

NASA/JPL SPACEBORNE IMAGING RADAR

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A researcher carefully puts a CD into the drive on a computer and pushes the tray closed. In a few seconds the drive is up to speed and detailed geographic images are available for viewing. Using radar data gathered by an orbiting spacecraft, valleys and hills, plateaux, landslides and even dry river beds can be seen on a scale of a few hundred metres over the entire planet. But until recently, although Venus could have been explored in this way, no such global map was available for our own planet Earth.

Mapping the Earth in 3D

A database for Earth is now being created as the result of the Shuttle Radar Topography Mission (SRTM) during an 11 day Shuttle Endeavour flight in February. [See p.xxx for a detailed report of the mission.]

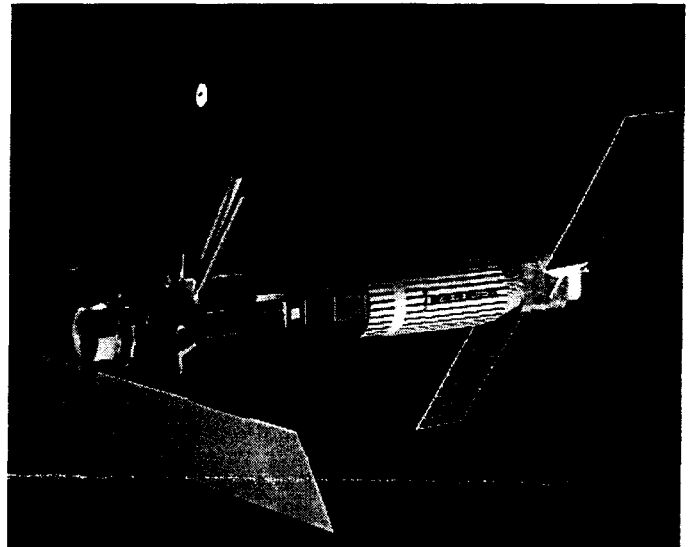
SRTM utilised a synthetic aperture radar (SAR) imaging system* in an interferometric mode to provide measurements for an exceptionally accurate three-dimensional (3D) picture of the Earth's many lumps and bumps**. SRTM was the latest in a series of radar experiments designed at the Jet Propulsion Laboratory (JPL) in Pasadena, California. SRTM was sponsored by NASA and the National Imaging and Mapping Agency (NIMA).

Early JPL Projects

JPL conducts the NASA imaging radar program, which has included planetary and Earth missions stretching back over the past 30 years. JPL started radar experiments in the early 1960s, placing them aboard a high-altitude Aerobee rocket to investigate the feasibility of space-based radar remote sensing. Early development of imaging radar hardware and techniques was subsequently accomplished primarily through the use of an airborne platform, initially a CV-990 aircraft. The aircraft system evolved to the multi-frequency, multi-polarisation, interferometric SAR capability of today aboard a DC-8. This continues to be a critical radar development tool.

The first space-based JPL radar came in December 1971, but it was not an Earth orbiter. The instrument was the Apollo Lunar Sounding Experiment (ALSE), carried on board Apollo 17. It operated at 5, 15 and 150 MHz (i.e. HF and VHF frequencies), making measurements of Moon's surface ter-

Right: The Seasat spacecraft which was launched in June 1978 and carried the first US Earth-orbiting SAR.



rain and subsurface structure from the Command Module "America". The longer wavelengths allowed penetration of the lunar surface to detect and locate subsurface discontinuities, while the vertical (nadir) return was used to construct a continuous profile of the lunar terrain and its altitude relative to the Command Module. Radar images were also made of the lunar surface using an experimental SAR mode.



Imaging from Earth Orbit

JPL's next spaceborne imaging radar venture was Seasat, launched in June 1978 into an 800 km orbit. Seasat included the United States' first Earth-orbiting SAR. Like the CV-990 device, the radar worked in the L-band frequency range (1-2 GHz), with a 1 kW transmitter and a 2.2 m x 10.7 m planar antenna array, which was designed primarily to capture reflections of signals from the ocean surface. The surface roughness and structure provided information regarding surface and internal waves, winds and subsurface features. Although the mission was limited by a power system failure after 100 days in orbit, Seasat collected more observations of wave features and of land-sea margins, than

Left: A Magellan image showing Dickinson, an impact crater 69 km in diameter, in the northeastern Atalanta Region of Venus. The image is approximately 185 km wide at the base. The crater is characterised by a partial central ring and a floor flooded by radar-dark and radar-bright materials, and is surrounded by extensive radar-bright flows.

