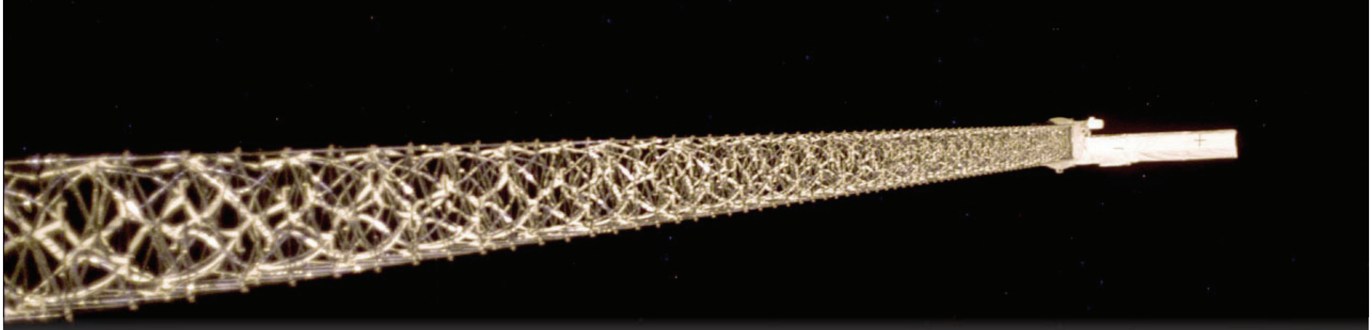

On the Toes of Giants – How SRTM was Born

by Michael Kobrick

In 1765 Sir Isaac Newton wrote to Robert Hooke "If I have been able to see farther, it was only because I stood on the shoulders of giants." Some think this famous phrase acknowledging fellow scientists actually contained a subtle dig at Hooke, who had begun to disagree with some of Newton's theories and was a bit short in stature. In this paper I would like not only to provide a brief review of the genesis of the SRTM project, but to also acknowledge some of the giants whose clever and creative efforts brought about

the success of the mission, possibly the most important science mission the Space Shuttle has ever flown. I can mention only a few individuals, with hopes the rest don't feel that their contributions have been overlooked or that their toes have been trampled.

In 1994, the Spaceborne Radar Laboratory (SRL) flew twice on Space Shuttle Endeavour. The payload consisted of two integrated microwave instruments, the Jet Propulsion Laboratory's SIR-C, a fully polarimetric synthetic aperture radar operating at both L-band and C-band, and the German and Italian Space Agencies' X-SAR, a single polarization X-band radar operating at 3 cm. In addition, SIR-C incorporated a number of new technologies, including an active phased-array antenna capable of electronically steering its beam through a range of off-nadir angles without utilizing any moving parts. With this antenna and its ability to simultaneously acquire images at all four polarizations and three wavelengths, SRL was easily the most capable imaging radar system ever flown.

A large international science team was selected to take advantage of this capability, with planned research studies in geology, hydrology, oceanography, ecology and archeology. Both Shuttle flights were quite successful and met all the essential SRL scientific objectives, so NASA decided to drop the planned third flight, even though the hardware was in good shape and certified to fly a third time.

Thus, in the fall of 1994, project officials had the world's most advanced imaging radar system in flight-qualified condition sitting in storage.

The STS-99 astronaut crew with the SRTM instrument at JPL's Spacecraft Assembly Facility. From left to right; Mission Specialist and Payload Commander Janice Voss, Mission specialists Mamoru Mohri, Janet Kavandi and Gerhard Thiele, Pilot Dom Gorie, and mission Commander Kevin Kregel.

Enter the Giants

Ed Caro was the chief engineer for the SIR-C instrument, and is a fellow well-known for a puckish sense of humor and the ability to concoct some quite creative concepts for radar implementations. Thanks to JPL's penchant for co-locating science and engineering offices, he and I would frequently run into each other and we would discuss ideas for a third SIR-C flight. One of his ideas was to borrow a flight-qualified engineering test model of a 30-meter long deployable mast being developed to support the solar arrays on the International Space Station, attach it to the SRL antenna structure, and place an additional X-band antenna at the other end to form a fixed-baseline interferometer.

The idea of extending this long "noodle" with a 1,000 pound antenna at the end from the Shuttle's payload bay was certainly a bold one, but we all knew that interferometry for topographic mapping and change detection was the next big thing in radar remote sensing. Project manager Mike Sander commissioned a short engineering study of the idea during a brief lull following an SRL launch slip. The conclusion was that Caro's idea was feasible, but not compelling.

