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THE VENUS ORBITAL IMAGING RADAR (VOIR) MISSION

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ABSTRACT

The Venus Orbital Imaging Radar (VOIR) mission is currently being prepared by NASA to map the surface of Venus with an orbiting side-looking radar (SLR) imaging device from an altitude of about 250 km. This will provide near global and detailed data on the surface comparable or even superior to that available on other terrestrial planets. So far, the surface of Venus is mapped only at a resolution of about 20 to 100 km, insufficient to analyse the planet's surface and processes that shaped it.

VOIR currently is planned to arrive at Venus in 1988, following a launch from the Space Shuttle. However, both detailed project parameters and timing are subject to considerable discussion and cost considerations. Mission design has thus not been frozen and a description is of only limited interest. Therefore the paper concentrates rather on a discussion of the current knowledge base and scientific environment in which VOIR is developing. This includes a review of the results from Earth based radar and from Pioneer Venus altimetry, and of previous experiences with the VOIR-type sensor, namely of orbital mapping with radar images, as demonstrated in the Apollo 17 Lunar Sounder Experiment and the terrestrial Seasat project. This serves to illustrate the essential objectives and techniques of VOIR to map the Venusian surface.

1. INTRODUCTION

Among the terrestrial planets Venus is least well understood. This is caused by the perennial cloud cover hiding the surface from observation (Fig. 1). Radar imaging is the only means of mapping this surface. This has been done from Earth using large antennas of radio telescopes, and from the Pioneer Venus orbiter using a radar altimeter. However, geometrical resolution so far was 10 to 30 km for Earth based methods, and 30 to 100 km for Pioneer Venus. This is far poorer than the resolutions at which all other terrestrial planets are known.

Figure 1: Mariner 10 vidicon image of the Venusian cloud cover in UV-light.

Venus Orbital Imaging Radar (VOIR) is thus a mission planned by NASA to map the entire surface of the planet at a resolution at least comparable to that at which other planets have been imaged. A high resolution side-looking radar (SLR) system will be carried into a 250 km circular orbit around Venus. The essential purpose of VOIR is a study of the Venusian surface; other experiments are being planned as well but are of secondary weight in mission design.

VOIR is the result of numerous proposals to map the Venusian surface through the heavy layer of clouds. Early project studies were by Brown et al. (1972), Saunders et al. (1973), Friedman and Rose (1973), Martin-Marietta (1974), Westinghouse (1974) and others. The engineering challenge of such an undertaking inspired numerous smaller preparatory projects, and it may have led to spin-offs in other areas, such as in the Apollo 17 Lunar Sounder Experiment (ALSE) in 1972 and Seasat in 1978, two projects for orbital mapping from radar images. These projects generated experiences that currently help greatly in preparing VOIR and they are providing a capability to predict the expected quality of VOIR images.

The paper will describe the scientific environment in which VOIR is developing, presenting a review of the current knowledge of the surface of Venus which resulted from Pioneer Venus and Earth based radar. It will then outline the operation of the synthetic aperture radar for VOIR and present examples of images as they might be generated in this mission.

2. CURRENT KNOWLEDGE OF THE SURFACE OF VENUS

So far 14 spacecraft have successfully been sent to Venus. Surface images exist, however, only from three missions: Venera 9 and 10 with one image each taken directly after landing (Florensky et al., 1977), and from Pioneer Venus orbiter data (Pettengill et al., 1979a, b, 1980; Masursky et al., 1980). Surface images also exist from Earth based radar employing either the radar telescope at Arecibo (Hagfors and Campbell, 1974; Rogers et al., 1970, Campbell et al., 1972,1976, 1979, 1980) or

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the Deep Space Network (DSN) antenna at Goldstone in California (Goldstein, 1965; Goldstein et al., 1972, 1976,1978; Jurgens, 1970, 1980; Rumsey et al., 1974).

2.1 Data from Pioneer Venus

The Pioneer Venus orbiter radar mapper provided the most extensive surface data available on Venus so far. It operated in two modes:

(a) as an altimeter;
(b) as a side-looking radar imaging system.

The results from this sensor were presented by Masursky et al. (1980) and by Pettengill et al. (1980).

Topographic relief was obtained from the altimeter measurements. This is shown in Figure 2 in the form of a shaded relief map, juxtaposed to a comparable presentation of the Earth for ease of comparison. Figure 3 is a contour map of Venus at a 1 km contour interval. It should be noted that the altimeter measurements after 16 months of data collection have a density of between 75 and 200 km. The accuracy of an individual height is estimated by Pettengill et al. (1980) to be about ± 200 m (standard deviation). Depending on the further duration of the Pioneer Venus mission a higher resolution topographic map can be accumulated.

The other main product from the orbiter radar mapper is a mosaic compiled from the data obtained in the side-looking radar imaging mode. This coverage is less than that produced in the altimeter mode since the orbit was elliptical and imaging was only done when the spacecraft was at altitudes below 550 km. Altimeter data, however, were taken also at higher spacecraft altitudes.

