175

HOW TO EXTRACT TOPOGRAPHIC INFORMATION FROM MAGELLAN RADAR IMAGES

Franz W. Leberl*)
Institute of Computer Graphics
Graz University of Technology, Graz, A-8010 Austria

Abstract

NASA's project to map planet Venus in the Magellan mission has become a great success, resulting in an unprecedented set of radar images covering the entire planet, much of it with more than one image. While not part of the nominal mission plan and original NASA-program, this data set has been demonstrated to support the extraction of detailed topographic data with accuracies in the range of perhaps ± 200 m. We discuss in this paper the techniques which were used so far to obtain such data, and we support the proposal to use the Magellan image data set to develop a topographic elevation model of all areas covered by multiple images.

This will not only result in topographic data, but also in a set of co-registered and ortho-rectified images which can be the basis of a unique and modern image data base and information system about the planet for use by future generations of planetary scientists.

1. Introduction

As of this time the imaging radar sensor aboard the space probe Magellan has been deactivated. No more images are being produced of the Venusian surface. However, since the arrival of the spacecraft at the planet, in August 1990, a total of 300 GigaBytes of image data were collected (see Tables 1 and 2). A total of three coverages were attempted, denoted as Cycles I, II and III. Due to various limitations, at times due to Sun-Venus-Earth geometries, at other times due to temporary malfunctions of the radar system, no coverage is complete. However, jointly the three cycles cover 99% of the planet, and a good part of perhaps more than 30% is covered in more than one Cycle.

The "raw" misssion data consist of the Operations Data Records (ODRs) as received from the spacecraft. These ODRs are being decoded into so-called Engineering Data Records (EDRs) representing the radar phase histories. These are subject to so-called Phase-History Processing (PHP) to obtain radar image pixels. The basic image result consists of the Full-resolution Basic Image Data Records (F-BIDRs) which are organised per orbit and represent a format of typically 220.000 x 350 pixels at 8 bits.

It is important to understand the dilemma of planetary imaging missions: since the funding levels are high during the mission and the attention is focussed as well, all energy goes towards rapid "first-cut" processing of images and quick-look analysis. As the mission ends, so does the funding and media-interest. Yet, the majority of the analysis work remains still to be done.

---

*) Also with: Vexcel Corporation, Boulder, Colorado, 80301 USA. Member of NASA's Magellan Science Team. Chairman of Magellan's Stereo Analysis Working Group

Table 1: Some characteristics of NASA's Magellan Mission

Launch	May 1989
Arrival at Venus	August 1990
Sensor	Imaging Synthetic Aperture Radar Altimeter, Radiometer
Radar Wavelength	12.6 cm
Geometric Resolution	75 Meter Pixels
Coverage	220,000 Pixels x 330 Pixels
Look Angles Off-Nadir	11^0 to 50^0
Orbit	Elliptical Periapsis @ 300 km, Apoapsis @ 8,400 km
Total Cost	Almost US$ 1 Billion
Image Data Quantity	300 Gigabytes

Table 2: Status of Magellan Image Acquisition and of Derived Mapping Products in the Form of Full-Resolution Mosaicked Image Data Records (F-MIDRS)

Data Type	Cycle 1	Cycle 2	Cycle 3	Total
Timing	9/90-5/91	5/91-1/92	1/92-9/92	243 days each
Orbits	1791	1791	1791	5,373
F-BIDR Nr (Approved)	1299	1672	832	3803
F-BIDR GBytes (Approx.)	90	120	< 46	256
F-MIDRs Approved	451	131	87	669

The rapid, quick-look processing of images was into a format that approximates "ortho-rectified" images, however without the proper knowledge of the Venusian topography. The F-BIDR image strips are thus projected onto an approximation of the surface as it was known from previous space missions, most notably Pioneer Venus with its altimeter and elevation postings perhaps every 70 to 100 km. "Projection" is based on a dead-reckoning concept using the predicted orbit parameters; as a result one will now have radar images that

* contain geometric errors due to an approximation of the spacecraft's orbit with errors of perhaps ± 1 to ± 2 kilometers, sometimes more, and

* contain geometric errrors due to unknown topographic relief, its size depending on the relief and on the radar look angles, amounting to 200 to 600 m errors for each 100 meters of error in topography.

A considerable effort was furthermore expended to "stitch" the individual image strips into rectangular image mosaics called Full-resolution Mosaicked Image Data Records, F-MIDRs, as listed in Table 2. Mosaics use unimproved F-BIDRs and thus contain all their errors.

As the mission closes with NASA's fiscal year 1993, an amount of nearly US$ 1 Billion will have been spent on Magellan. One may well argue that this is the cost of the unique radar image data set, in combination with altimetry and radiometry data, as well as gravity observations.

