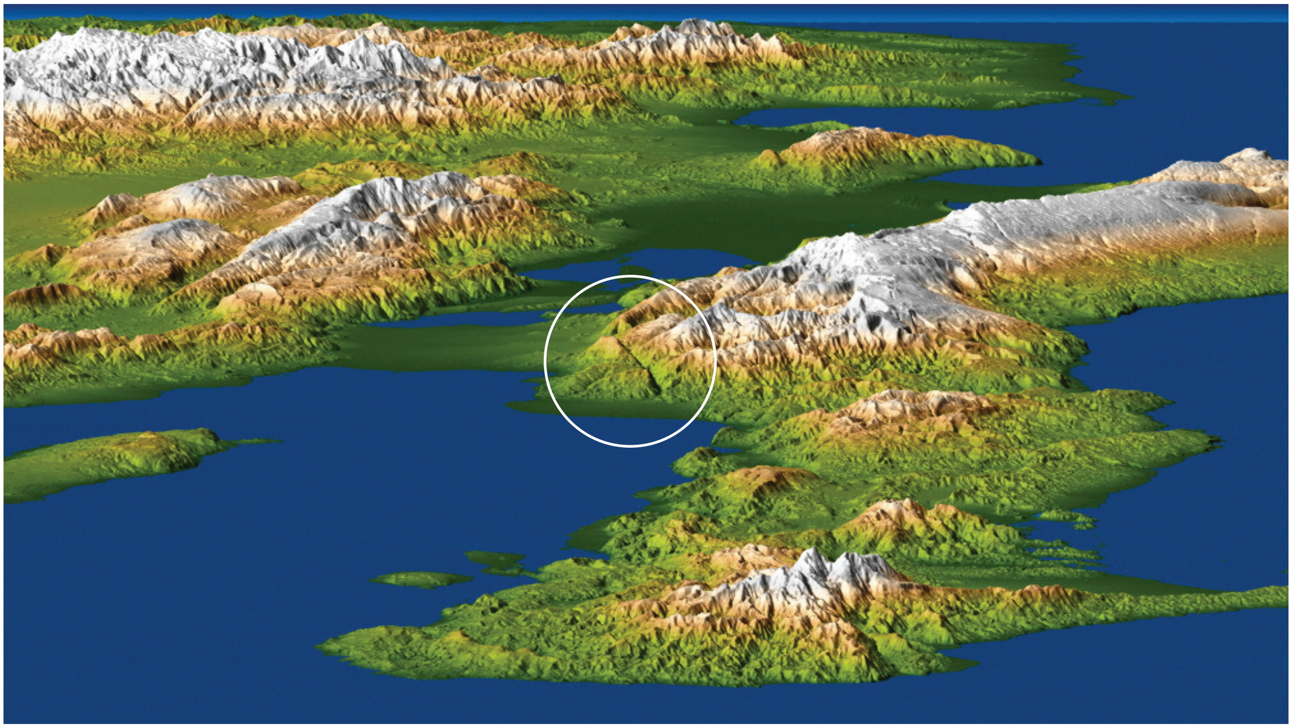
The mast-Orbiter combination measured 72 m (236 ft) from wingtip to the end of the mast, making it the largest solid object ever flown in space at that time. This size created one interesting problem: The Orbiter had to perform a small orbit maintenance burn using the Reaction Control System about once per day to maintain the proper altitude, and analysis showed that the resulting impulse would generate oscillations in the mast that would take hours to die out and be too large for the Shuttle Radar Topography Mission to operate.

By collaborating, Johnson Space Center flight controllers and Jet Propulsion Laboratory mechanical engineers arrived at a firing sequence involving a series of pulses that promised to stop the mast dead at the end of the burn. They called it the "flycast maneuver" since it mimicked the way a fisherman controls a fly rod while casting. The maneuver involved some tricky flying by the pilots and required much practice in the simulators, but it worked as planned. It also gave the crew an excuse to wear fishing gear in orbit—complete with hats adorned with lures—and produced some amusing photos.

NASA developed the original flight plan to maximize the map accuracy by imaging the entire landscape at least twice while operating on both ascending and descending orbits,



Turkey: Mount Ararat was mapped with a Shuttle Radar Topographic Mapping elevation model and draped with a color satellite image. This view has been vertically exaggerated 1.25 times to enhance topographic expression. This peak is a well-known site for searches for the remains of Noah's Ark. The tallest peak rises to 5,165 m (16,945 ft).