* See "What is SAR?" on p.xxx.

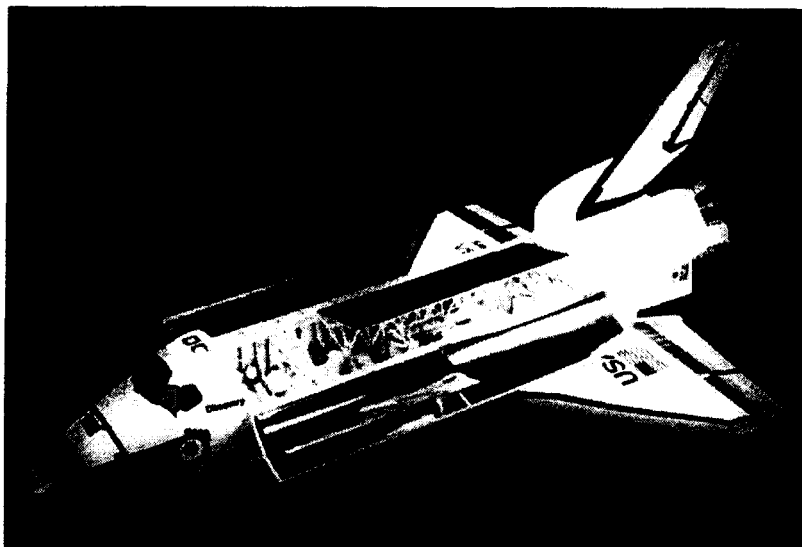
** See "What is Interferometric SAR?" on p.xxx.

had been gathered in the previous 100 years of shipboard measurement.

The success of Seasat resulted in a series of land-imaging development flights for the Space Shuttle program, beginning with the Shuttle Imaging Radar A (SIR-A) mission. SIR-A flew on the second Shuttle mission (STS-2, Columbia, 1981) and used mainly spare parts from Seasat, augmented with some optical data recording hardware left over from the ALSE.

Although the SIR-A flight lasted only two days, reduced from five days by a Shuttle fuel cell problem, the images acquired produced some dramatic land remote sensing results. One of the most spectacular results from SIR-A illustrated an additional property of radar images. The extreme dryness of windblown sand in the eastern Sahara, coupled with its fine-grain nature, allowed the radar to penetrate up to 2m below the surface, uncovering hydrological and geological features buried beneath. Evidence of prehistoric settlements were later found near sites identified by SIR-A as ancient drainage systems.

The next mission, SIR-B, flew in October 1984 (STS-41G, Challenger) and included several technical improvements. It had an antenna that could be mechanically steered to provide different imaging angles, giving rise to different backscatter patterns and thus better classification of surface features, e.g. vegetation types. The an-



Depiction of the SIR-A radar imager mounted in a Shuttle cargo bay. SIR-A flew on the Shuttle Columbia in November 1981.

tenna was also bigger than SIR-A's, improving resolution, and data was relayed to the ground during the flight, rather than being stored on-board. SIR-B was scheduled for a re-flight in March 1987 in a polar orbit, as the first Shuttle NASA payload launched from Vandenburg AFB. However, Vandenburg launches were abandoned after the Challenger accident, and the SIR-B re-flight never came about.

Magellan at Venus

Although the ability of radar to pen-

etrate cloud cover is considered a very important advantage for Earth remote sensing there are several places in the solar system where it is essential. One of these is Venus, where thick carbon dioxide clouds permanently obscure the surface. A Venus radar mapper was the primary instrument on the Magellan mission, developed by JPL and launched from the Shuttle Atlantis (STS-30) in May 1989. Using the 3.7m dish antenna installed for high-rate data transmissions to Earth, the mapper employed a 2.385 GHz (S-band) SAR and altimeter to penetrate the thick cloud layers that shroud Venus, revealing a landscape scarred by volcanoes, canyons and craters. The SAR had a resolution of 100m and mapped out 25 km wide swaths on each pass, eventually imaging 98% of the planet.

