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RADARGRAMMETRIC ANALYSIS WITH MAGELLAN DATA OF PLANET VENUS

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RADARGRAMMETRIC ANALYSIS WITH MAGELLAN DATA OF PLANET VENUS

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ABSTRACT

Radar images of the surface of Venus are being produced since September 1990 and cover nearly the entire planet. The Magellan spacecraft and radar imaging system are continuing to function exceptionally well to now produce already the third nearly complete coverage of the planet. The nominal mission as authorized by Congress ended in May of 1991 when about 1,600 image strips covering the planet more or less from pole to pole had been acquired, covering more than 80% of the entire planet. A second cycle was then authorized to image the planet a second time, however, by illuminating the surface from an opposite side. We are now seeing a third cycle being produced which combines with the original nominal cycle into same-side stereo coverage. We are reporting in this paper that stereo coverage of the planet is feasible with accuracies in the range of about ± 100 m and with a height sensitivity in the range of perhaps ± 30 m.

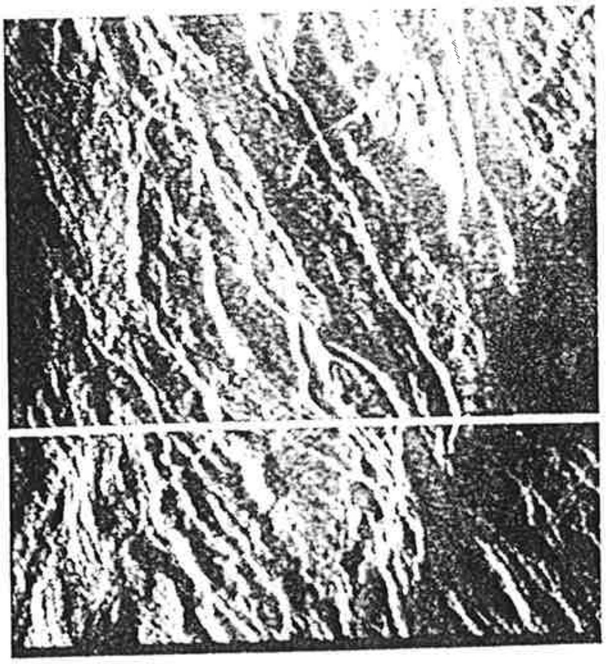
INTRODUCTION

NASA's Magellan radar mapping mission to planet Venus goes on. What started as a nerve-racking sequence of events in September of 1990, when the signal from the spacecraft was temporarily lost, has turned into a major technological accomplishment and success of NASA. By now planet Venus is covered nearly twice on more than 3,000 images, each image covering about 20 km in swath width and 17,000 km in length. These very long and thin images are sometimes denoted as "noodles" and are represented by 350 x 220,000 pixels, each at 75 m diameter. We presented an initial description of the mission in a recent paper (Leberl, et al., 1991) where relevant parameters of the radar sensor and its collateral material were listed.

We want to focus in this paper on some examples of work done with a data set that was experimentally produced on the 24th of July 1991 as part of the second coverage of the planet. So-called Cycle 2 was planned to produce an opposite side illumination of the planet's surface. In the original (nominal) mission, the satellite was looking to the left (looking East); the second cycle was looking right or West. This results in a second coverage that is unsuitable for stereoscopic work (Figure 1). However, for one day this imaging arrangement was suspended and was replaced by producing eight orbits, again looking East or left, but at a look-angle off-nadir that was different than that of the nominal mission. Figure 2 shows the two look angles off-nadir that were used in the nominal mission and then in the one-day stereo experiment. We can see that the two look angles off-nadir differ by up to 21° and change along the orbit. These changes are a result of the highly elliptical orbit of the spacecraft which was necessitated by cost constraints. The elliptical orbit requires that the planet be imaged with a steep look-angle at high altitudes and shallower angles at lower altitudes near periapsis.

We have processed imagery from this experimental data set to verify that stereoscopic mapping from Magellan radar images is feasible and to determine, as best as possible, what the accuracies are. We can show accuracies in the range of ± 100 m and an acuity of a skilled operator to surface changes of perhaps ± 30 m.