2.2 Data from Earth Based Radar

Mapping of segments of the Venusian surface began in the sixties with the reception of echoes from radar pulses sent to Venus. Early images were obtained with interferometric methods at 3.8 cm wavelength by Rogers and Ingalls (1969). Currently these images are generated with the antenna in

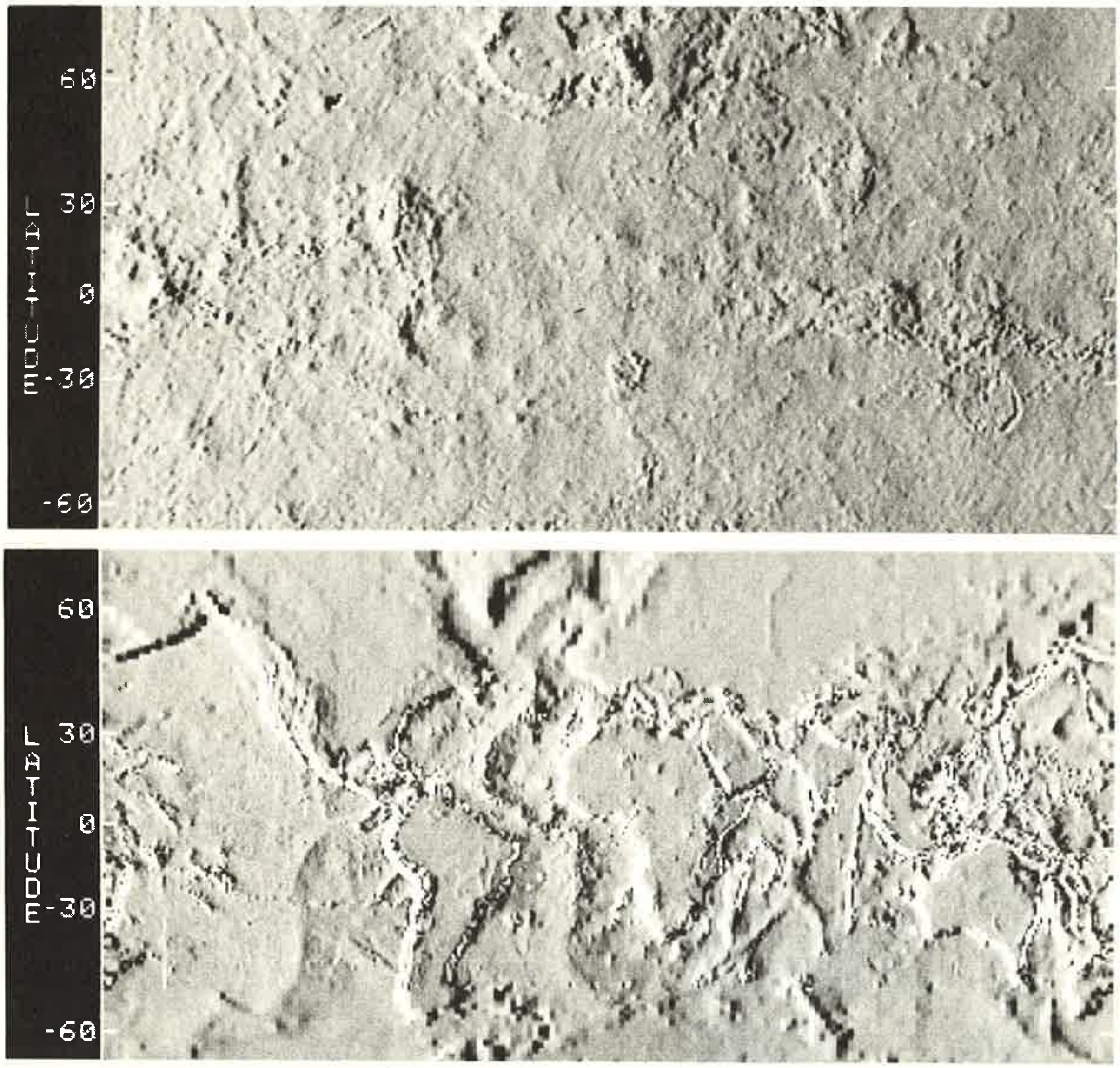

Figure 2: Shaded relief maps of Venus and Earth. Venus data (above) are compiled from Pioneer Venus altimeter at a grid spacing of 75 to 200 km (from Masursky et al., 1980; Pettengill et al., 1980). Earth presentation for comparison.