Ironically, the idea was just not bold enough! Pass-to-pass interferometry had been demonstrated a number of times; in fact the SRL flights had generated interferograms and digital elevations maps by combining data from repeat orbits on the second flight as well as matching orbits between the two flights. No one doubted that fixed-baseline interferometry from space would work so a proof-of-concept test was unnecessary, and with a data swath only a few tens of kilometers wide, not enough real estate could be mapped during a single Shuttle flight to make it scientifically useful.

New Innovations

ScanSAR was a concept that had been discussed for a number of years, where instead of continuously pulsing a radar beam to sweep out a single swath it should be possible to hop the beam through a number of off-nadir angles and sweep out a much wider swath, albeit with some decrease in image quality. Since this switching had to take place many times a second, a phased array antenna was required. As SIR-C radar system engineer Rolando Jordan reminded us, this was just what we had.

So a ScanSAR mode with four beam angles, or subswaths, was implemented and tested during several data takes on both SRL flights, with splendid results. We were fond of displaying a beautiful 250 kilometer-wide image of ocean eddies in the Weddell Sea; the first ever ScanSAR image from space.

My own modest contribution occurred in the form of a single good idea. As with so many good ideas it wasn't really original but it combined two other notions – interferometry, using Caro's mast, and a wide swath, using Jordan's ScanSAR. If the outboard antenna at the end of the mast was made to be a C-band phased array and scanned it in unison with the antenna in the payload bay we would have a wide-swath interferometer.

It was unkown as to whether this would actually work since combining ScanSAR with interferometry had never been demonstrated or even discussed. The two questions to be answered were 1) would it work, and 2) if so, how wide would the swath be?

I had written some software in graduate school to calculate exact repeat orbit altitudes. These occur when the orbit period, rotation of the Earth, and precession of the orbit at a particular inclination just balance so that the ground track repeats exactly after some interval. The solutions are quantized and showed that there were just a few at 57 degrees inclination (the highest the Shuttle could attain from the Kennedy Space Center) that were high enough to avoid the atmosphere and low enough for the Shuttle to reach with the heavy payload. The obvious best solution was at 233 kilometers altitude, producing a pattern that repeated in 159 orbits, or about 10 days.

The key element would be the separation between ground tracks at the equator, which would dictate the gap between adjacent swaths and how much of the Earth's surface that could be covered. The calculation is easy; just divide 159 into the Earth's circumference and multiply by the sine of the angle at which you cross the equator, about 60 degrees. The answer was 218 kilometers.

By this time, Jordan had completed his computer analysis and his cautious answer to the first question was not the hoped-for, "It would work," but instead, "We haven't found any reason why it wouldn't work." His second answer, "I'm pretty sure the swath would be at least 225 kilometers," was much more exciting.

This meant that the swath was wider than the equatorial separation, and there would be no gaps. We could completely map in 3-D all the landmass between ±60° latitude in a single Shuttle flight using mostly

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Space Shuttle Endeavour launched from the Kennedy Space Center on February 11, 2000 on mission STS-99, carrying a crew of six and the SRTM instrument into orbit.

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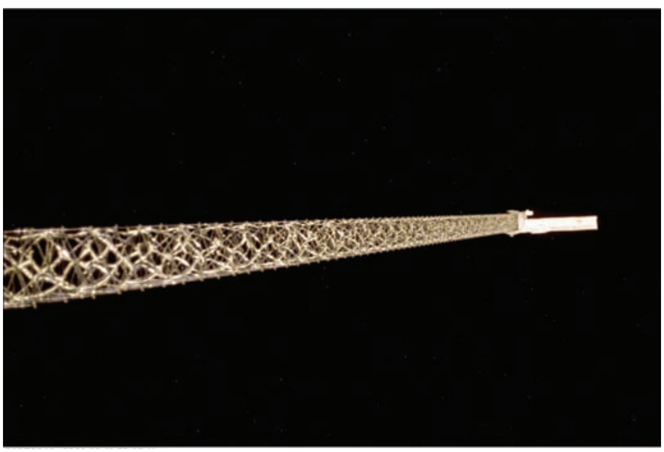
leftover hardware. This was so unbelievable that we spent several weeks trying to figure out if we had made any mistakes, and found nothing. In fact, so many things fell into that Goldilocks "just right" category that I called them "Miracles of Nature".