(a) Left- or East-looking



(b) Right- or West-looking

Figure 1. Example of opposite-side image pair obtained from Magellan's Cycle 1 (Sep. '90 - May '91) and Cycle 2 (May '91 - Jan. '92). Area covered is 135 km x 135 km, and located at 8° S.

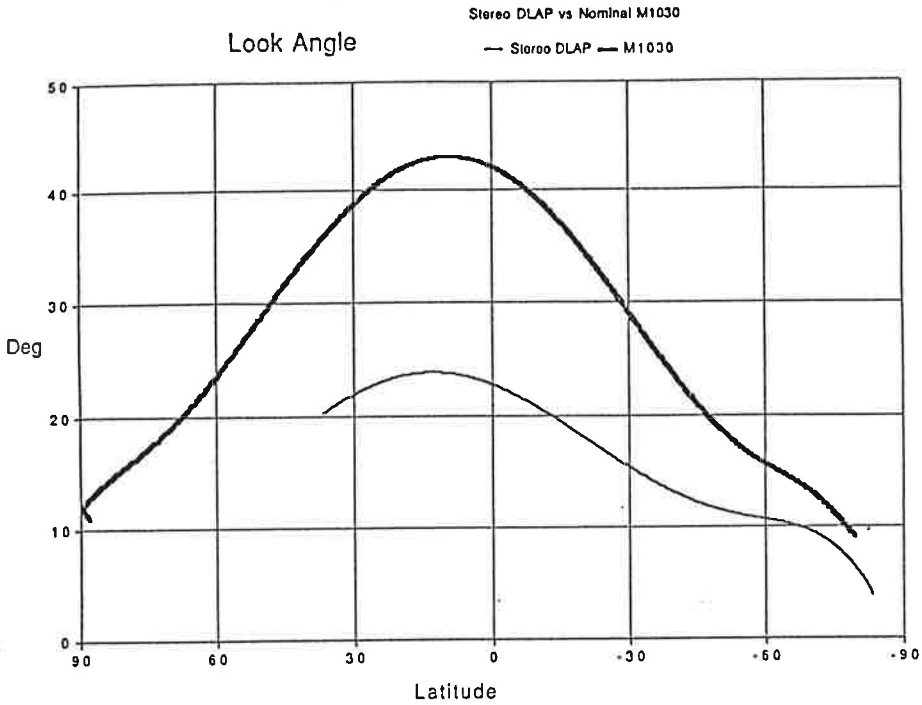


Figure 2. Look-angle profiles for Magellan's Cycle 1 (nominal mission) and the stereo-experiment in Cycle 2.

STEREO RADAR MAPPING TECHNOLOGY

An initial look at radar stereo data can simply be based on the radargrammetric equivalent of "parallax-bar photogrammetry." Two images are put under the stereoscope, any parallax differences are observed and converted to terrain elevation under approximating assumptions of look angles and spacecraft positions. Figure 3 illustrates the approach in the original Magellan-cycle. An object may be illuminated and imaged at a look angle off-nadir θ' that may be 40° or so near periapsis or 13° near the pole. In the second coverage the radar looks steeper at the same terrain using a look angle off-nadir θ'' which may be 21° at periapsis or 9° near the pole. The net result is a parallax difference between the two images which is the difference of the relief displacements that one encounters at an object that is elevated and above the reference datum.

It is important to understand that parallax differences are the differences of relief displacements rather than the sum. If one could successfully match two images from opposite-side geometries, then the parallax difference would be the sum of the two relief displacements rather than their difference. This has been extensively discussed in the early days of radargrammetry by Levine (1963), LaPrade (1963, 1970) and others. The application to Magellan has been reviewed by Leberl et al. (submitted).

Figure 4 is an example of a stereo pair at 39° South. It turns out that most Magellan stereo data produce stereo at a vertical exaggeration that is more less identical, even though the look angle differences vary from 21° at periapsis to 4° near the poles.