SRL Missions

Back near Earth, although incremental in name, SIR-C represented a significant technical advance over previous Shuttle missions. Flown on Endeavour in both April and October 1994 (STS-59 and STS-68), these Space Radar Laboratory (SRL) missions, as they were known, used an active phased array, the first such NASA array flown in space. This allowed the introduction of electronic beam steering, a process to direct the radar beam without having to move the antenna itself. SIR-C was also complemented by a X-band radar provided by German and Italian researchers. Other first-of-a-kind features tested by SIR-C included a radar operating at several different frequencies, with both horizontal and vertical polarisations. These were used because, as well surface orientation and texture, radar backscatter can also depend on the exact signal frequency and polarisation. Backscatter intensities from different combinations

What Is Radar Imaging?

Radar image generation and interpretation are most easily explained using the analogue of an optical camera. An optical camera captures light reflected with differing intensities by objects in the field of view, which have been illuminated by the Sun or a flash bulb. The result is a photograph - a two-dimensional array of reflected light patterns. Analogous to a photograph generation, a radar image is a two-dimensional array of reflected energy from an area illuminated by pulses from a radar transmitter.

The antenna boresight for an imaging radar is perpendicular to the direction of flight (side-looking). Originally this was due to the physical convenience of mounting the antenna parallel to an aircraft body. Each radar image "frame" covers the "across-track" surface area illuminated through the antenna by a transmitted pulse. The reflected pulses within the frame are positioned in the across-track direction by time delay and have a resolution proportional to the pulse duration. As the radar flies along, the frames are assembled into an image "swath", and successive swaths can be used to build a contiguous image of the surface over a large area.

Photographic interpretation is a well-

evolved human capability, since our eyes operate at visible wavelengths the same as an optical camera. But a radar image is a pictorial representation of a surface's electromagnetic reflection characteristics at the radar transmission wavelength. The strength of the reflected radar signal in the direction of the transmitting antenna, known as backscatter, determines the radar image brightness. The surface characteristics which affect the backscatter are primarily the electrical properties, texture and orientation. Interpretation of radar imagery is unnatural and has to be acquired. A smooth surface, such as a river or a street, appears dark because it reflects the signal away from the direction of the radar and returns very little. Vegetation, such as a tree canopy, appears moderately bright because it scatters signals in many directions. Man-made features, such as buildings, appear as a patchwork of bright and dark areas because of their organised structure.

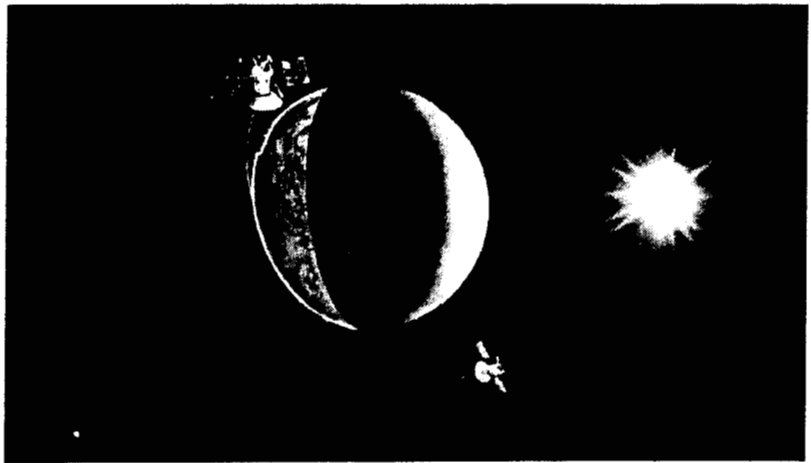
Because radar provides its own source of electromagnetic illumination at significantly longer wavelengths than light, it can "see" through darkness and clouds. This is a powerful feature of radar imaging.

of these provided extra information to help identify the properties of surfaces and objects below.

