SECTION 2

SCIENCE AND RADARGRAMMETRY

2.1 SCIENCE CONSIDERATIONS

The exploration of Venus is perhaps one of the easier nonterrestrial space missions to justify, even to the general public. In the popular mind the space program has not yielded great rewards in terms of solving earth-bound problems, and of increasing concern is the fate of our own planet given the perturbations technology has made us capable of exerting on it. Since Venus is almost the twin of the earth in mass and density, it provides a convenient laboratory for evaluating the effects of some of these perturbations. A mission to map Venus would therefore be a major step in expanding the knowledge of the origin, evolution and eventual fate of the terrestrial planets, including the earth.

Of course to justify a mission an orbital radar should be able to provide information not obtainable from the earth, given equal expenditures. A separate study would be required to evaluate the earth-based radar capability as a function of funding, so Figure 2-1 shows the ultimate coverage and resolution that is probably attainable, along with that of the candidate VOIR. In this plot "identification resolution" has been used to provide a comparison with Mariner coverage of Mars and is taken to be four radar resolution elements. The low resolution mode of VOIR provides an improvement in resolution by a factor of about three over the best that could be obtained from the earth. More important though is the coverage. Earth-based coverage will always be limited in principle by the fact that Venus presents the same side to the earth at each inferior conjunction. VOIR, on the other hand, would provide virtually 100% coverage at uniform resolution.

As far as observable, all of the terrestrial planets and satellites show a fairly strong global assymmetry, or at least substantial low order terms in their topography. Venus' suspected tidal lock with the earth indicates that it too probably shares this trait. Therefore, total global coverage is quite important and is a strong factor in favor of a VOIR. The experience with Mars is well-known, where early missions provided small and misleading samples of the surface, and Mariner 9 revealed the true active nature of the

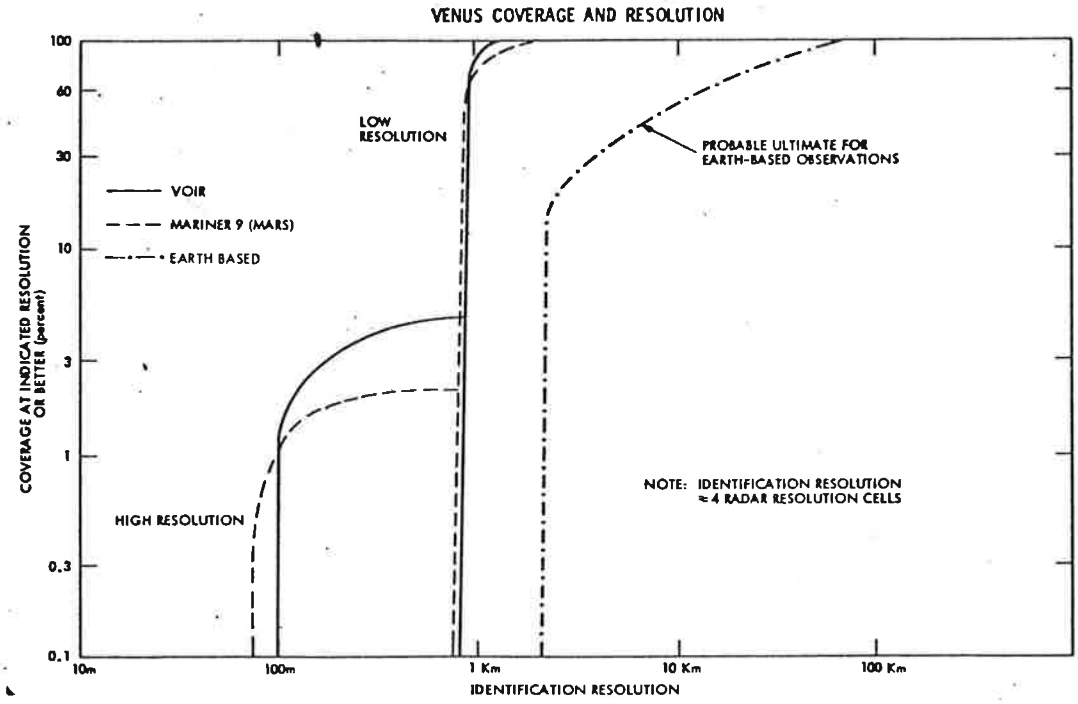


Figure 2-1. Earth-Based Versus Orbiting Radar Capabilities

planet with it's global coverage. Given the complete coverage possible with the low resolution mode of VOIR, one could then construct a mosaiced globe of Venus similar to that produced for Mars from Mariner 9, a feat that could not be accomplished using earth-based data alone.

In addition, of course, several percent of the planet would be covered in the high resolution mode, allowing geologists to study interesting features in detail as was done with Mars. This again could not be accomplished from the earth.

2.1.1 Topography

Theory is of little help in predicting what kind of topography to expect on Venus. There are several reasons to expect Venus to be generally much rougher than the earth, and a corresponding number of reasons to expect it to be smoother. For example, the high surface temperature means the interior is at least 200° hotter than the earth at all depths and therefore volcanism and tectonic mountain building may be more active. Also, the primary cause of erosion on the earth is water (even in very dry deserts) and there is none on Venus (now, at least). On the other hand, the higher temperature may indicate a different viscosity or strength for Venus rocks and more rapid relaxation of large uncompensated surface features. In addition, since there seems now to be substantial amounts of sulfuric acid in the atmosphere, there could be chemical erosion of the surface. So data presently available must be relied upon. Basically, the earth-based radar images show that there are large scale variations in radar backscatter, and elevation differences of several kilometers (Goldstein, et al., 1976; Campbell, et al., 1976; and earlier papers).

The high resolution images show craters, but their depths seem to be less than expected. This could mean that they are impact features that have been subdued by isostatic compensation or volcano calderas partially filled with lava. Venera 9 landed on a 15° to 25° slope and is surrounded by flat boulders up to 50-70 cm across and up to 15-20 cm thick. Venera 10 landed on a plain composed of fracturing and weathering (Florensky, et al., 1977; Keldysh, 1977). The Venera bistatic radar experiment (Kucheryavenkov, 1976) showed, along with two rougher areas, one region about 800 cm across with characteristic slopes of 1° to 2°, and height differences of less than 1 km. This is quite smooth and could indicate desert-like terrain or a lava flow. In any case, imaging an area like this will probably be about equivalent to imaging an earth desert or lunar maria, which can be taken as worst cases for design purposes.

Globally, then, Venus seems to possess a number of different regimes as far as backscatter goes, and the best that can be said from the present data is that it is indistinguishable from earth as far as the distribution of major landforms (mountains, plains, etc.), except for a possible higher density of craters.

2.1.2 Look Angle

Selection of an optimum look angle is basically a tradeoff among shadowing, layover and foreshortening. Layover occurs when the slant range to the top of a feature is shorter than the range to the base so the top images closer to the radar. Generally this happens when the topographic slope angle is greater than the look angle (Figure 2-2). When layover occurs, the image becomes very confused and almost worthless for geologic interpretation.