ASSESSING THE QUALITY OF THE STEREO IMPRESSION AND THE ACCURACY OF STEREO MAPPING

A factor in the quality of a stereo impression can be described by the vertical exaggeration as described in the Manual of Photogrammetry (LaPrade, et al., 1980). The vertical exaggeration "q" is basicallv the scale difference between the perceived horizontal dimensions and the perceived vertical dimensions in a stereo model. In photography under a stereoscope, this ratio q is typically 3 for wide-angle photography and 5 for super-wide angle photography. It turns out that the Magellan stereo parallaxes are surprisingly large, larger than they would be from equivalent aerial photography with a wide-angle camera. Note that a wide-angle camera will produce a stereo parallax that is about 0.6 of the observed height difference. In the Magellan radar the stereo parallax is larger than the observed height difference. How can this be?

Figure 5 explains that this is a result of the fairly steep look-angles that Magellan's radar has to employ. As a result the relief displacements are very large and the differences of relief displacement are also large. The sensitivity to height difference is great because the projection lines (circles in space) are intersected with a reference plane that is nearly tangent to the projection circles. Therefore, any small change in incidence angle or look-angle off-nadir results in a large change of parallax. Table 1 produces examples that show how the parallax differences from radar are larger than those that wide-angle photography would give at 60% overlap and an 0.6 base-to-height ratio.

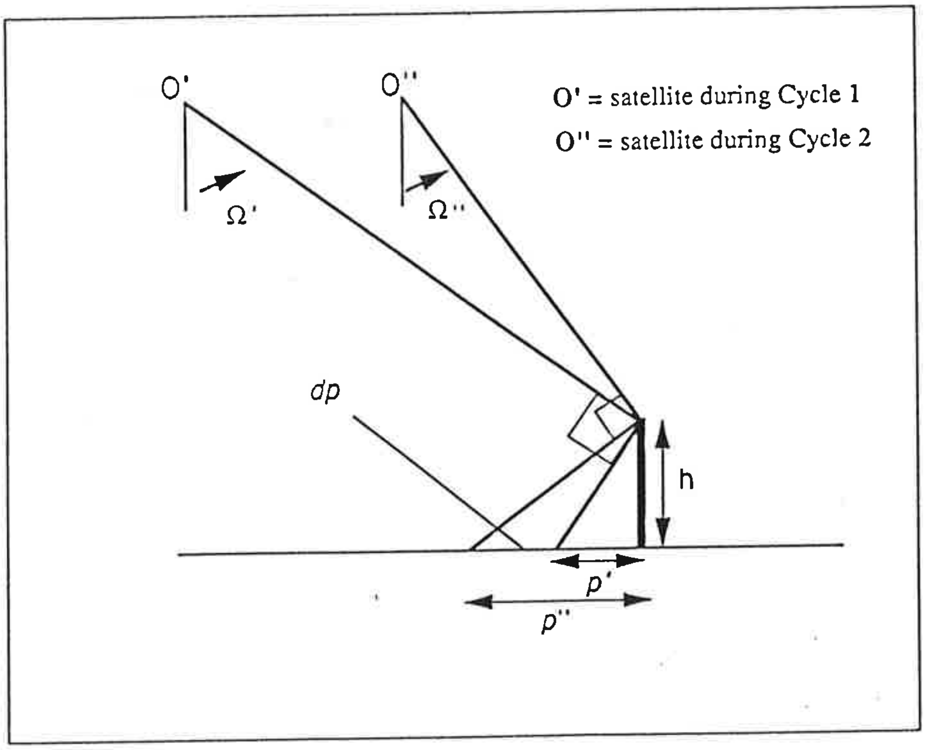
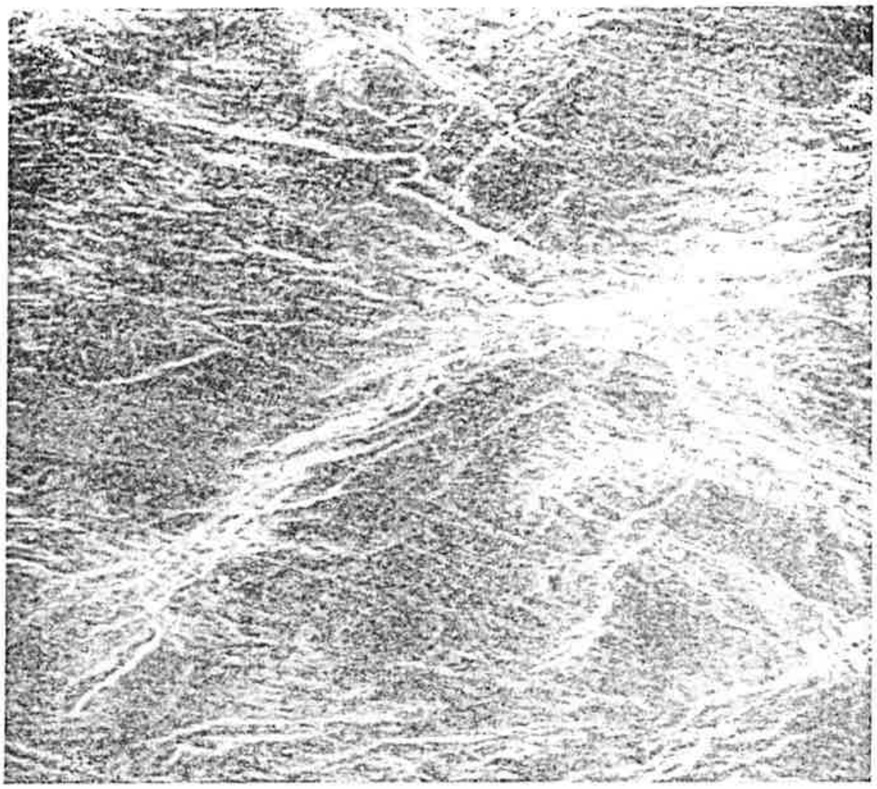