For example, the Earth's landmass covers almost exactly 30% of its surface, so operating only over land meant a duty cycle of 30%, or about 80 hours of data. These were the same perameters we had used during each previous SRL flight so there should obviously be enough fuel, electricity, data tapes, and other consumables to complete the mission.

Better yet, all the landmass of the Earth, except Antactica, lies to the north of the southern extent of the ground tracks for a 57° inclination orbit, so the side-looking radar needed to point in only one direction—north, which meant we could maintain the same Shuttle attitude. Eliminating time-consuming spacecraft maneuvers would save a lot of propellant, which would be in short supply.

The best miracle that occurred was the Shuttle attitude itself. Deploying the mast to starboard to match the antenna's tilt and maximize the baseline would have the orbiter flying tail first. This is the only attitude the Shuttle orbital debris avoidance rules allow for an entire flight. What luck.



View from the Commander's seat of the SRTM mast and outboard antennas 60 meters away.

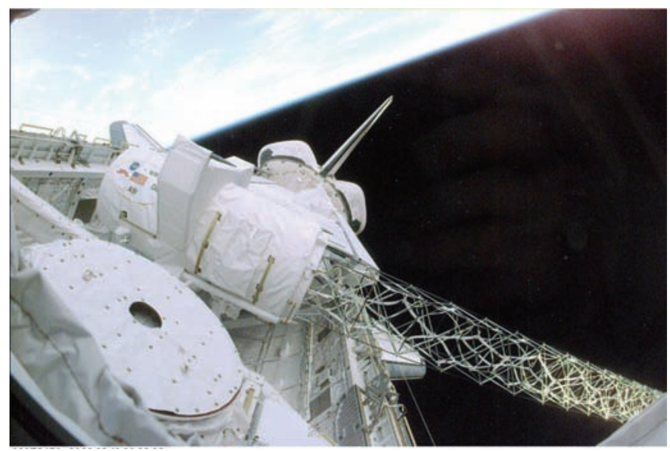
The list of lucky breaks went on, but suffice it to say we were confident enough by the beginning of 1995 to propose the mission to NASA. This is not to say that some convincing within JPL wasn't necessary first. With a 30 meter mast at C-band we thought the horizontal resolution would be about 100 meters, but it seems we scientists have so conditioned remote sensing engineers to always strive for higher and higher resolution that their main reaction was, "100 meters? We can do better than that!"

My most important contribution to SRTM was to understand the importance of a global uniform data set, even at this moderate resolution. Digital elevation models had been around for some time, had found myriad uses both in science and civil applications, and there was great demand for more data. Although the USGS was distributing data at 30 meters for the U.S., the best global data available to civilians was GTOPO30 at around one kilometer resolution. As good a resource as this was it had been cobbled together from numerous disparate data sets with different characteristics, numerous artifacts, and often not even referenced to the same datum. At ten times better resolution SRTM could produce data in a globally consistent fashion for the 80% of the Earth's landmass between the southern tip of South America and the tip of Greenland, and all using mostly leftover hardware!

The program managers at NASA also recognized the potential, but with the International Space Station in full development money was tight. They suggested we try to find a partner from the international community, industry, or another agency to help defray the cost. For this, we turned to the Defense Mapping Agency (DMA) [later NIMA, and now NGA].

For those first concept studies we had invited DMA Chief Scientist Dr. Gerry Elphingstone to sit in as an adviser, so we went back to DMA to talk about a joint project and found we were at the right place at the right time. They were working to complete their DTED Level 1 product at 3 arc-second (93 meter) posting by the year 2000, but had only completed about 60% and were stymied by the Earth's cloud cover.