Figures 2-3 and 2-4 are examples of radar imagery from the far side of the Moon (Apollo 17 Lunar Sounder, 2 m wavelength), where the look angle extended from about 0 - 15°. Some of the crater walls have laid over and even though the craters are many hundreds of resolution cells in size, their individual morphologies are virtually indistinguishable.

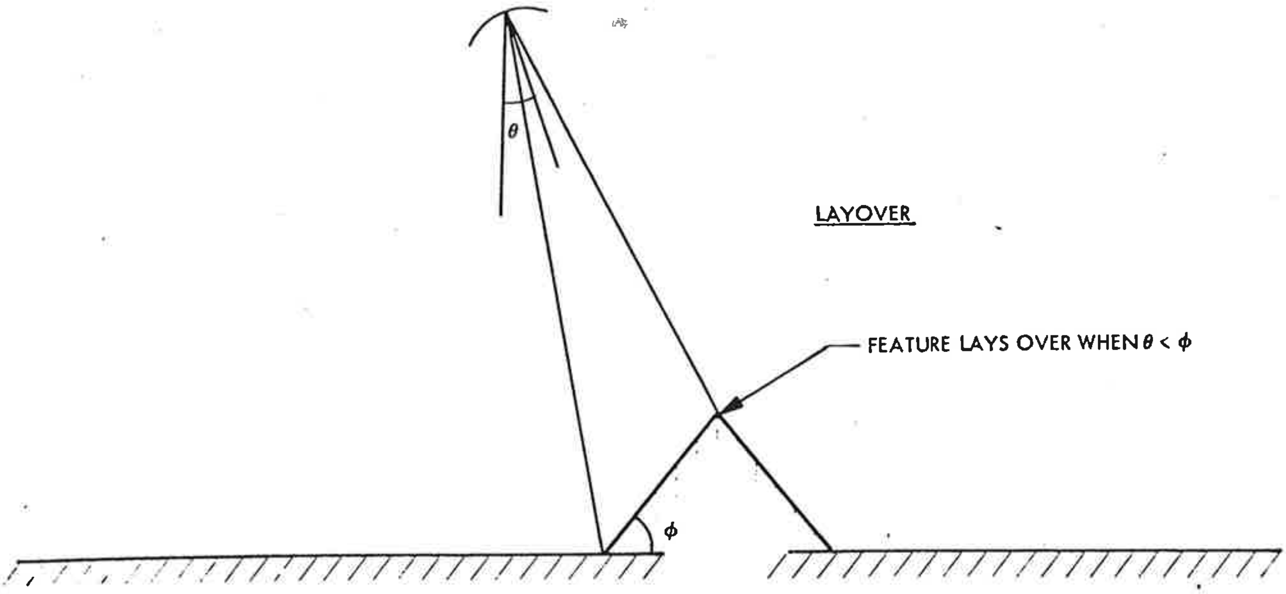
Foreshortening is a fundamental feature of radar images just as in optical images and can be corrected if the topography is fairly flat. The fractional foreshortening for a flat surface is given by

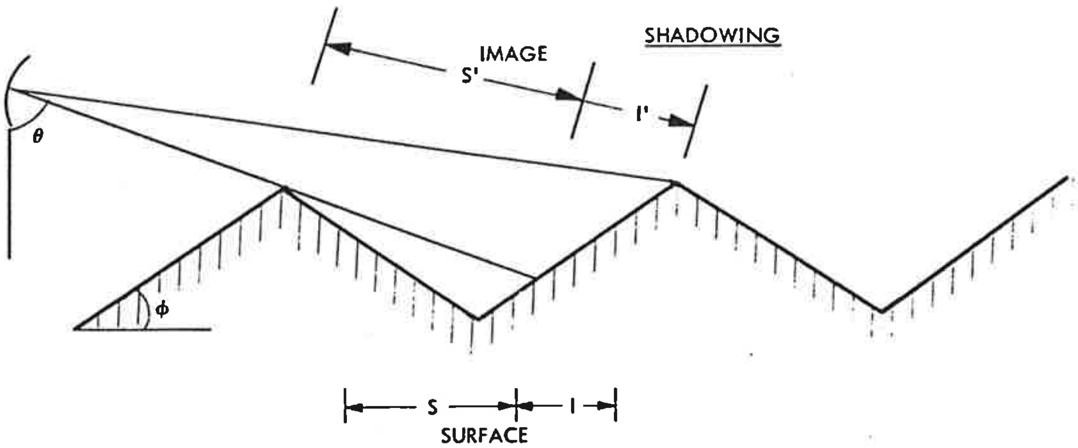
$$f = 1 - \sin \theta$$

where θ = look angle. More correctly, f is a function of the incidence angle which is also affected by the topographic slope. For mountainous terrain, foreshortening introduces distortions which cannot be simply geometrically corrected, as can data taken over the ocean, for example. Generally, foreshortening should be minimized when designing a system, but some degree of it is not disastrous. Layover is the extreme case of foreshortening and it should be avoided at all cost, as mentioned above.

Figure 2-5 shows a radar image of several volcanoes in northern Iceland obtained with the JPL L-band (25 cm) airborne radar and demonstrates some of the effects of foreshortening. The swath for this system extends from the nadir out to 45°, and a scale of the look angles is marked on the image. Note from Figure 2-6 (a section of a topographic map of the same region) that the slope of the flanks of the volcano Gaesafjöll is the same almost all the way around the base of the volcano (10° - 20°).

On the radar image, however, the slope facing and closest to the nadir (top edge of the image) has been foreshortened to a narrow bright line and is just on the verge of laying over. The slope facing away from the aircraft has, on the other hand, been slightly "lengthened" and appears closer to its true proportions since it is further from the nadir. In addition, notice how the overall shape of the central elevation has been distorted compared to the map with the edge closer to nadir "flattened out." Compare this with the shape





FRACTION OF SURFACE SHADOWED = S/(S+I)

$$= \frac{\text{SIN}\,\theta'\ \text{SIN}\phi}{\text{COS}\,(\theta' - \phi)} \quad \frac{(\theta' + \phi + \pi/2)}{\phi}$$

$\theta' = \text{TAN}^{-1}$ (TAN COS α)