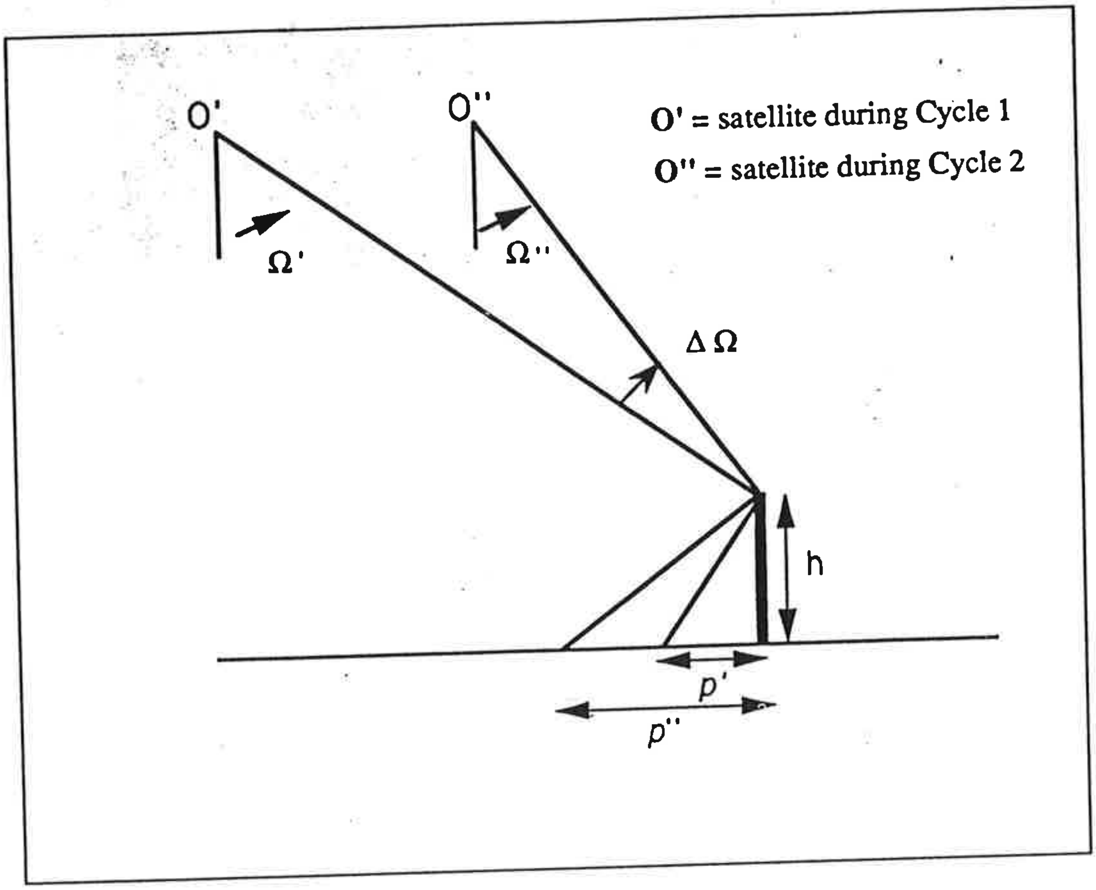
Figure 3. Simplified parallax-to-height conversion substituting tangents for the actual circular wavefronts.