DMA agreed to a partnership only if we could find a way to squeeze a little more performance from the system and get to DTED Level 2, or 1 arc-second posting. It turned out that AEC-Able, builders of the mast, had developed an alternate design that could fit twice as

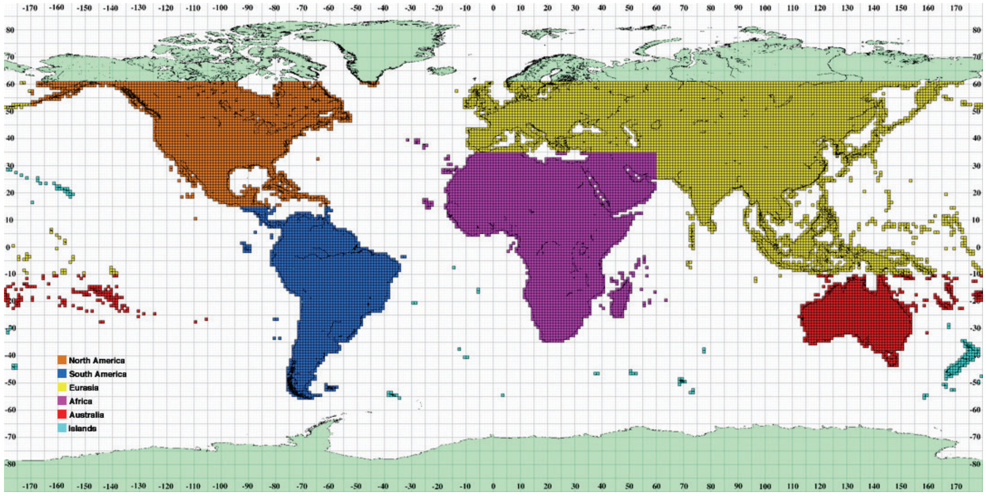


Astronaut's eye view of the SRTM payload. The mast canister partially obscures the main antenna structure, with the 60 meter-long mast extending out to the right. The structure in the foreground is part of the airlock and docking adapter.

much mast into the same size canister, but that it would cost a little more. With a 60-meter long baseline, and by using dual ScanSAR beams (illuminating two of the four subswaths simultaneously and thus doubling the number of samples) we could just make it.

The Shuttle Radar Topography Mission was on its Way

The creativity didn't stop there. For example, we knew that determining the interferometric baseline attitude would be a major challenge – a tiny one arc-second error in our knowledge of this orientation would result in a one meter height error in the resulting map. The challenge was met when avionics engineer Riley Duren managed to acquire an inertial reference unit (IRU) and star tracker left over from an astronomy mission. He refocused the tracker to 60 meters, mounted it in the payload bay, and pointed it at some LEDS positioned on the outboard antenna at the end of the mast. While the IRU (continuously recalibrated with a new star tracker) provided the basic Shuttle



SRTM data were processed continent by continent into almost 15,000 data cells covering one by one degrees of latitude and longitude. Total coverage is 80% of Earth's landmass.

orientation, the tracker monitored the LEDs as if they were stars and thus measured any small oscillation of the mast itself. This was an exceptionally clever solution.

The most entertaining idea was provided by mechanical system engineer Bill Layman. We knew the orbiter would have to perform a small orbit maintenance burn using the reactions control system jets about once a day to maintain altitude, but analysis showed that this impulse would generate oscillations in the mast that would take hours to die out and be too large for us to take data. Working with the engineers at the Johnson Space Center, Layman worked out a firing sequence that promised to stop the mast dead at the end of the burn and allow us to resume operations immediately. He called it the "flycast maneuver," since it mimicked the way a fisherman controls a flyrod while casting. It involved some tricky flying by the pilots and required a lot of practice, but it gave them the opportunity to wear fishing gear in orbit, complete with hats adorned with lures, and produced some hilarious photos.

The STS-99 astronaut crew with the SRTM instrument at JPL's Spacecraft Assembly Facility. From left to right; Mission Specialist Mamoru Mohri, Pilot Dom Gorie, Mission Specialist and Payload Commander Janice Voss, mission Commander Kevin Kregel, and Mission Specialist Janet Kavandi. Behind them is the main SRTM antenna structure, to the technician's right is the canister containing the 60 meter long mast, and at lower left is the outboard antenna structure.

Partnerships

Of course the project was greatly enhanced by the participation of the German and Italian space agencies, who added an X-band antenna to the mast to also turn the X-SAR instrument into an interferometer. Operating simultaneously with C-band and sharing some of the electronics and data systems, the X-band instrument produced a valuable independent topographic data set, although without a ScanSAR mode it did not provide continuous coverage.

Probably the most "interesting" aspect of the project was the partnership between NASA and DMA. As part of the Defense Department, DMA worked often in the black world, and as part of Caltech and NASA, JPL lived in a world of publish or perish. This potential culture clash was resolved when it was agreed that although the whole project would be unclassified, the final data products would be generated and distributed at two different levels; a 3 arc-second product available to the general public, and a 1 arc-second product restricted to DMA use, as was the existing DTED.