How SRTM Came About

By the time of the SIR-C missions, interferometric SAR had been well-developed through experimentation by JPL aboard airborne systems and using repeat-passes of spaceborne systems. SRTM was conceived as a means of producing a global elevation map quickly and relatively inexpensively by taking advantage of the existing capabilities and hardware. SIR-C equipment was augmented by the addition of a second interferometric receiving antenna system. Also, metrology capabilities were added to measure the baseline characteristics and to provide accurate Shuttle posi-

A false-colour radar image of Central Africa, showing the Virunga Volcano chain, acquired by SIR-C/X-SAR on 12 April 1994. The image covers an area 58 km by 178 km, and reveals a variety of vegetation types, an important factor in the study of the habitat of the endangered mountain gorillas that live there.



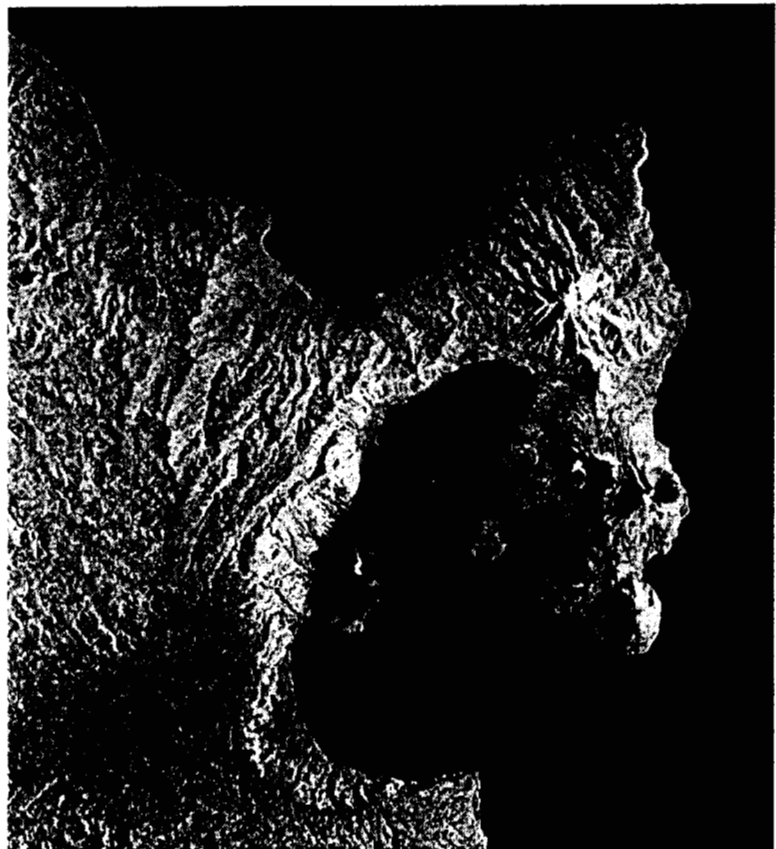
Magellan at Venus. During each orbit the spacecraft's high-gain antenna was alternately used for SAR mapping and data transmission to Earth.

tion and time data.

One of the first things researchers looked at was how to separate the receiving antennas. This was eventually accomplished by using a mast that could be extended from a canister in Endeavour's cargo bay. Reaching out 60 m, this mast made the SRTM/Endeavour combination the largest structure ever assembled in space. Due to launch restrictions at Cape Canaveral the highest latitudes that can be reached by the Shuttle are $\pm 57^\circ$. To achieve global coverage in the 10-14 days typically available for

a Shuttle flight, the swath covered by the instrument would therefore have had to be several times larger than for the SIR series of instruments. However, by steering the radar beam electronically, a technique known as ScanSAR, which had been tested briefly by SIR-C, could switch between two adjacent swaths. In addition, both polarisations were utilised for a simultaneous dual-beam capability. This allowed a total swath approximately four times as wide as SIR-C, for contiguous mapping of the Earth from the Shuttle in only 11 days (not counting the

A SIR-C/X-SAR image of the Rabaul volcano on the island of New Britain, Papua New Guinea taken almost a month after the 19 September 1994, eruption that killed five people and covered the town of Rabaul and nearby villages with up to 75 cm of ash. More than 53,000 people were displaced by the eruption. The area shown is approximately 21 km by 25 km. Ash deposits appear red-orange. The faint blue area in the bay in the centre of the image is a large raft of floating pumice fragments that clogged the inner bay.