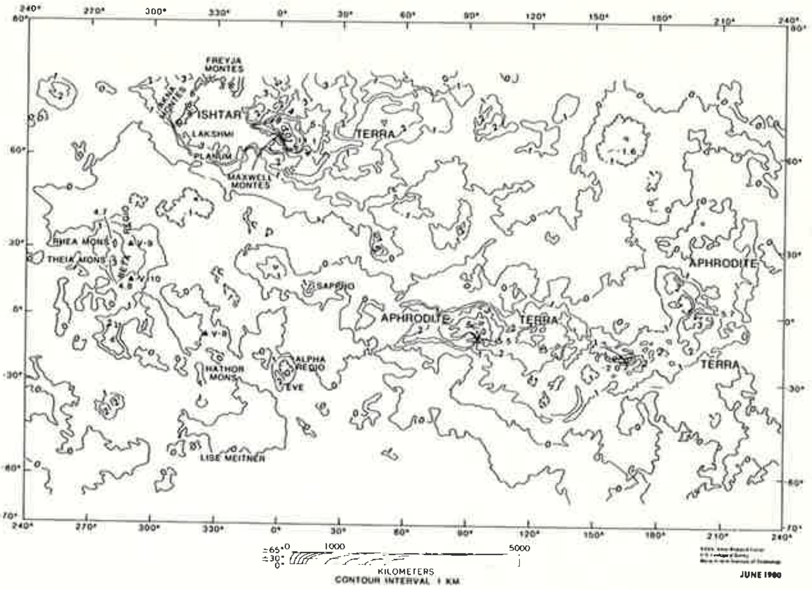

Figure 3: Contour map with 1 km equidistance, compiled from Pioneer Venus altimeter data with a grid spacing of 75 to 200 km (from Masursky et al., 1980).

Arecibo, Puerto Rico (Campbell et al., 1980) and with the Goldstone antenna in California (Jurgens et al., 1980).

The technique employed is explained in Figure 4: A transmitted, highly focussed radar pulse illuminates the surface of the planet. The echo is received on the Earth by the transmitting antenna. Echo time serves to resolve the illuminated area into parallel slices as shown in Figure 4, where the Doppler effect is created by the revolution of the planet.

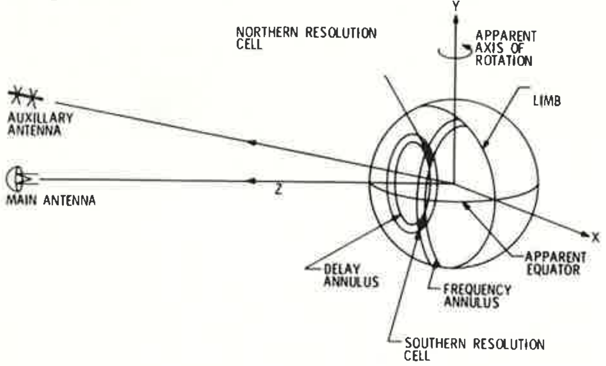

Figure 4: Concept of Earth based radar to map planetary surfaces.

We can observe in Figure 4 that the received echo can be resolved into separate though ambiguous image points: each point corresponds to two object areas, one in the northern, one in the southern hemisphere. This ambiguity can be resolved if the beam is sufficiently focussed to illuminate just one hemisphere, as is being done in comparable work on the Moon. If sufficient focussing is not feasible, such as is the case with Venus, then an interferometric method must be used to resolve the ambiguity. The radar echos are received at two antennas rather than one, and are summed up. This allows to measure phase differences at the two receiving antennas. Phases are different in the echos from the northern and southern hemisphere at the two antennas. Goldstein et al. (1978) carried the interferometric technique even further and employed three antennas: the large one for transmission and reception, and the two secondary antennas for reception only. This configuration not only allows for the separation of north-south signals, but also for the creation of a three-dimensional model of the topography. The technique has an analogy to stereo at very steep look angles and with small stereo bases. We know that this results in comparatively high accuracies of the vertical dimension, similar to an altimeter, but leaves a weak planimetric solution.

Earth based radar images of Venus have a resolution of 10 to 30 km (diameter of a pixel). Campbell et al. (1980) report on images of selected areas at a resolution of 5 km. Presentations are in one of two forms: (a) as normal radar images where image density is proportional to the radar backscatter; (b) as a relief presentation with coded gray tones for a digital height model, or other similar displays of height.

Examples of Earth-based radar images are shown in Figures 5 and 6. Figure 5 is a mosaic presenting an overview of results from Campbell et al. (1980) obtained at Arecibo. Figure 6 is a set of illustrations typical of the results obtained at Goldstone (Jurgens et al., 1980), presenting both a reflectivity map and a map of topographic heights.

These images all show a higher geometric resolution than those obtained from Pioneer Venus. This demonstrates the value of Earth based observations inspite of existing orbiting spacecraft. The essential advantage of the current coverage by Pioneer Venus over the Earth based radar is the more global coverage and the higher accuracy of individual topographic height measurements.

2.3 Interpretations of the Available Images

Malin and Saunders (1977) were the first to attempt a geological interpretation of the data received through Earth based radar. They described landforms, identified features with a tentative classification as volcanic and as impact craters. A mo-

Figure 5: Mosaic of Earth-based radar images of Venus, obtained by Campbell et al. (1980) in Arecibo. Shown is northern hemisphere.

re thorough analysis had to wait, however, for the more global, accurate, but less densely sampling Pioneer Venus mission. Pettengill et al. (1980) and Masursky et al. (1980) gave an exhaustive analysis from the currently available data, combining Earth-based with satellite measurements.