(a) Cycle 1 Image at Look-angle Off-nadir od 25°

(b) Cycle 2 at Look-angle Off-nadir of 15°

Figure 4. Example of a Magellan stereo image pair at 39° South, covering an area of 115 km x 115 km.



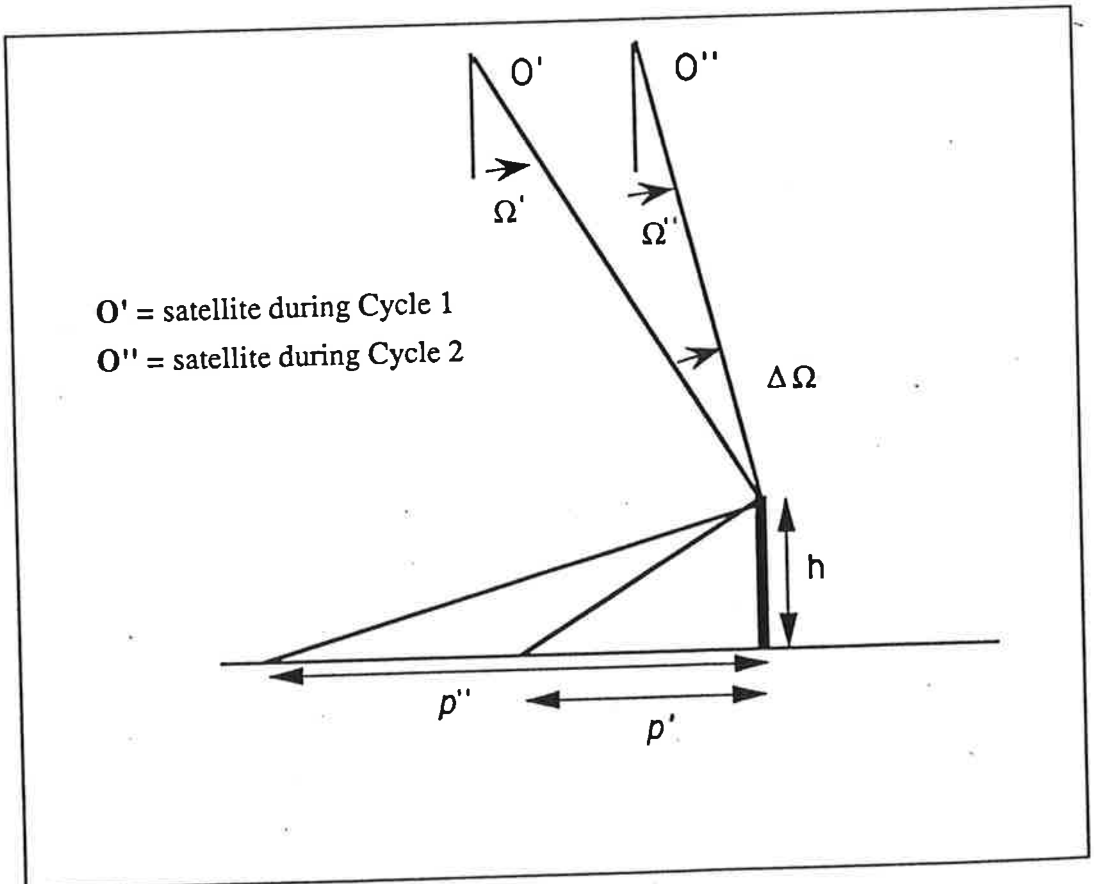


Figure 5. At steep look-angles θ', θ'' off-nadir, even a small look-angle difference $\theta'-\theta''$ will result in large stereo parallax differences, whereas at shallow (large) look-angles, the stereo parallaxes will be small.