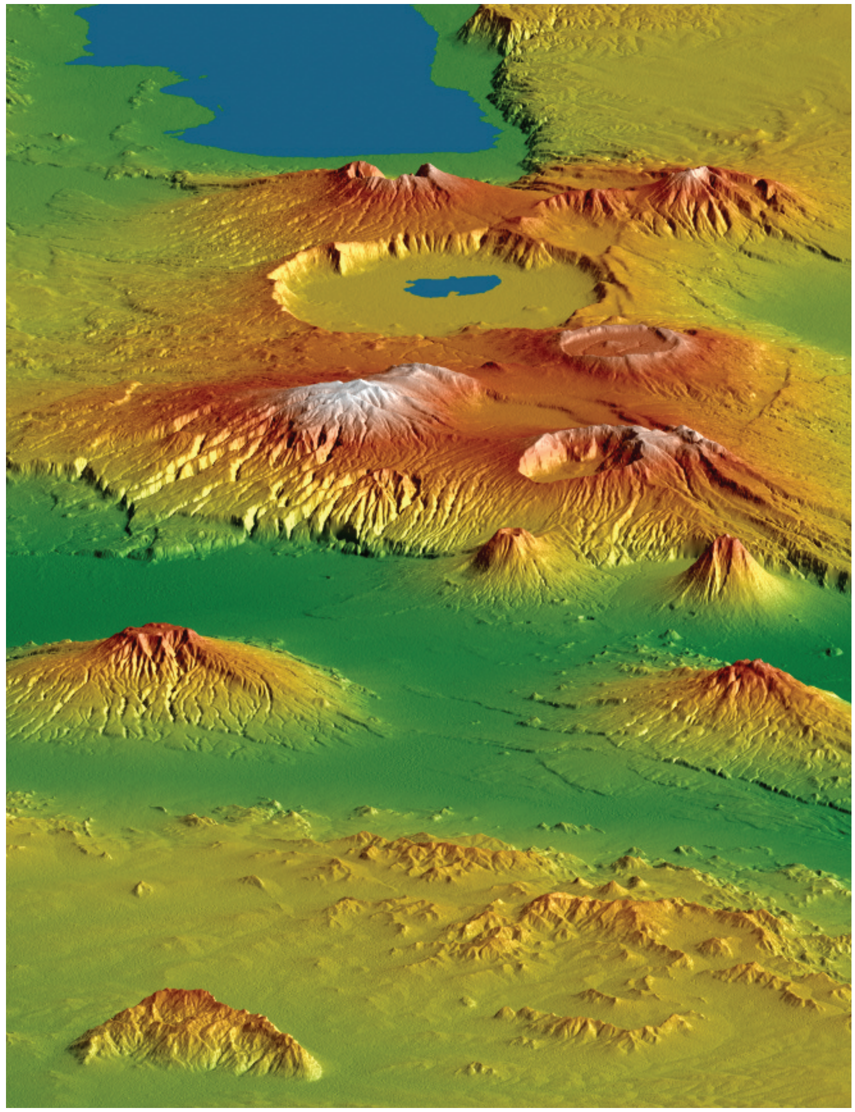


Haiti: This pre-earthquake image clearly shows the Enriquillo fault that probably was responsible for the 7.0-magnitude earthquake on January 12, 2010. The fault is visible as a prominent linear landform that forms a sharp diagonal line at the center of the image. The city of Port-au-Prince is immediately to the left (North) at the mountain front and shoreline.

but it turned out that a limited region was covered only once because the mapping had to be terminated a few orbits early when the propellant ran low. This had a minor impact, however, because even a single image could meet the accuracy specifications. In addition, the affected regions were mostly within the already well-mapped US terrain near the northern and southern limits of the orbits where the swaths converged were covered as much as 15 to 20 times. In all, the instrument covered 99.96% of the targeted landmass.

Converting Data Sets Into Real Topographic Maps

NASA assembled a highly effective computerized production system to produce topographic maps for users. Successful completion of radar data collection from Endeavour's flight was a major step, but it was only the first step. Teams from several technical areas of microwave imaging, orbital mechanics, signal processing, computer image processing, and networking worked together to generate the products that could be used by the public and other end users. Major steps included: rectifying the radar data to map coordinates, generating mosaics for each continent, performing quality checks at each stage, and assessing accuracy.



Africa: Tanzania's Crater Highlands along the East African Rift Valley are depicted here as mapped with the Shuttle Radar Topographic Mapping elevation model with vertical exaggeration of two times to enhance topographic variations. Lake Eyasi (top of the image, in blue) and a smaller crater lake are easily seen in this volcanic region. Mount Loolmalasin (center) is 3,648 m (11,968 ft).