Maxwell Mons is the highest feature (compare Figure 3 for feature names), about 11.1 km above the reference radius of 6051.0 km. The lowest area seems to be Diana Chasma in Aphrodite Regio[1]. The entire relief seems to amount to about 2/3 of the Earth's (20 km). Venus topography is less accentuated than the Earth's (compare the shaded relief maps of Figure 2). The contours in Figure 3 show that highlands indeed are of a limited extent.

There is an abundance of evidence for craters of both volcanic and impact origin. An example of a volcanic feature probably is Rhea Mons at 30°N, 80°W, in Beta Regio. The early speculation of Malin and Saunders (1977) regarding plate tectonic activity on Venus still is a valid hypothesis: tectonic activity seems probable, for example due to the existence of highlands and of deep trenches such as Diana Chasma. Early attempts have been made at crater counts to compare Venus to other terrestrial planets. The coarse resolution of current images impairs the success of such attempts.

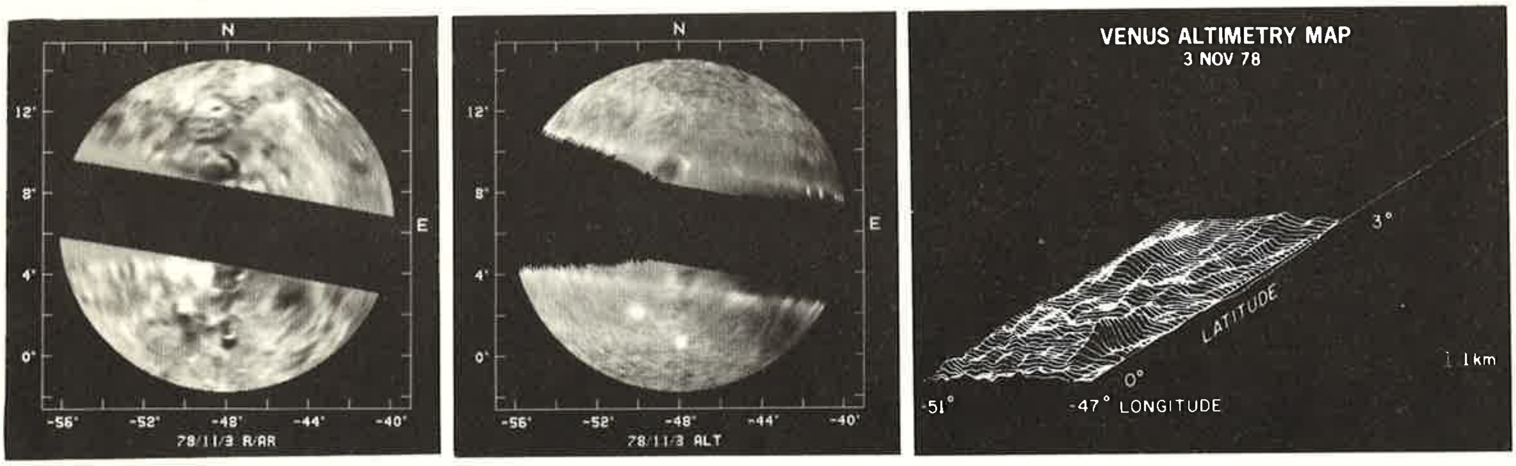

Figure 6: Earth-based radar image and derived presentations; (a) reflectivity image, (b) digital height model coded with gray tones, (c) digital height model of a section presented as as a profile plot. Illustrations obtained through the Goldstone antenna (courtesy R. Jurgens, Jet Propulsion Laboratory).

Planned launch	November 1987
Launch vehicle	Space Shuttle, Centaur
Beginning of imaging	July 1988
Duration of science acquisition	126 days nominal mission
Orbit type	Circular
Circularization of orbit	Aerobraking
Orbit inclination	87°
Orbit altitude	250 km ± 25 km
Imaging sensor	Synthetic aperture radar
Sensor wavelength	L-band (25 cm)
SAR antenna look angle	45° to 50° off-nadir
Pointable antenna	Still under discussion
Ground resolution, mapping	600 per line pair
Ground resolution, high	150 m per line pair
Swath width, mapping	30 km
Swath width, high resolution	12 km
Length of image strips	45 min. (time) per orbit
Multiple looks in mapping mode	16
Multiple looks in high resolution	4
Expected orbit accuracy, 1 sigma	Still under discussion
72 hrs after occurrence, absolute	1 km radial, 10 km plan
72 hrs after occurrence, relative	.3 km radial, 1 km plan
Other primary data acquisition	Altimetry
Secondary science experiments	Various (5 in total)
Altimeter accuracy	As SAR high resolution

Table 1: Proposed VOIR mission parameters (1981).