Table 1: Comparison of parallax-differences dp (in meters) from Magellan stereo radar and wide-angle aerial photography given a terrain elevation difference of 100 m.

	Magellan				Aerial Photographs
Where	θ′ (°)	θ″ (°)	Δθ′ (°)	dp	B/H = 0.6
10° N	44	23	21	132	60
2° S	43	22	21	140	
39° S	25	14	11	187	
73° S	13	9	4	198	

The phenomenon that stereo radar is very sensitive to height and that we have large vertical exaggeration, larger even than what we get in aerial photography, also reflects itself in a surprising stability of the height measurement itself. Given that we may make a matching error, ddp, between the two images of 1 pixel (or 75 m), we can speculate that the elevation uncertainty, dh, that results from that matching uncertainty is 52 m near periapsis, and 37 m near the pole:

$$dh = ddp/(1/\tan\theta'' - 1/\tan\theta') \tag{1}$$

A second source for uncertainty of elevation measurements is the uncertainty of the range measurement associated with each image point that we have identified by the stereo process. The error of range, σ_r, propagates into an error of elevation, σ_h, according to Leberl (1979) as follows:

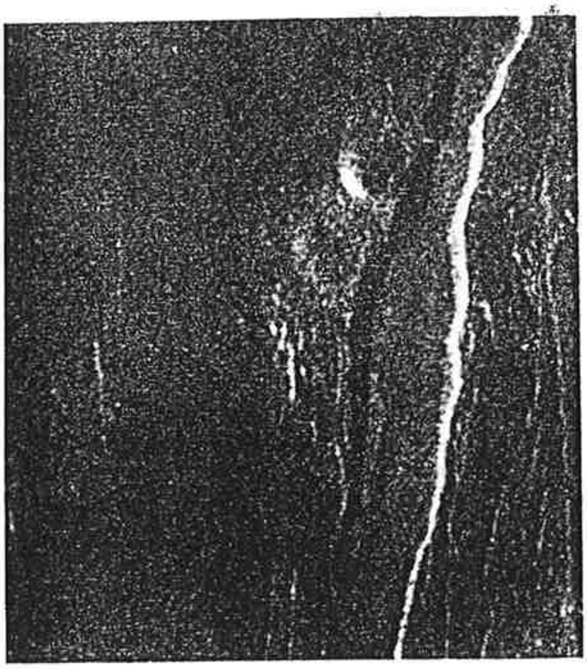
$$\sigma_h = \{(\sin^2\theta' + \sin^2\theta'')^{1/2}/\sin(\theta'-\theta'')\} \cdot \sigma_r \tag{2}$$

Clearly the inability to match the two images perfectly and the limitations on range measurement accuracies are correlated. Therefore, those two errors indicated in Equations 1 and 2 are not simply summed up.

AN ASSESSMENT OF ACCURACY

In an attempt to assess the stereo-accuracy, one needs to have a reference measurement or test-object. This is not available on planet Venus. However, there exist symmetric features and near-vertical objects. Figure 6 is one of a few examples. Stereo breakline measurements taken along the top and bottom of the feature reveal an elevation difference of about 500 m with elevations varying by about 90 m as one moves along part of the feature.

Cycle 2, look-angle off-nadir = 11°



Cycle 1, look-angle off-nadir = 15°

Figure 6. A so-called "collapsed feature" with near-vertical walls serves as a tool to check on the stereo-accuracy; look angle $\theta' = 15°$, look angle $\theta'' = 11°$ (see Maurice et al., submitted).