What Is Synthetic Aperture Radar (SAR)?

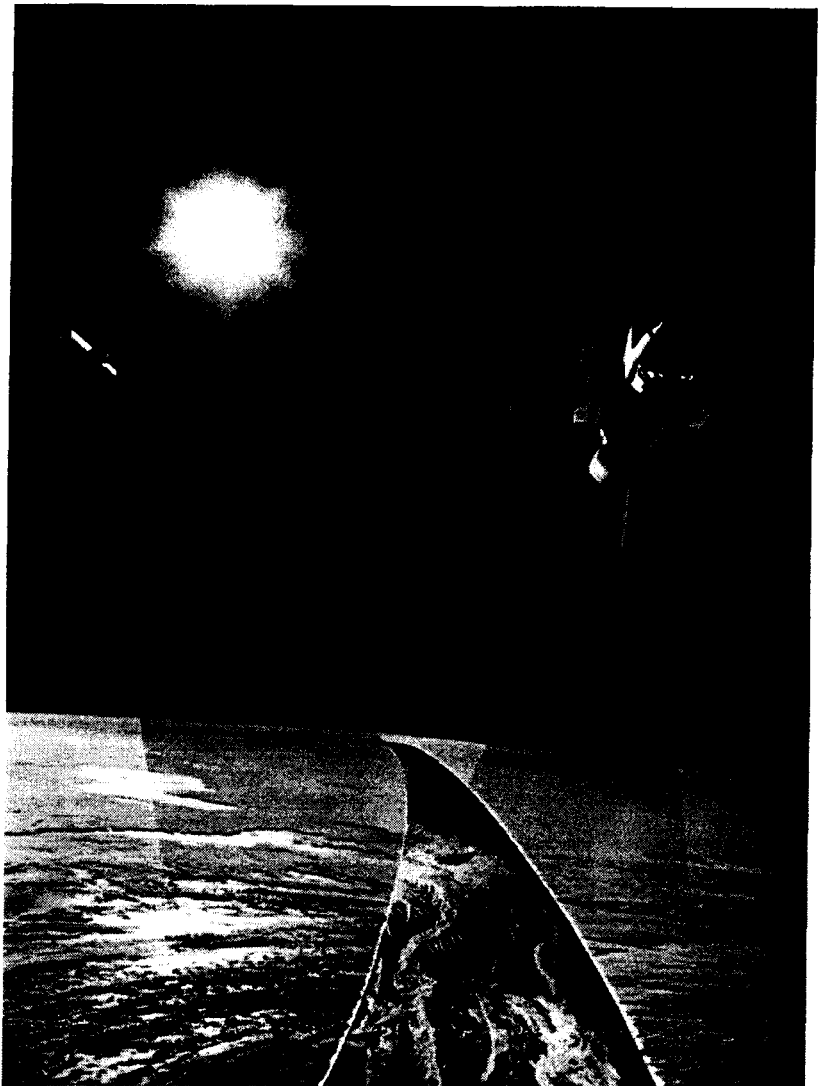
The along-track resolution for "real aperture" imaging radars is the width of the antenna illumination on the surface, so that increased resolution requires a longer antenna and/or a lower altitude. "Synthetic aperture" radar (SAR) was theorised by Carl Wiley in 1951 as a technique for achieving higher along-track resolution than the width illuminated by the antenna - independent of altitude. Each point on the surface produces a different Doppler profile in the reflected pulses as the radar flies by. By combining radar returns using the Doppler and time-delay information, a longer "virtual" antenna is synthesised. SAR requires a side-looking configuration. The SAR technique allows the acquisition of high-resolution radar images from space.

years of pre-mission planning, of course!).