Many questions remain unanswered, such as regarding plate tectonics, the history of the planet's surface, the type and origin of craters, the interaction between atmosphere and surface etc. Such questions can only be tackled with improved imaging capabilities. Available data on Venus are limited when compared to Mars, where Mariner 9 imaged at a resolution of up to 250 m per pixel; Mercury was mapped with 1 km per pixel. Venus is mapped at 100 km resolution, and some small segments with 5 km per pixel.

An improved imaging capability comparable to that of Mariner 9 is required to achieve a similarly thorough understanding of Venus than that we have had after Mariner 9 from Mars. Venus Orbital Imaging Radar (VOIR) promises to provide this capability.

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[1] Venusian features are named after mythical and other famous women, except for Maxwell Mons.

3. VOIR MISSION PLAN

Early concepts for orbital side-looking radar exploration of Venus were studied in an extensive report by Brown et al. (1972). Since then the parameters of the mission have been changed several times. The current plan is shown in Table 1. A spacecraft, launched from the Space Shuttle in November 1987, will arrive at Venus four months later and enter into a highly elliptical orbit. By a technique called 'aerobraking', the orbit will be circularized using atmospheric friction near periapsis (Figure 7).

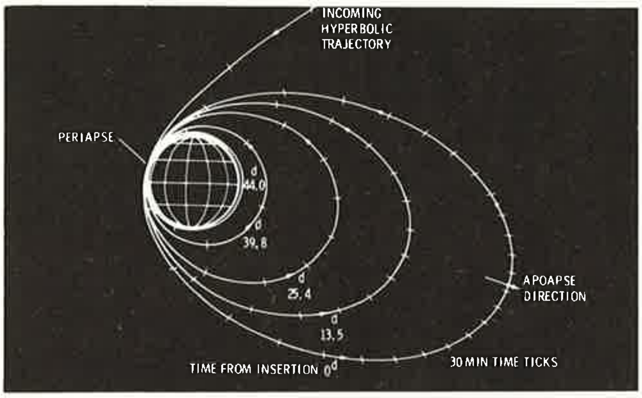

Figure 7: Aerobraking for the VOIR mission to circularize the elliptical orbit without fuel consumption.

From the circular orbit a radar coverage of nearly the entire planet will be generated during 126 days. Multiple coverages in near-polar regions will serve to define the rotation axis and a coordinate grid. Radar coverage will be tied to this grid based on orbit data and on the use of overlapping coverages. Limitations on energy and data rates result in a requirement to use an intricate imaging stretegy to sequentially cover the entire surface in a patchwork pattern.

The currently envisaged data rates are 1 Mbits per second for imaging and recording, and 1 Mbits per second for transmission to the Earth. Intermediate storage of the radar signals is planned on tape recorder. for coverage of the plant's backside.

There will be two geometric resolutions: the so-called 'mapping mode' at 600 m per line-pair and a 'high-resolution mode' at 150 m per line-pair. The global coverage is only for the lower resolution. Higher resolution will be used as the mission develops. Current provisions are for a 1% coverage at this high resolution during the nominal mission, of areas that will be selected on the basis of the mapping mode data. This strategy is motivated by the experiences on Mars, where lower resolution images led to misinterpretations that became obvious with later higher resolution images (Mariner 9).

The radar look angle will be at about 50° off the nadir. This is seen as a compromise between the accentuation of gentle relief with a simultaneous lack of lay-over distortion (obtainable with large look angles off-nadir) and the accentuation of backscatter differences of various materials and roughnesses with simultaneous lack of shadowing (obtainable with small look angles).

A discussion still concerns stereo (Figure 8). Clearly stereo intersection angles will be poor if look angles are kept constant throughout the mission. Stereo intersection angles of only 3° or so must be accepted if no look angle variation is provided. However, much larger intersection angles are optimal. The current VOIR science investigation group still is pressing for the inclusion of a variable look angle in the design of the mission, not only for stereo, but also to be capable to illuminate the Venusian surface during the mission at whatever angle then appears to be the optimum. This may be guided by the surface features and materials to be encountered at the time of the mission.

The main argument against a variable look angle is the added complexity and resulting cost. A simple spacecraft roll, or the use of ascending and descending orbit passes could result in a 'free' second look from the opposite side; however, one must expect this to produce image pairs that cannot be used for stereo analysis by planetologists nor for the measurements of topographic contours.

Besides imaging radar also altimetric data are planned to be acquired in VOIR. For this purpose the imaging radar system is to be used as an altimeter, imaging the nadir. These data will help to improve the knowledge of surface topography and eventually shall be combined with the results from imaging into a composite product. Techniques for this task have not yet been developed.

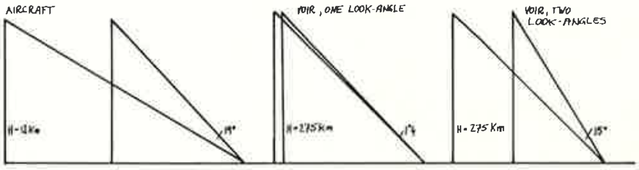

Figure 8: Stereo configurations for aircraft, VOIR without variable look angles, and with variable look angle.