α = ORIENTATION TO FLIGHT LINE

Figure 2-2. Topographic Slope

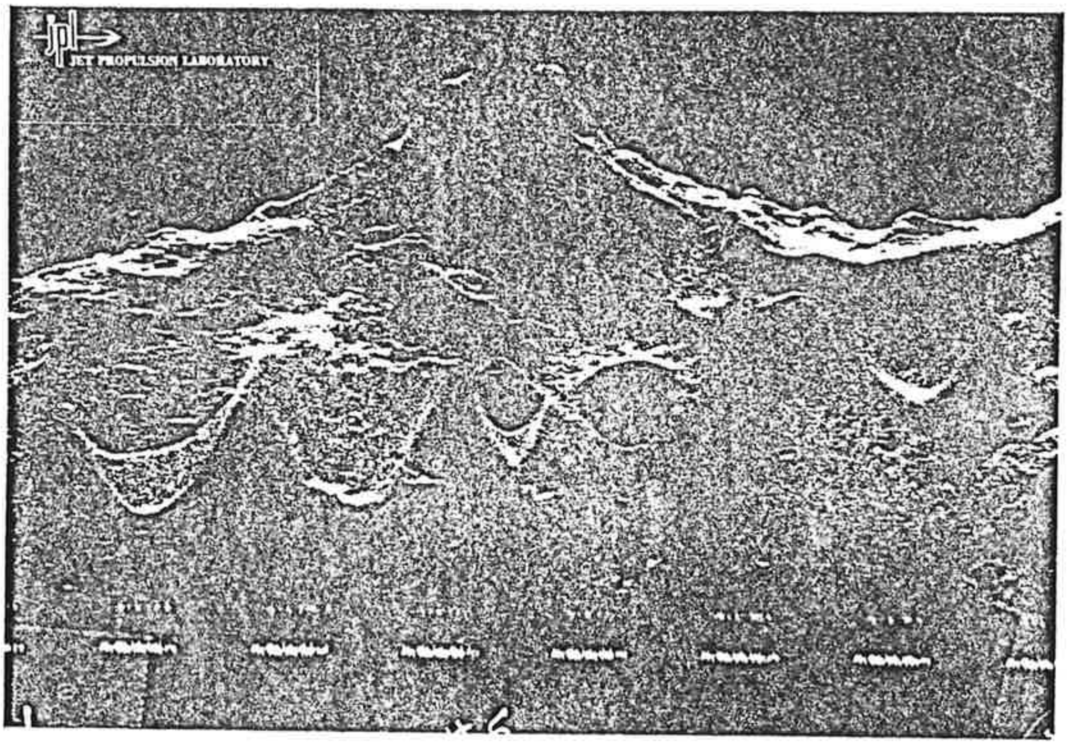


Figure 2-3. Apollo Lunar Radar Imagery

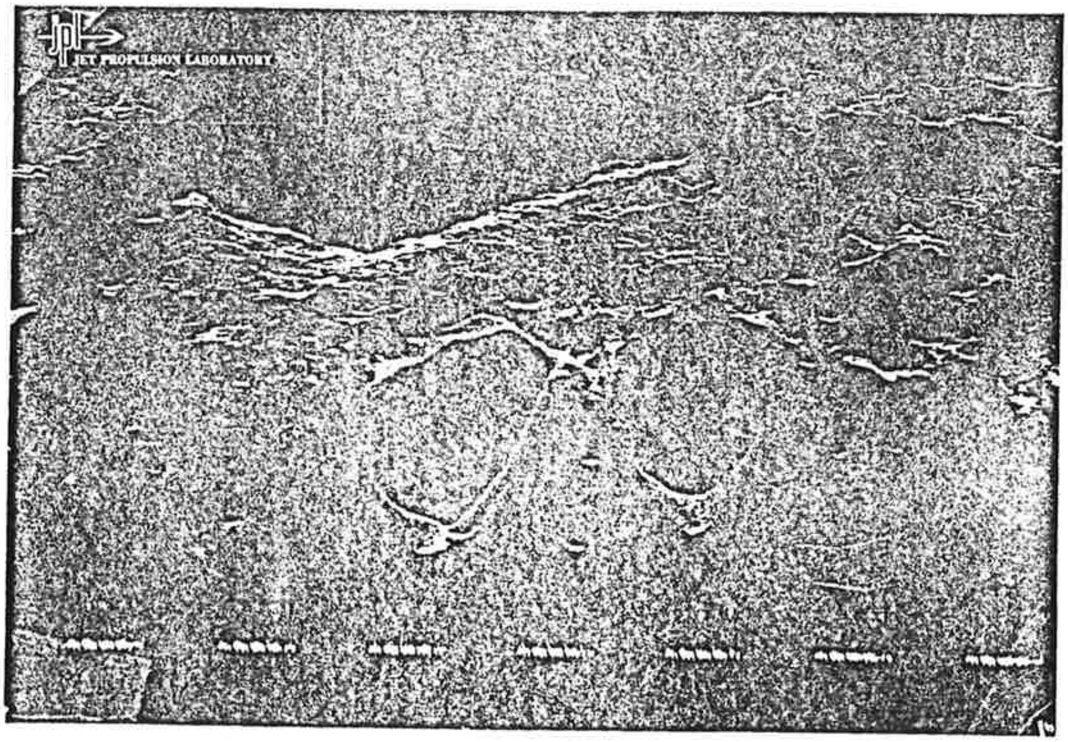


Figure 2-4. Apollo Lunar Radar Imagery

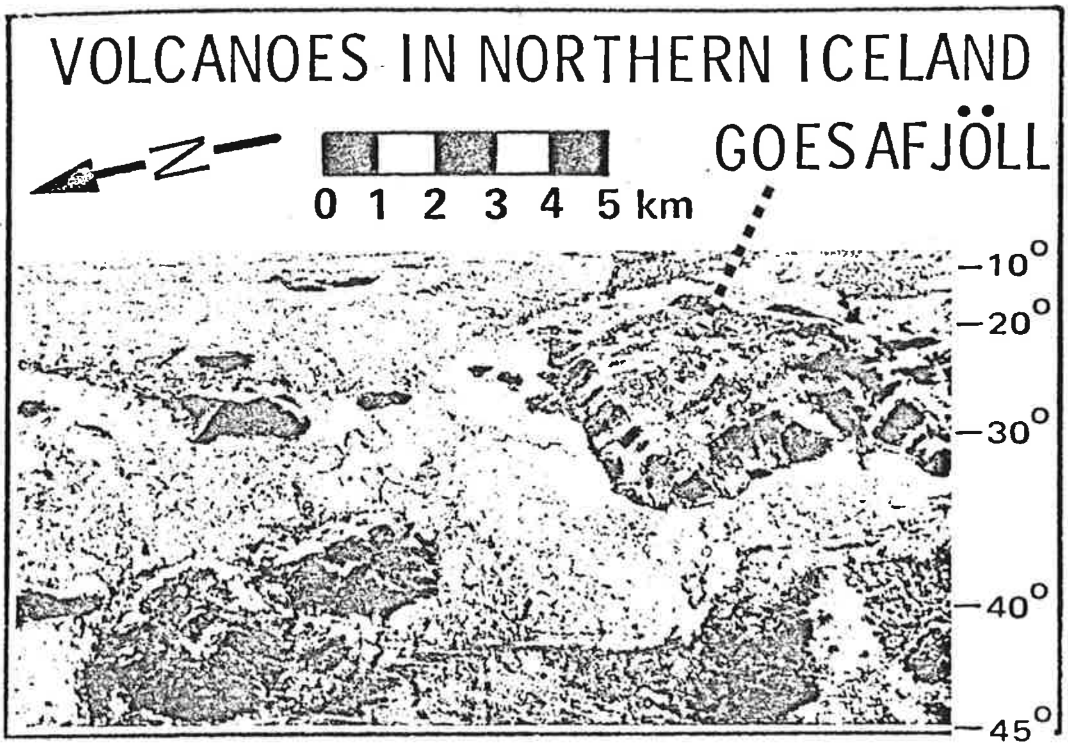


Figure 2-5. Volcanos in Northern Iceland

of the two smaller volcanos which are at the lower left in the image and which are far from nadir and appear in almost a true "map-like" projection.