Results of Shuttle Radar Topography Mission

The mission collected 12 terabytes of raw data—about the same volume of information contained in the US Library of Congress.

Processing those data into digital elevation maps took several years, even while using the latest supercomputers. Yet, the Shuttle Radar Topography Mission eventually produced almost 15,000 data files, each covering 1° by 1° of latitude and longitude and covering Earth's entire landmass from the tip of South America to the southern tip of Greenland. The data were delivered to both the National Geospatial Agency and the Land Processes Distributed Active Archive Center at the US Geological Survey's EROS (Earth Resources Observation and Science) Data Center in Sioux Falls, South Dakota, for distribution to the public. The maps can be downloaded from their Web site (*http://srtm.usgs.gov/*) at no charge, and they are consistently the most popular data set in their archive.

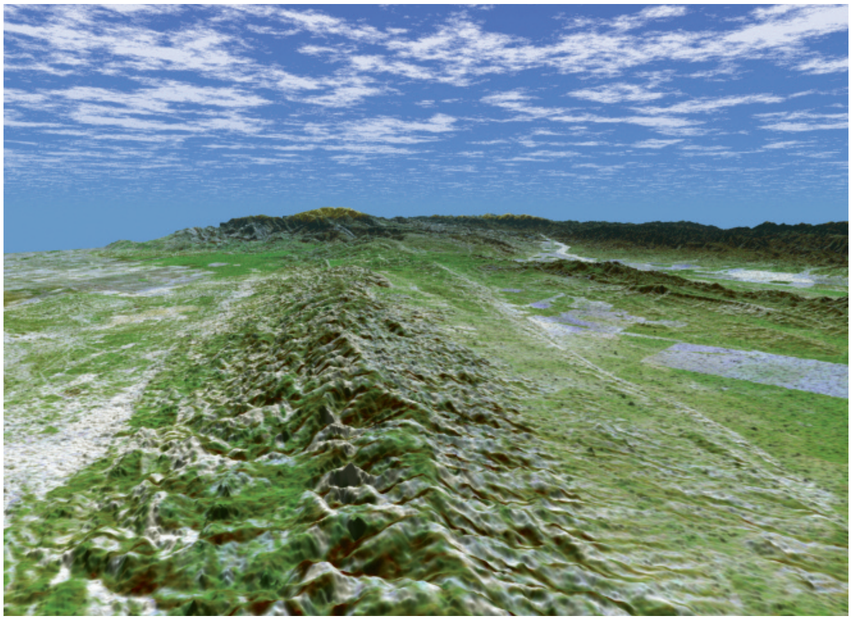
Elevation accuracy was determined by comparing the mission's map to other higher-resolution elevation maps. Results confirmed the findings of the National Geospatial-Intelligence Agency and the US Geological Survey that Shuttle Radar Topography Mission data exceeded their 16-m (52-ft) height accuracy specification by at least a factor of 3.

In all, the Shuttle Radar Topography Mission successfully imaged 80% of Earth's landmass and produced topographic maps 30 times as precise as the best maps available at that time.

Charles Elachi, PhD
Director of Jet Propulsion Laboratory
California Institute of Technology.

"The Space Shuttle played a key role, as the orbiting platform, in advancing the field of radar observation of the Earth. Five flights were conducted between 1981 and 2004, each one with successively more capability. Probably the two most dramatic advances occurred with: 1) the SIR-C flight, which demonstrated for the first time 'color' imaging radars with multifrequency/multi-polarization capability, and it is still considered the 'gold standard' for later missions; and 2) the Shuttle Radar Topography Mission flight, which revolutionized topographic mapping by acquiring global digital topography data using interferometric radar. These missions were enabled by the volumetric and lift capability of the shuttle. These two advances in our ability to map the Earth will go down in history as two of the most important contributions of the shuttle to the field of Earth Science."*

** Shuttle Imaging Radar-C*



US: California's San Andreas fault (1,200 km [800 miles]) is one of the longest faults in North America. This view of a section of it was generated using a Shuttle Radar Topographic Mapping elevation model and draped with a color satellite image. The view shows the fault as it cuts along the base of Temblor Range near Bakersfield, California.

Summary

The successful shuttle radar missions demonstrated the capabilities of Earth mapping and paved the way for the Shuttle Radar Topography Mission. This mission was bold and innovative, and resulted in vast improvement by acquiring a new topographic data set for global mapping. It was an excellent example of a mission that brought together the best engineering and the best science minds to provide uniform accuracy elevation information for users worldwide. This success has been enshrined at the Smithsonian Air and Space Museum's Udvar-Hazy Center in Virginia, where the radar mast and outboard systems are displayed.