Independently we can measure the depth h of this feature from the assumption that the walls are symmetric, using the length of the layover, l′, in Cycle 1 and l″ in Cycle 2 of slopes looking towards the antenna or west and the length s', s" of the back slope (slope looking east). We use the formulation by Elachi (1990) and discussed by Leberl et al. (1991):

$$h = \frac{l' + s'}{2} \tan \theta' = \frac{l'' + s''}{2} \tan \theta''$$

This results in a value of h of about 400 m, with a variation also of about 100 m. The uncertainty of this measurement lies in the uncertainty about the symmetry of the feature.

We conclude from these observations that the difference between the measurement by stereo and the independent measurement exploiting the object's assumed symmetry is about 100 m. This is consistent with the speculation that the accuracy of stereo-measurements should be at ± 100 m or better (see Leberl et al., submitted). More such features need to be found and more analysis is required to strengthen this conclusion.

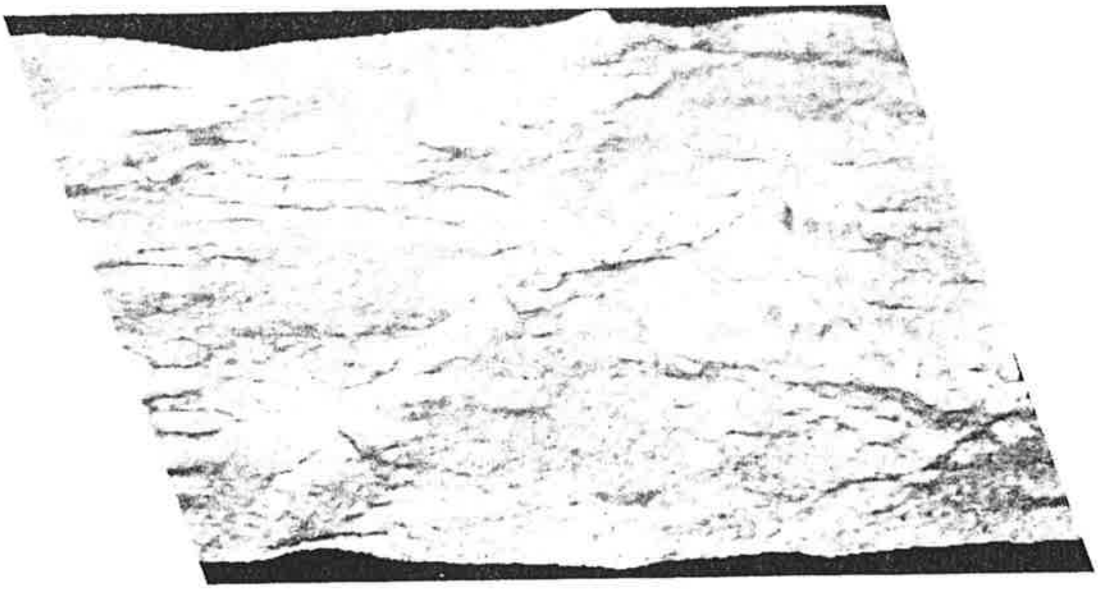


Figure 7. Perspective view of Venus terrain obtained from the stereo pair in Figure 4. Elevations are up to 0.6 km. The area covers 133 km x 106 km.

CONCLUSION

As planet Venus gets imaged a third time by Magellan's radar, NASA is producing currently a unique data set consisting of a coverage of nearly the entire planet by three sets of radar images that are larger and more comprehensive than anything currently in existence on Earth. At a pixel size of

75 m stereo measurements are possible from this data set with an accuracy of ± 100 m and a resolution of perhaps ± 30m. The processing of this vast quantity of data covering the entire planet in stereo is a challenge that is currently being faced at NASA. We look forward to the development of a new global Venus data set of detailed digital elevation models (DEMs). These elevation data will not only be the result of the stereo process, but are expected to be refined by shape-from-shading technology (Thomas et al., 1991) and supported by the accurate global coverage from the Magellan altimeter (Pettengill et al., 1991).

The use of this technology leads to the development of exciting secondary image products from the input radar images. Figure 7 is a perspective view of topographic relief generated from the data shown earlier in Figure 4. This product helps in the analysis of detailed geological interpretation and supports the computerized quantitative study of terrain formations.

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