Shadowing (Figure 2-2) occurs when a feature blocks the beam from illuminating the terrain behind it. Some shadowing is desirable, especially in smooth areas, but in mountainous regions, a significant portion of the image can be in shadow with a subsequent loss of information. The fraction of the ground that is shadowed from the simple model of Figure 2-2 is

$$f = \frac{\sin \theta' \sin \ (\theta' + \phi + \pi/2)}{\cos (\theta' - \phi) \ \phi}$$

where

$\theta' = \tan^{-1} (\tan \theta \ \cos \alpha)$

θ = look angle

ϕ = slope

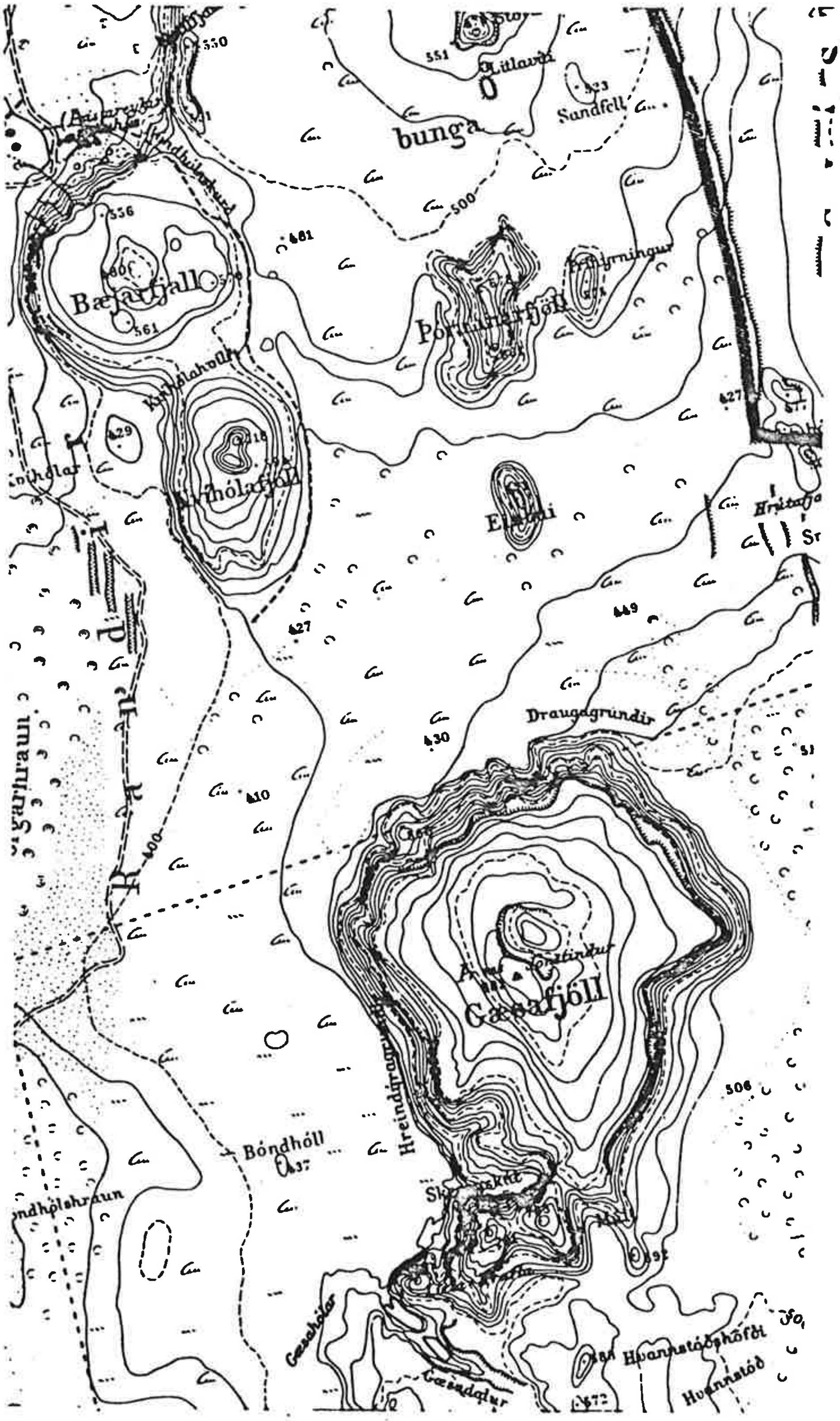


Figure 2-6. Topographic Map of Northern Iceland

θ' is a "modified" look angle that takes into account the orientation α of the mountain chain with respect to the flight line (i. e., if $\alpha =$ 0 the radar is moving parallel to the mountain). For this equation, it has been assumed that the slopes in the imaged region are uniformly distributed from zero to ϕ.

In Figure 2-3 fractional foreshortening and shadowing have been plotted as a function of look angle for different topographic slopes. As stated above layover and foreshortening should be minimized, and this pushes the desirable look angle up. Mountainous terrain is the driver, since not only does it suffere the most distortion, it is impossible to correct geometrically. In addition, volcanoes, crater walls, and such are some of the more geologically interesting areas and should not be lost due to these effects.

At the top end, look angle is limited by shadowing. The curves in Figure 2-7 have been drawn assuming a uniformly random distribution of orientations α. In some areas, shadowing could be much higher for a given θ (for example flying along parallel rows of mountains).