4. CURRENT IMAGING RADAR IN VIEW OF VOIR

4.1 Imaging Side-Looking Radar (SLR) System

Extensive literature exists on imaging radar and applications to mapping and geoscience (see f.e. Matthews, 1975; Radar Geology, 1980). From orbital altitudes a reasonably high resolution can only be expected using a synthetic aperture technique. In real aperture radars imaging is achieved by illuminating a small segment (line) on the ground using an electro magnetic pulse, and by receiving and recording the reflected energy according to Figure 9. An areally extended image of terrain is generated by sequentially composing repeated pulses and lines while the sensor is transported past the terrain.

Synthetic aperture radars (SAR) do not record the received echo directly but only after summing it up with a coherent reference frequency identical to that of the transmitted pulse. This creates a holographic record containing phase and Doppler frequency information about the received echo. A processing step, usually in a laboratory, is required to convert these holographic raw signals to a usable image of the object. The processing step is called 'correlation' An example of a raw signal recording and correlated SAR image is shown as Figure 10.

Currently correlation of SAR signals is done optically with laser light; however, digital correlation techniques are quickly becoming operational and are the ones to be used for VOIR exclusively, possibly requiring the establishment of optimal computer architectures.

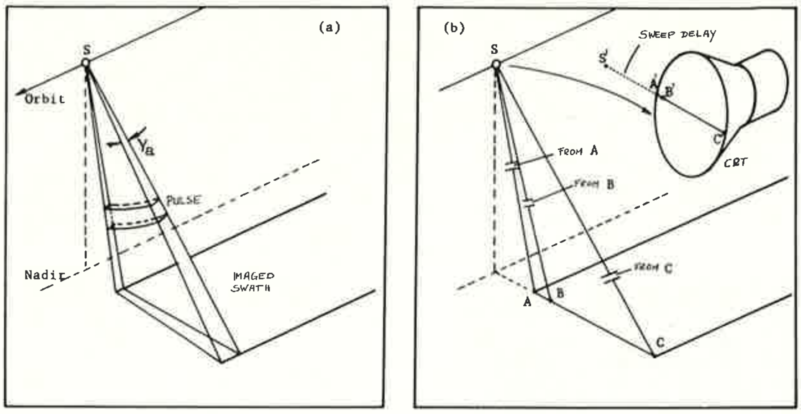

Figure 9: Principle of real aperture radar imaging system with the operation in object space, transmitting a pulse (a), and receiving echoes to be recorded on tape or on a cathode ray tube (b).

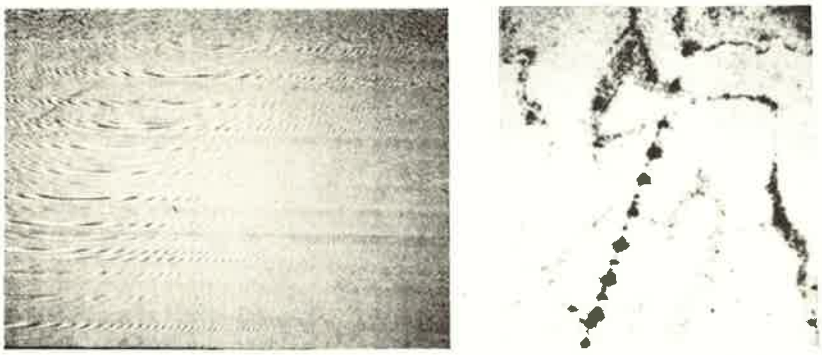

Figure 10: Example of a synthetic aperture radar image, (a) in its holographic raw form, (b) in its final iamge form after correlation. Shown are a series of transmission line towers (courtesy W. Brown, JPL).

4.2 Side-Looking Radar from Satellites

Side-looking radars are being used in civilian applications from aircraft since the early 1960's. Orbital SAR was employed for the first time in the Apollo 17 Lunar Sounder Experiment (ALSE). Results were presented by Phillips et al. (1973). Attempts at mapping segments of the lunar surface were undertaken by Tiernan et al. (1976) using single radar images, and by Leberl (1976) using both single and stereo images. An example of a lunar ALSE stereo pair is shown as Figure 11.