SRTM Data for Commercial Applications

Much of our planet has been mapped previously, by everyone from the Micronesian navigators to the Ordnance Survey, on scales of continents

This SIR-C/X-SAR radar image shows three of the Society Islands located 220 km northwest of Tahiti in French Polynesia in the south Pacific ocean; Raiatea (bottom), Tahaa (centre), and Bora Bora (top). The area shown is 39 by 67 km. Ocean swells caused by trade winds are seen as small ripples on the ocean surface around all of the islands; dark areas are regions of low wind.



The SRTM radar penetrating clouds to uncover a ground swath as it flies over the Earth.

to city streets. So one might wonder what use is yet another representation of our planet. The answer lies in SRTM's unique combination of global coverage, local accuracy and availability of the product in digital form. Although restricted to a flight path

between 57°N and 57°S, by making measurements on the northerly side of its ground track SRTM was able to gather high resolution, digital, topographic information over every land surface between 60°N and 54°S. While not the whole globe, these latitudes

What is Interferometric SAR?

Interferometric SAR is a technique, analogous to optical stereo, for measuring changes in surface heights by observing the phase differences between two interfering signals.

A pair of complex SAR images of the same surface area are formed with receivers at two different, but closely spaced, observational positions. The pair of images are combined to produce an interferogram, which is a two-dimensional display of the phase differences between the received signals in the two images. The interferograms are translated to changes in height, which is used to produce a terrain elevation map. The elevation data can be subsequently used to remove distortions and produce a three-dimensional image. Height measurement accuracy depends on precise knowledge of the across-

track interferometer baseline length and attitude. Baseline knowledge at the mm and arcsec levels are required for metre level height accuracy.

Terrain change over time in the direction of the radar can be measured with very high precision (cm level) by differencing two interferograms of the same target area at different times. This requires at least three observations of the same surface area.

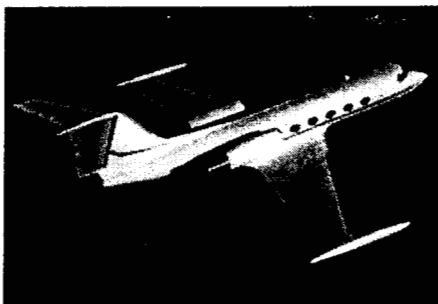
A properly equipped spaceborne interferometric SAR system can produce a highly accurate global digital elevation map, including cloud-covered areas, and can measure small changes in surface height with high precision. This can be done in significantly less time and at significantly lower cost than with other systems.

bound nearly 80% of the Earth's land surface, including many areas not previously mapped in this way, and nearly 95% of its population.

The SRTM maps will have a horizontal resolution of 30 m and a relative height accuracy of 10 m. For maps on a global scale it far exceeds anything previously available. This satisfies a long-term goal of NIMA, a part of the US Department of Defense, and its predecessors to build accurate global topographic maps for mission planning and rehearsal, modelling and for flight simulations. Similarly, scientists are looking forward to using SRTM data for studies as diverse as flooding, erosion, landslide hazards, earthquakes, ecological zones, weather forecasts and climate change. More commercial applications will include improved topographic maps for hikers, fire-fighters and geologists.