It is evident from Figure 2-2 that each terrain type has it's own most desirable look angle (higher for smoother areas). MacDonald and Waite

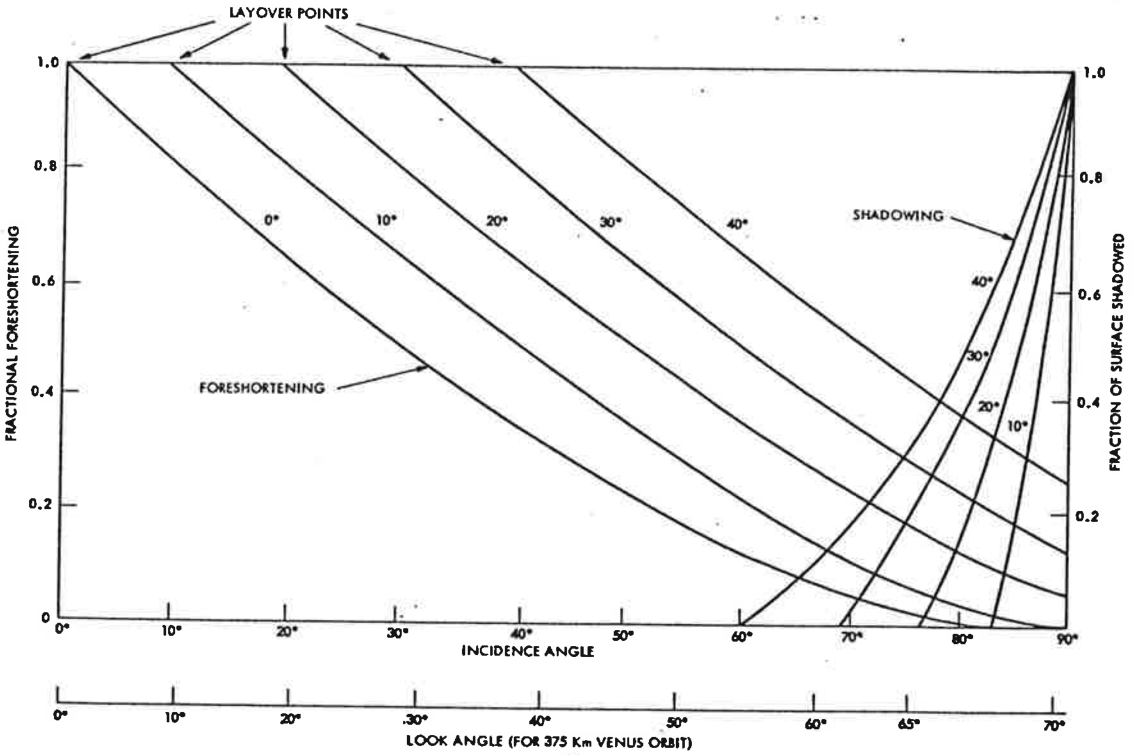


Figure 2-7. VOIR Fractional Foreshortening vs Incidence Angle

(1971) have evaluated the amount of geologic information available in side-looking airborne radar data as a function of look angle and produce maps of optimum angles for use over various terrain regimes on the earth. Generally these extend from 35° - 55° for mountainous areas to 60° - 80° for the smoothest terrain. For imaging an entire planet with relatively unknown distribution of terrain types, the optimum incidence angle is probably in the range of 60° to 65°, implying a look angle of 55° to 60° for Venus orbit. At about 45°, the roughest areas and highest peaks will start to lay over, so this is probably the minimum θ acceptable. At 30° and less, foreshortening is becoming high and layover of interesting features is common so these are basically unacceptable.

2.1.3 Wavelength

Since resolution would not be affected, there is no obvious science advantage to S- over L-band.

2.1.4 Coverage Strategy

The ideal strategy, of course, would be low resolution coverage of the entire surface as rapidly as possible (120 days) with "real time" selection of high resolution targets. This may be possible given on-board processing and rapid enough transmission and interpretation such that targets will still be in the beam. Another possibility would be to rotate the spacecraft, assuming a symmetric beam, and image an area when it passes on the "other side" several orbits later. This is only possible for half of the planet (rotation carries points away from the spacecraft on the opposite hemisphere), and provides time lag of 4.9 days for a look-angle of 45°. This is 9.3 days for a 60° look-angle.

If real-time selection of high resolution targets is not possible, a strategy should be worked out beforehand for coverage during the first 120 days. This would probably involve choosing areas from the earth-based data (on the hemisphere facing us at conjunction) to provide a sort of "ground truth." Following completion of the global coverage (120 days), additional high (and low) resolution data could be gathered as deemed appropriate.

An important consideration is that following the first 120 days the spacecraft could be reoriented (e. g., "left-looking" instead of "right-looking") to give multiple coverage at a different illumination. This is extremely helpful in interpreting radar images (for example it illuminates areas that were shadowed on the previous image). In addition, it would allow triangulating on recognizable features to get topographic profiles, although the accuracy is dependent on how well the difference between the two orbits is known. (This might not be too accurate after 120 days.)

2.1.5 Altimetry

Geophysically speaking, altimetry is probably as important as imaging since it supports the gravity analysis and tells us the planet's overall shape (this is especially important for Venus because of its seemingly huge moment of inertia differences).

The imaging radar can be used for altimetry in several ways. The most straightforward is simply measuring shadows (another argument for high look-angle) and converting to time delay and therefore relative height. If a secondary antenna is present, fringes can be generated on the image which follow the topography, or a two frequency technique can accomplish the same thing. Both these methods have the disadvantage that they yield only relative elevations (height of one feature above another in the same image). Also, the shadow method is extremely limited in coverage, and the fringe method degrades the images.

If two images of some feature are available at different look angles, triangulation will yield its absolute elevation (height above the center of mass of Venus - this is the one we want). This method is limited to the number of features that can be identified in separate images but is an argument for the multiple look-angle strategy (first "left-looking" then "right-looking") mentioned earlier. The major drawback of this technique is the same one inherent in all space altimetry - the orbit is not as well known (spacecraft height above center of mass) as the altitude (above surface). This was the major accuracy limiter in the Apollo altimetry, and it's even worse in triangulation since knowledge of two orbits widely space in time is required.

The last method possible using the imager is to measure the nadir return. This is probably the best of those mentioned so far but has the disadvantage of having a very wide effective "footprint." This footprint should be a spot about 2 km in radius (as on LPO) to do effective altimetry.

Probably the only way to get this is to have a separate altimeter. The weight and power based on LPO are modest (10 kilograms and 17 Watts) but to get a 2 km spot would require almost a 3 m dish. If this is not acceptable the VOIR antenna could be used by adding an X-band element at each end (12 m separation) and two more with a 3 m separation on booms orthogonal to the main antenna. This would produce a surface element just under 1 km in the azimuth direction and about 2 km in the range direction and would satisfy the altimetry requirement nicely. PRF for this instrument would be about 7 Hz.

The main disadvantage at X-band is that atmospheric absorption becomes large. Going to longer wavelengths would require an even larger antenna to maintain the spot size. Altogether, altimetry is important enough and the details complex enough to justify a separate study.

2.1.6 Backscatter

A knowledge of the minimum backscatter σ^o (radar cross-section/unit area) to be expected for different areas is an important factor in fulfilling the objective of mapping the entire planet. Figure 2-8 shows the average backscatter laws presented by Muhleman (1964) and Hagfors (1968) for Venus along with some data from individual locations on the earth by Shultz, et al. (1969) and Daley, et al. (1968).

It is immediately apparent that, for a given incidence angle, the range of values of σ^o to be expected for real terrain is much larger than that given by the "average" laws. Areas of low reflectivity especially get swamped by these laws since, if two regions of equal area with σ^o = 0 dB and 30 dB respectively get combined within a resolution cell, the average σ^o for the combined area is -3 dB! Therefore if one designed to the average backscatter at 45^o (17 dB), it would miss at least half the planet. To map the entire planet, one should design to the worst example of earth terrain that would be expected on Venus. This would be desert-like terrain at about -30 dB.