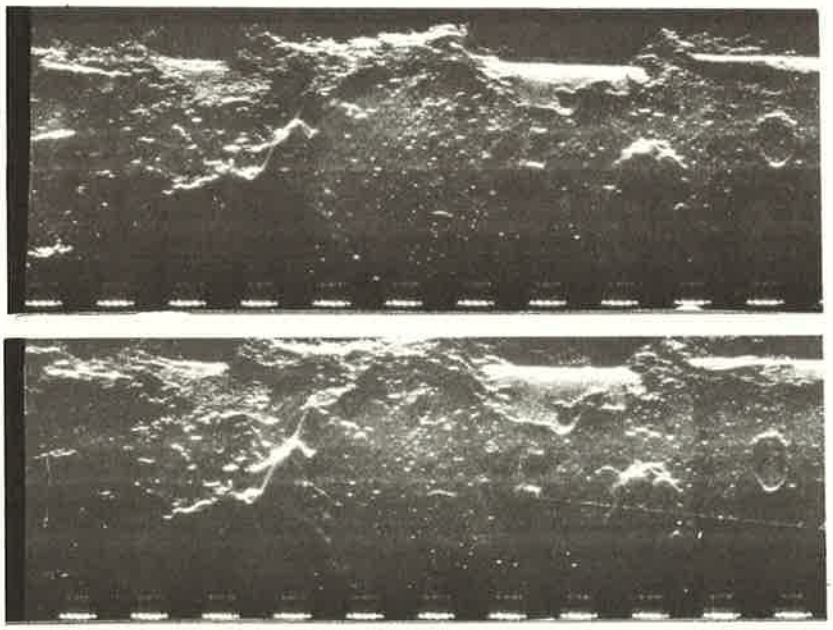

Figure 11: Apollo 17 Lunar Sounder Experiment (ALSE) radar stereo pair, VHF (2 m) wavelength, taken over crater Maraldi.

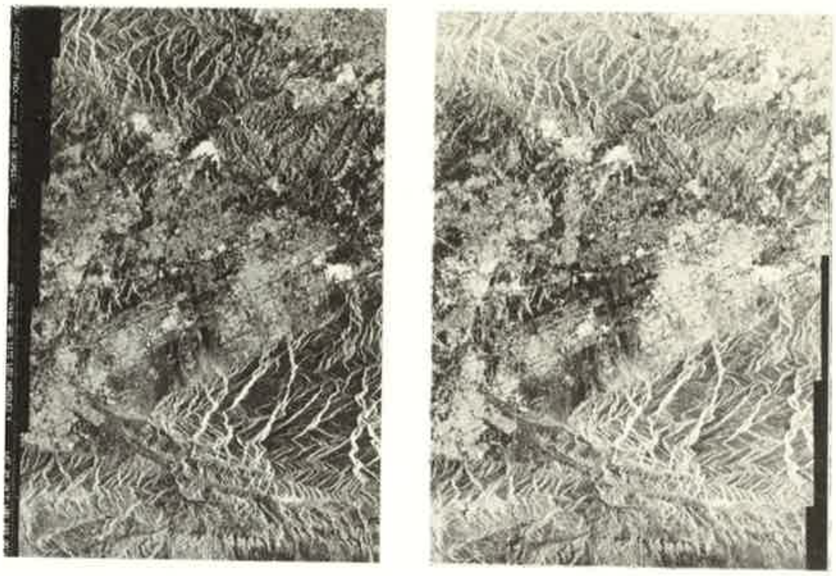

Figure 12: Example of a Seasat SAR stereo image pair generated over Los Angeles, digitally correlated at NASA Jet Propulsion Laboratory. Orbits 1291 (left) and 416 (right). Stereo base is 40 km, flight altitude is 800 km, base height ratio is thus small compared to stereo photogrammetric standards. This stereo case is called 'same side'.

Orbital radar was also generated in the Seasat mission of 1978 to map the oceans and continents of the Earth (e.g. Teleki and Ramseier, 1978). Results are shown in Figure 12 in the form of a stereo pair of the area of Los Angeles. The characteristic radar image projection leads to typical distortion of high relief. Stereo observation allows one to interpret such distorted presentations. The example is a 'same side stereo arrangment', where illumination is from one side only. This is different from 'opposite side stereo' with illumination from two opposing sides. The latter does normally not produce valid stereo for binocular stereo viewing.

4.3 Some Observations on Geometry

In order to correctly interpret a radar image it is necessary to understand the imaging geometry. Echo time imaging is the basis of SLR. Therefore all points on the planet's surface that are at the same distance from the antenna will project into the same image point. We have here a 'range projection' as opposed to the central projection of camera imaging. A crater on the Moon was therefore imaged by the ALSE system as shown in Figure 13.

The bottom of the crater is imaged, but the sidewall is laid over it in the projection.

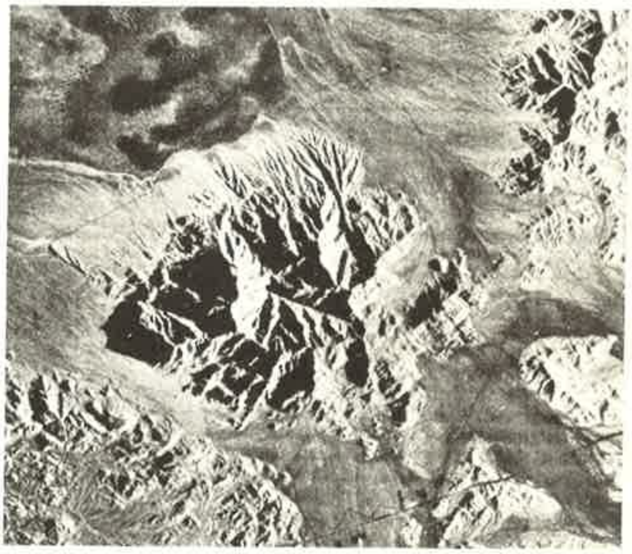

Figure 14: Aircraft radar image of Granite Mountain, California, with a large look angle off nadir; 3 cm wavelength, 12 km altitude. (Courtesy Aero Service - Goodyear).