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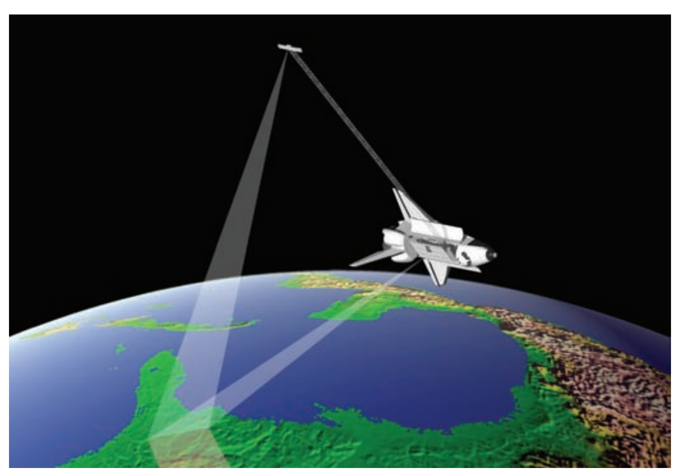

Artist's conception of the Shuttle with mast extended in data-taking attitude. Flying tail-first, the SRTM instrument sweeps out a data swath about as wide as the Florida peninsula.

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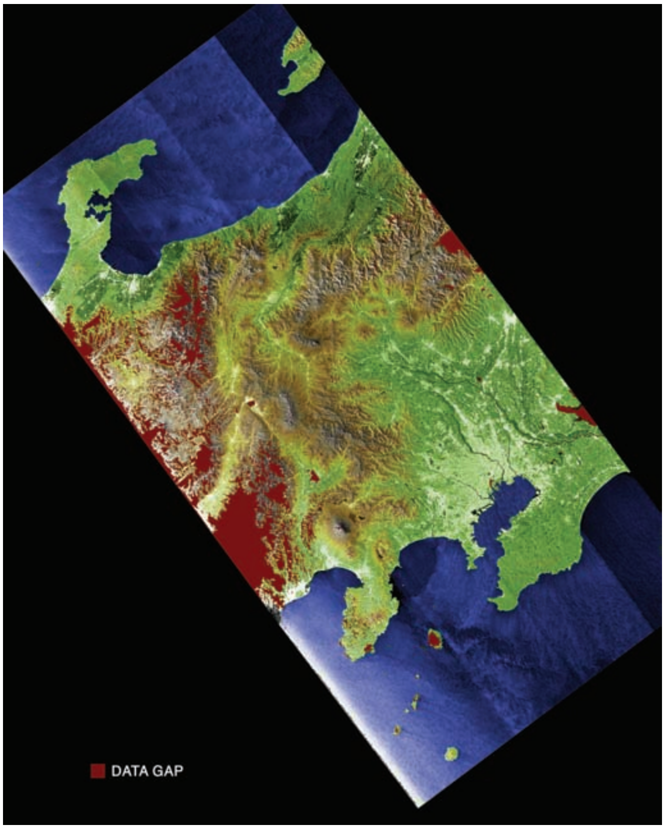

A single SRTM data swath crossing Japan, with Tokyo visible at the lower right and Mount Fuji near the center. Edges of the four ScanSAR sub-swaths are visible in the ocean. The red areas are data voids caused by shadowing or low signal-to-noise ratio, and will be mostly filled in when multiple swaths are assembled into a mosaic.

A Successful Mission

On February 11, 2000, the Shuttle Endeavour launched with a six-person international crew and 30,000 pounds of SRTM hardware. They returned to Earth 11 days later with 12 terabytes of raw radar echo data, having executed a virtually flawless mission that had covered 99.96% of the targeted landmass. After several years of processing with a supercomputer, the digital elevation models have been produced, edited by NGA and are being distributed by the USGS. The fact that they have turned out to far exceed their promised accuracy and precision is a real tribute to all of the giants who helped produce them.

Acknowledgements

Many thanks to Dean Gesch, Jan-Peter Muller and Tom Farr for organizing the SRTM Workshop in June, 2005, and editing this special issue of *PE&RS*.

The SRTM mast, canister and outboard antennas are on display at the National Air and Space Museum's Steven F. Udvar-Hazy Center near the Washington Dulles International Airport. The display, co-located with the Space Shuttle Enterprise, is a truly impressive sight.

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