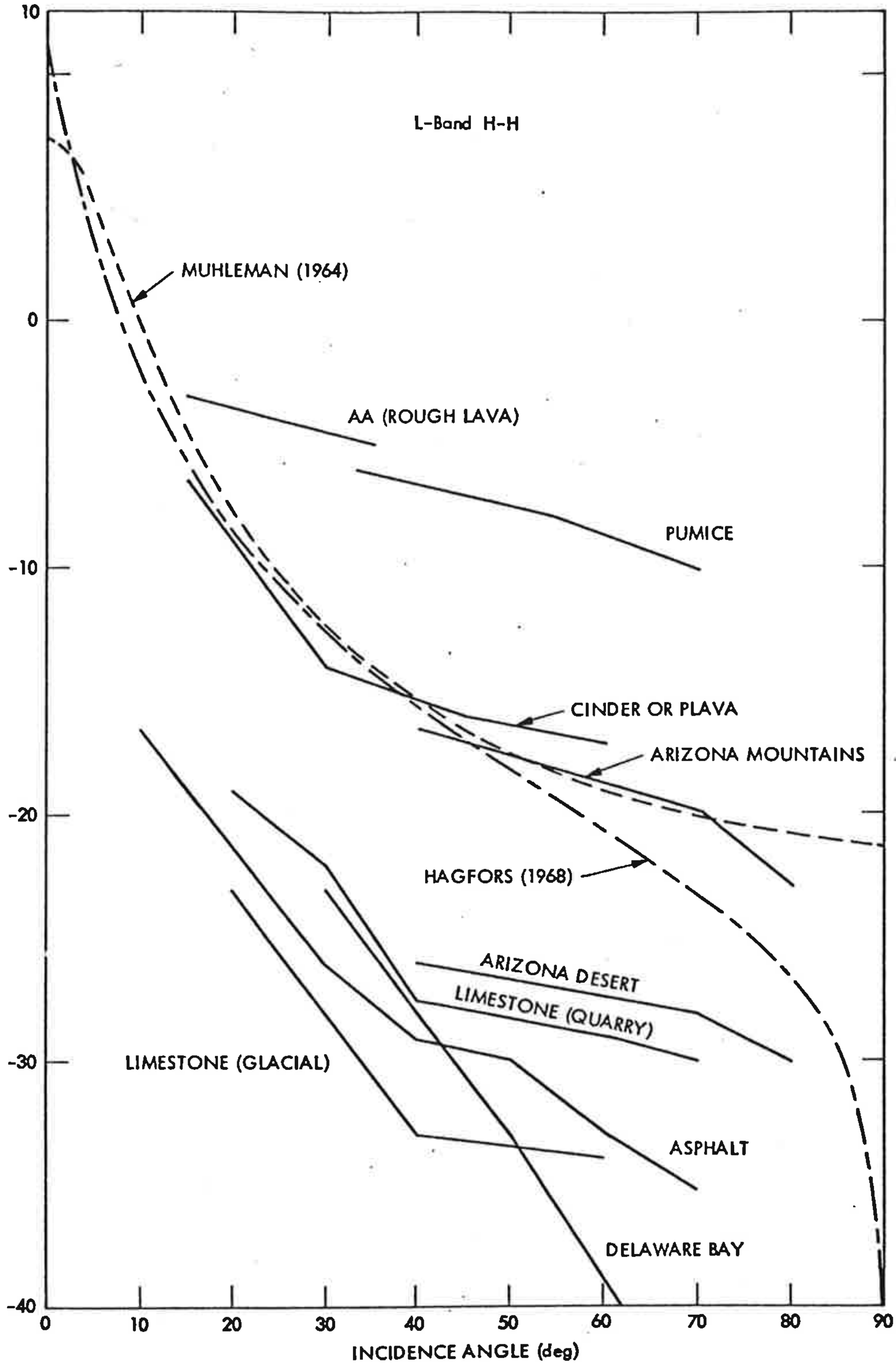


Figure 2-8. Radar Backscatter Coefficient σ^o vs Incidence Angle for Various Classes of Target

2.2 RADARGRAMMETRIC CONSIDERATIONS

Radargrammetric aspects will affect the logical interpretation of VOIR imagery as well as cartographic mapping and geodetic point positioning. These aspects concern questions such as: stereo look-angles, overlaps, coverage strategy, stability of sensor position and velocity vector (attitude), and altimetry. Each of these will be discussed below from a radargrammetric point of view.

2.2.1 Stereo

Stereo-viewing of overlapping radar imagery can greatly enhance the interpretation of the images since it provides the means to observe morphological details (Koopmans, 1974) and to measure slopes and relative height differences. Similarly, cartographic mapping accuracies and geodetic point positioning may significantly improve through the use of overlapping imagery (Dowideit, 1976; Gracie, et al., 1970; Leberl, 1976).

The visual stereo perception of radar images is possible when the overlapping stereo images are sufficiently similar to each other in geometry and image content so that the images can successfully be fused in the observer's brain. The exact limits of the required "similarity" of the images are presently not well understood and both theoretical as well as experimental analyses are lacking. A very limited amount of empirical knowledge of visual stereo perception of radar is presently available. Only the stereo intersection geometry itself has been thoroughly studied.

A basic differentiation of stereo imaging arrangements is that in "same side" and "opposite side" geometries (see Figure 2-9). For geometric strength of intersection of projection rays (circles), an opposite side arrangement is preferred. Unfortunately, however, image pairs of mountainous areas in an opposite side geometry have such dissimilar contents that stereo viewing is not possible: a slope that is strongly reflecting in one image may be either in the radar shadow or only very weakly reflecting in the stereo mate. Even the use of a photographic negative stereo mate cannot resolve the problem. Therefore, opposite side geometry is only useful in gently rolling areas where the illumination differences of the image pairs do not cause entirely different images.