Looking Ahead at JPL

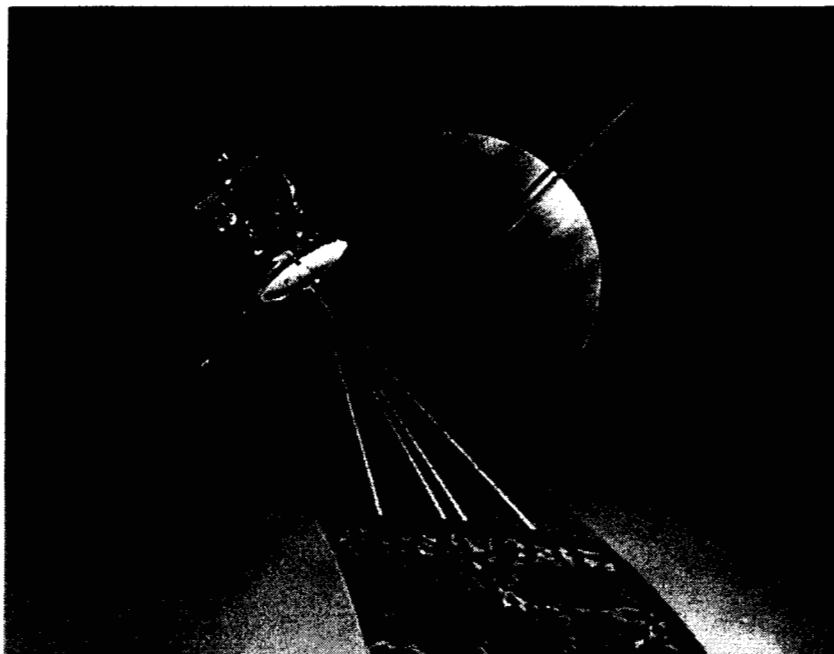
For the future, JPL scientists and engineers are pursuing several Earth-orbiting and planetary radar imaging initiatives. To lower the cost of future SARs systems will be developed in cooperation with industrial partners, which are much smaller and lighter than the SIR/Shuttle series. These systems will be able to operate in orbit



The GeoSAR system on board a Gulfstream II jet.

for five years, providing complete coverage of the Earth's surface every 8-10 days with multiple repeats of ground tracks. This will provide the capability to continuously monitor changes in the Earth's topography on the level of a few millimetres, through "repeat-pass" interferometry, and to image features as small as 1-3 metres across.

On a technical level though, such will use many aspects of radar technology developed on the Shuttle. Science applications will continue to favour 1.2575 GHz (L-band). The L-band will be augmented by higher resolution X or C-band instruments. Multiple polarisations in the returned signals will also be accommodated, to better distinguish surface textures, water content, etc. As with SRTM, the anticipated scientific uses include measuring the movement of surface features,



Artist's conception of Cassini using radar imaging at Titan.

such as glaciers, volcanoes and fault lines, monitoring floods, archaeology, and constructing detailed and accurate elevation maps, while the commercial partners expect to market the data in areas such as land management, planning and development, topographic mapping, and for oil and coal monitoring.

In another collaborative effort JPL, the California Department of Conservation, the Caigis Corp. and the US Department of Defense have been working on the GeoSAR airborne radar. This comprises X and P-band radars mounted on a Gulfstream II business jet. In an interferometric mode they will be able to make local, single-pass topographic maps, as well accomplishing other imaging tasks. A notable feature will be the long wavelength P-band system (350 MHz, i.e. UHF), which is able to image through tree

canopies.

Finally, in the tradition begun by the ALSE and Magellan, another JPL radar imager is pursuing a planetary exploration mission. The Cassini spacecraft has already conducted flybys of Venus and the Earth and is currently engaged in its long cruise to the Saturnian system. On board is a 4 m communications dish antenna, which will also be used by a 13.78 GHz (Ku-band) SAR. In 2004 Cassini will arrive at the Saturnian system, where the radar will be used to pierce the haze of nitrogen and hydrocarbon compounds that surrounds Saturn's biggest moon, Titan, searching for liquid ethane oceans and imaging the surface features.

Acknowledgements

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Related Web Sites

NASA/JPL imaging radar homepage:

<http://southport.jpl.nasa.gov/>

SRTM homepage at JPL:

<http://www-radar.jpl.nasa.gov/srtm/>

SIR-C/X-SAR images website:

<http://www.jpl.nasa.gov/radar/sircxsar/>



Left: This image of San Francisco, California, taken by SIR-C/X-SAR, shows how radar distinguishes between densely populated urban areas and nearby unsettled areas. Downtown San Francisco is at the centre, while Oakland is on the right. Some city areas appear bright red due to the alignment of streets and buildings to the incoming radar beam. Bridges in the area are also visible including the Golden Gate Bridge (left centre), the Bay Bridge (right centre), and the San Mateo Bridge (bottom centre). The San Andreas (lower left) and Hayward (right) faults are also visible. The image is about 42 km by 58 km with north toward the upper right.