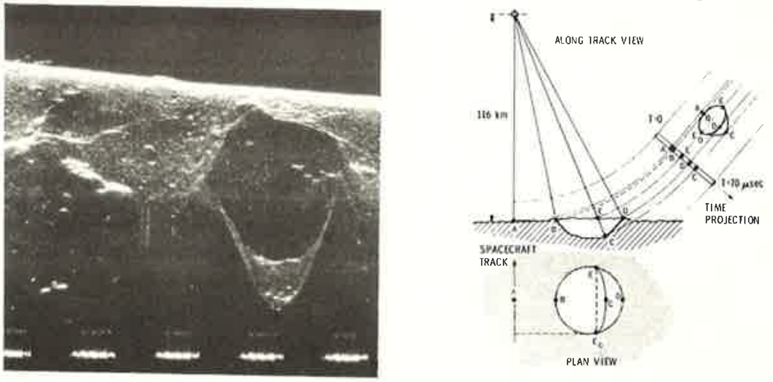

Figure 13: ALSE radar iamge of a lunar crater and geometrical sketch to explain imaging geometry for this crater using the range geometry.

In Seasat and in ALSE, the surface was viewed under steep look angles, with the imaged area at about 20° off-nadir in Seasat, and even near nadir in ALSE. Usually one has not with aircraft radar such steep look angles, but prefers to use much larger ones, anywhere between 45° to 80°, depending on the local circumstances and the purpose of the project. Figure 14 presents an aircraft image. One can note that topographic relief is not distorted to the extent seen in Seasat and ALSE data, and that relief is even accentuated by typical radar shadowing effects, similar to shadows in photography at small sun angles.

From orbital altitudes one cannot expect to achieve comparably large look angles as with aircraft radar due to radar design constraints.

Geometric resolution of SAR is not a function of the distance to the object, but entirely a design parameter. Resolution improves with increasing look angle off-nadir. This is another reason why one prefers larger look angles for imaging. Near nadir resolution is poor. Current aircraft high performance mapping radars resolve the ground with 3m to 10m. Seasat nominally provided a 25 m ground resolution.

4.4 Expected Results from VOIR

Seasat SAR images of land areas on the Earth can be used to simulate expected VOIR images. Figure 15 shows a sequence of Seasat images with artificially degraded geometric resolution to approach that one expected for the VOIR project, and from improved Earth based radar. There are thus images at 4 km, 600 m and 150 m per line pair resolutions. Visual inspection quickly reveals that VOIR -- if successful -- will greatly improve our knowledge of the planet Venus over the state of knowledge available today or to be anticipated with even improved Earth based radar imaging.

5. CONCLUSION

VOIR is being prepared for launch in 1987 to study the surface of the planet Venus with a technique that poses numerous technical challenges. Imaging radar has been used successfully on Earth from aircraft. Orbital imaging with radar, however, is not a widely explored technique. There have only been one mission to the Moon (Apollo 17), one Earth satellite (Seasat) and the orbital flight test 2 of the Space Shuttle with imaging radars on board.

These missions, and available experiences with side-looking radar lead to the expectation that VOIR can produce very valuable data on the surface of Venus. Current knowledge of this surface is comparatively limited. Venus is the least well known of the terrestrial planets inspite of the fact that unique and complex efforts are being undertaken to penetrate the Venusian clouds. The Pioneer Venus radar mapper/altimeter, and Earth based radar are producing a stream of data to analyze the planet's surface, however at a coarse level only.

VOIR on the other hand,is expected to generate images of much greater resolution and more favourable imaging concepts. If a stereo arrangement is incorporated, e.g. by providing a movable antenna, then the detailed morphology of the topography will become accessible to study. This feature of the mission is still under discussion.

There is no doubt that SAR technology will experience a significant boost from VOIR. Digital processing of large volumes of data covering an entire planet will depend on the compilation of sophisticated computer architectures. The SAR sensor itself will have to satisfy extreme requirements. But it is the only tool to unravel the secrets that lie hidden underneath the Venusian clouds.

Figure 15: Expected future Venus radar images, demonstrated and derived from Seasat SAR of the Apalachian Fault Belt, Tennessee. Above: 4km resolution of future Earth based imaging; Center: 600m per line pair; 150 m per line pair. Data provided by D. Held, C. Elachi, M. Kobrick, NASA-JPL.

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