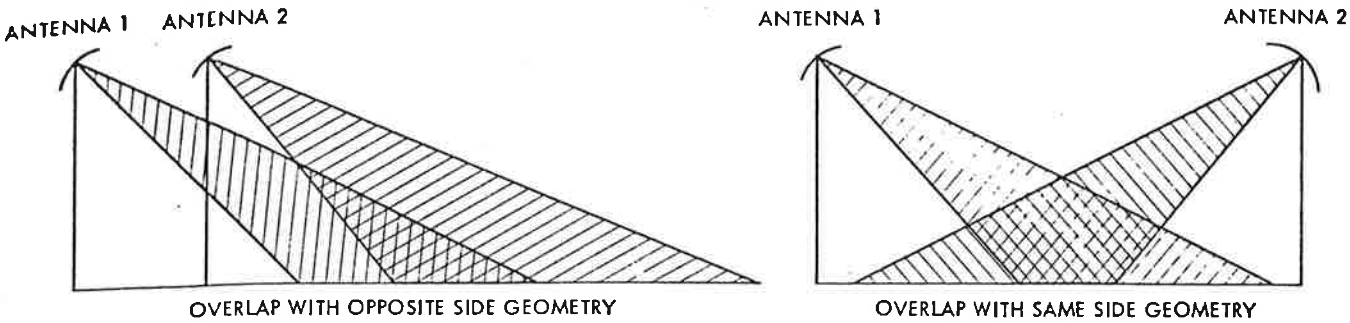


Figure 2-9. Principles of Same Side and Opposite Side Geometries for Radar Stereo

This is why generally only the same side arrangement is used for radar stereo mapping. This produces image pairs in which the object is illuminated in the same way in both components. The same side stereo arrangement presents no difficulties to stereo viewing if the look-angles are not very steep. In commercial radar systems, elevation angles are 45° and more (see Figure 2-10). However, as the look angles become steeper, the layovers increase and so do the dissimilarities of overlapping images, even in the case of rather small stereo bases.

The geometric height accuracy of a radar stereo model is a function of the angle of stereo intersection (see Figure 2-11). However, for a given angle of intersection, stereo perception may become impossible at near vertical look-angles. As look-angles grow steeper for a given angle of intersection, the geometric height accuracy improves at the expense of accuracy in the cross-track coordinate. A requirement for optimum radar stereo is thus to have a maximum angle of stereo intersection and a look-angle larger than 45° off

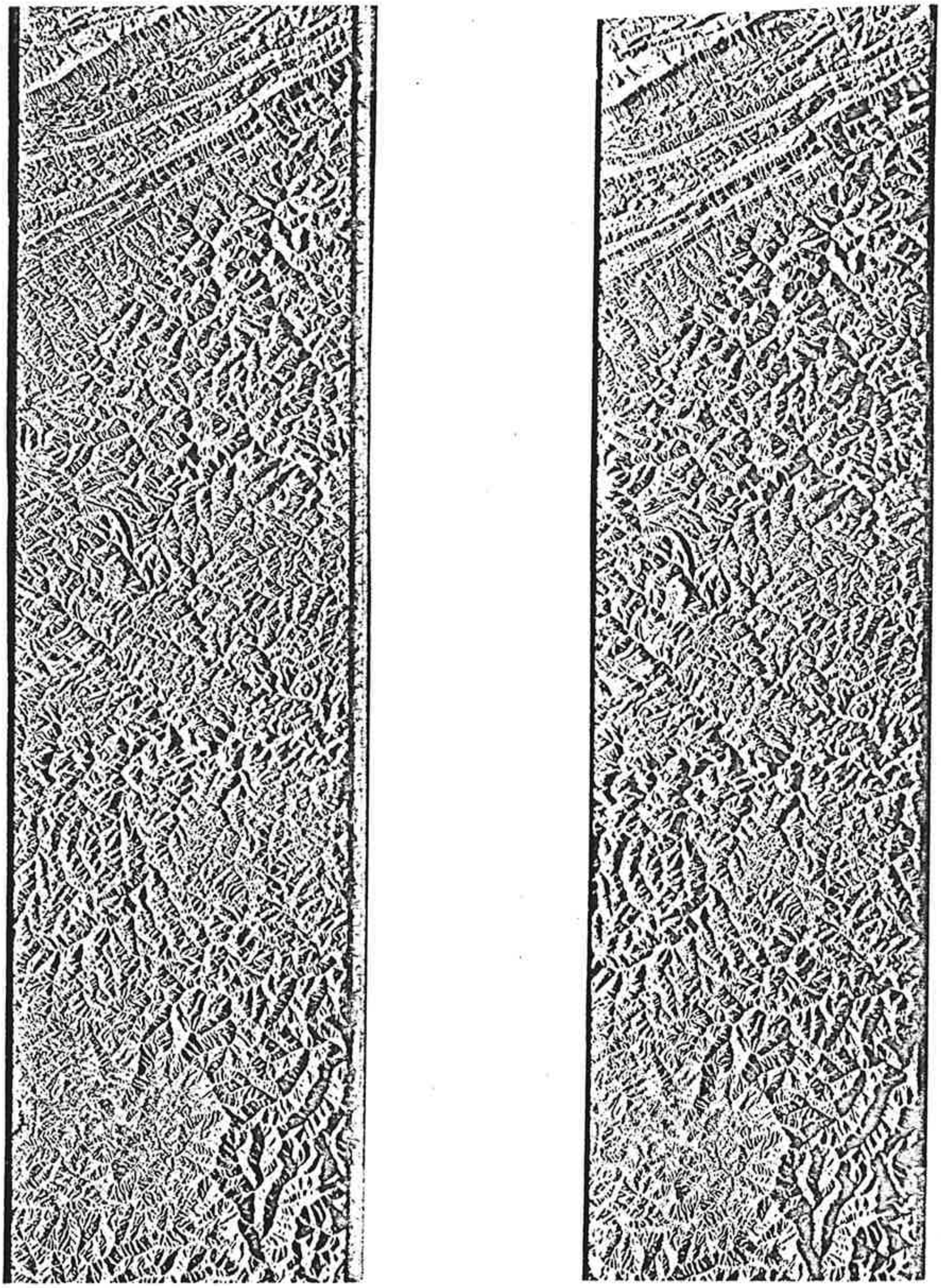


Figure 2-10. Example of a Goodyear GEMS 1000 airborne synthetic aperture radar stereo image pair with same side geometry and very good visual stereo. Flight height 12 km, offset in the left image 18. 5 km, in the right image 37 km. Angle of stereo intersection is about 15^{o}. Elevation angles are 57^{o} and more. (Courtesy: Goodyear Aerospace - Litton Aero Service)

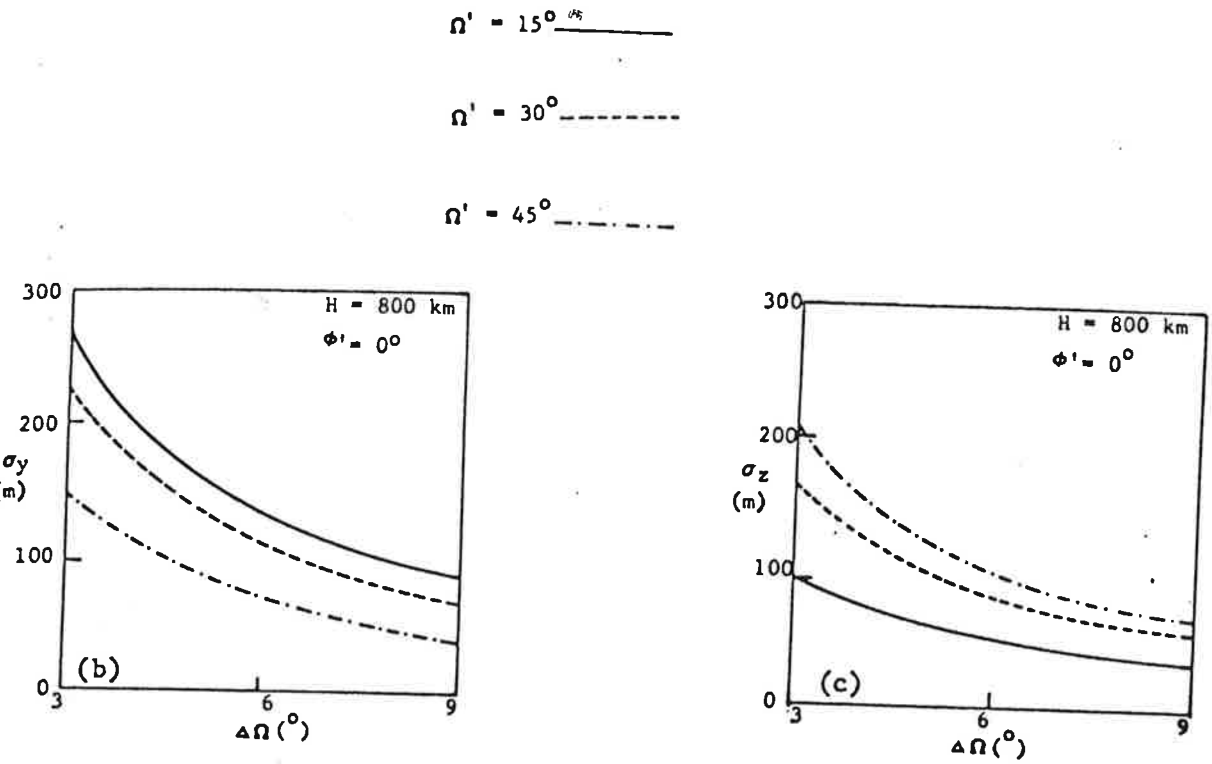


Figure 2-11. Results of theoretical prediction of mean cross orbit coordinate error σ_y and height error σ_z in meters, assuming an orbit of 800 km height at the equator ($\theta' = 0^\circ$), satellite position errors of 10 m, errors of the velocity vector of 10 m per 100 km in all three directions, and a slant range resolution of about 7 m. Note the rapid decrease of errors as the intersection angles increase. Note also that with a given angle of stereo intersection ($\Delta\Omega$), height errors are smaller for smaller elevation angles Ω', but that errors of across orbit coordinates increase with smaller elevation angles.

vertical to ensure perception. The angle of intersection from 60% overlapping imagery will safely permit stereo perception at look angles 45° off vertical or more.

Based on present empirical knowledge, the following conclusions can be drawn:

1) Opposite side geometry can only be used in flat or gently rolling areas.

2) Generally, stereo is only possible with same side geometry.

3) Look-angles should be 45° off vertical and more for good stereo.

4) The accuracy of height measurements is only a function of the angle of stereo intersection.

5) VOIR stereo intersection angles with a 100 km swath, 400 km altitude and 60% overlap would amount to 3°. This would lead to a weak height accuracy of about 20 times the range resolution. From this conclusion, and Figure 2-11, a requirement emerges to increase stereo convergence angles beyond the 3° possible with a fixed look angle.

6) For optimum stereo, the stereo mate should be acquired with a different look-angle (experience with aircraft data show that changes of about 15° produce useful stereo).

2.2.2 Look-Angles

The foregoing discussion of stereo resulted in a requirement of look-angles of 45° off the vertical axis. This may result in shadowing of mountainous terrain, but an independent second look from the opposite side can fill in the areas blanked by the shadow of the first look. Although such an opposite side look may not result in visual stereo perception, it may permit the monocular identification of homologous details in the opposite side image pair and lead to computational determination of height or differences.

The most desirable situation is that where each surface feature is being imaged four times so that two stereo looks are possible, one each from opposing side. The same side combinations enable one to visually interpret the data and to take two independent measurements of height, slope, etc. ; while the opposite side combinations may allow for the computation of a network of more accurately determined radiogrammetic pass points for point positioning, cartographic mapping, rectification, mosaicking, etc., and can be applied to specific methods of geologic analysis (Dalke and McCoy, 1968).

From a radargrammetric point-of-view that does not aim at visual stereo, the following conclusion results:

> Imaging should be from opposite sides to fill in blanks due to shadowing and to permit opposite side stereo geometry where applicable.

2.2.3 Overlaps

Overlaps must at least be 60% among adjacent image strips for stereo. Also for cartographic mapping or point positioning an overlap of at least 60% is absolutely necessary. According to a basic principle of measurement, at least two, preferably more, observations of each point are required to permit an independent check of measurements and eliminate gross errors. This requirement coincides with that for stereo. A 60% overlap instead of 50% is necessary to have overlap among adjacent stereo models and provide a safety margin to avoid gaps in the stereo coverage due to orbit perturbations. In summary the conclusion is

> Overlaps among adjacent images should be 60%.

2.2.4 Coverage Strategy

From a radargrammetric point-of-view, there are no objections to a coverage strategy that would initially aim at single coverage of the entire planet. However, stereo coverage requires a same side geometry with 60% overlap in mountainous areas. In flat areas and rolling terrain, an opposite side geometry may result in stereo pairs that permit good visual stereo. From this point-of-view, the following strategy is proposed:

1) Initially obtain single coverage that provides information on the type of relief and then make the decision onthe areas in which a same side stereo coverage and where opposite side coverage should be obtained.

2) Ideally, areas of high interest that are mountainous should be covered four times: two times each from opposite sides.

2.2.5 Altimetry

Altimetry would complement radar stereo information by providing reference height data of high absolute accuracy while radar stereo results in poor absolute but high relative accuracy. Areas between altimeter profiles can be filled with radar stereo data. It is, therefore, concluded that

Altimetry is very valuable for cartographic mapping and point positioning.

2.2.6 Accuracy of Spacecraft Tracking

For radargrammetry, the spacecraft position and direction of the velocity vector should be measured with the highest possible accuracy. The spacecraft attitude is of no concern. Absolute tracking errors with long periods (trend-like) are of lesser concern than are relative, high frequency errors. Absolute errors of tracking can be largely eliminated if altimetry data are available. Therefore,

Spacecraft tracking should have minimum relative (high frequency) error components.

2.2.7 Conclusion

From the point-of-view of radargrammetric mapping, multiple coverage of the surface of Venus is necessary to

1) Permit stereo interpretation and mapping.
2) Cover areas blanked out by shadows on single coverage images.
3) Obtain duplicate measurements for mapping and point positioning according to basic principles of measurement.

Elevation angles should be large (45° off nadir or more) to permit good stereo. Stereo coverage should be of the same side geometry except in areas of very moderate relief. A decision on whether same side or opposite side stereo is to be acquired should be made after information about the relief on the surface of Venus is available.

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