We present in this paper the flow of procedures needed to achieve a satisfactory global topographic elevation model (Digital Elevation Model, DEM) at an accuracy of perhaps $\pm$ 200 m. This has been assessed in some preliminary work (Leberl et al., 1992a,b), and has been further refined in studies internal to the Magellan Project Science Group (PSG). However, this preliminary work must still be applied to unlock from the source material the surface information hidden in it.

2. Topographic Information From Radar Images

We can use several radar-based techniques to determine topographic shape. In planetary exploration it has *primarily* been a radar altitude measuring device (altimeter) to develop global data sets. Altimetry can be characterized by an accuracy that depends on the topographic shapes themselves: as terrain is accentuated, the altimeter's leading echo comes from an unknown nearest reflector whithin the radar foot print. However, in flat terrain the nearest reflector is the nadir point and its elevation simply is the radius of the satellite, reduced by the "clearance measurement" between radar antenna and nadir point. Magellan altimetry has been well developed and a global topographic surface model exists through the on-line processing work at the Massachusetts Institute of Technology (Ford and Pettengill, 1992). Some accuracy assessment was presented by Leberl et al. (1991). Figure 1 illusrtaes the shape of a crater as represented in the altimetry data, and documents the rough approximations one must expect to obtain of features that exhibit detailed topographic accents.

A *second* technique employs radar shadows and knowledge about a feature's symmetry, simply relying on a single image of that feature. This is only applicable, however, when shadows exist and fall on a surface of known shape. This therefore may only be of use in rather special circumstances, for example for craters or volcanoes located on a flat background. Figure 2 shows a feature with a shadow, and it also supports an assumption of symmetry. The measurements are strictly of elevation differences over small distances on the surface. We have

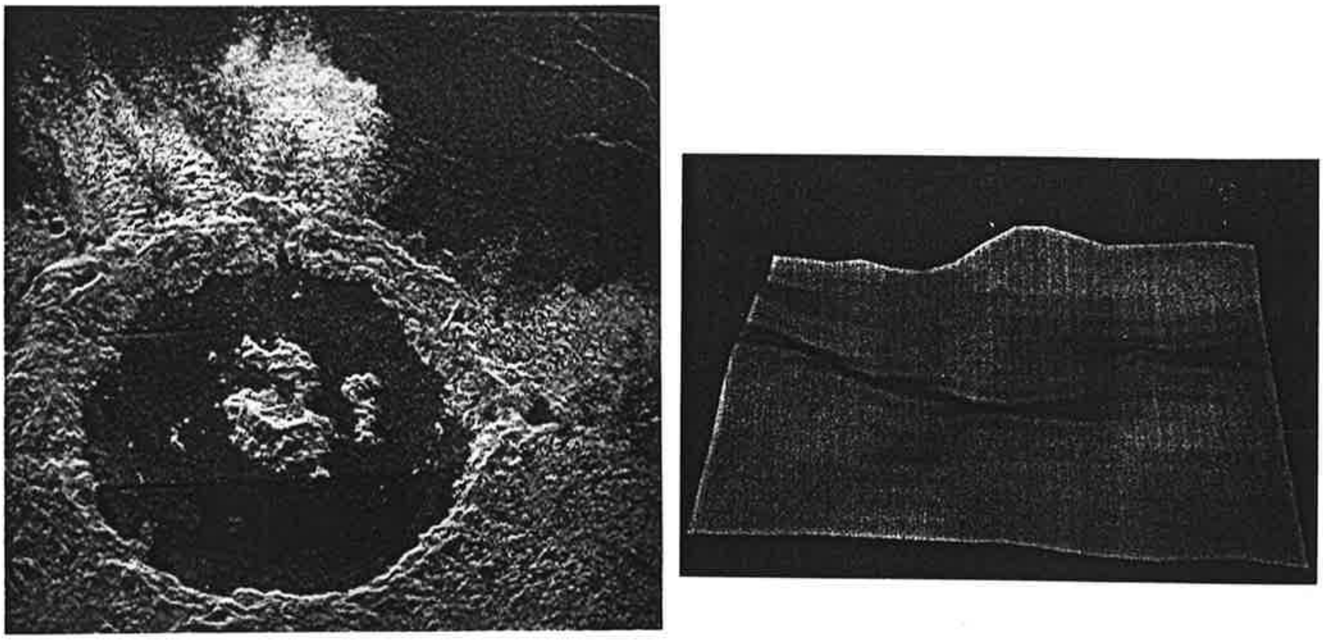

Figure 1: Example of a crater shown on a Magellan image mosaic, and its topographic model from altimetry. Crater depth is obtained at 380 meters from altimetry. Independent observations reveal, however, that this crater depth is at 1,500 meters (from Leberl et al., 1991).

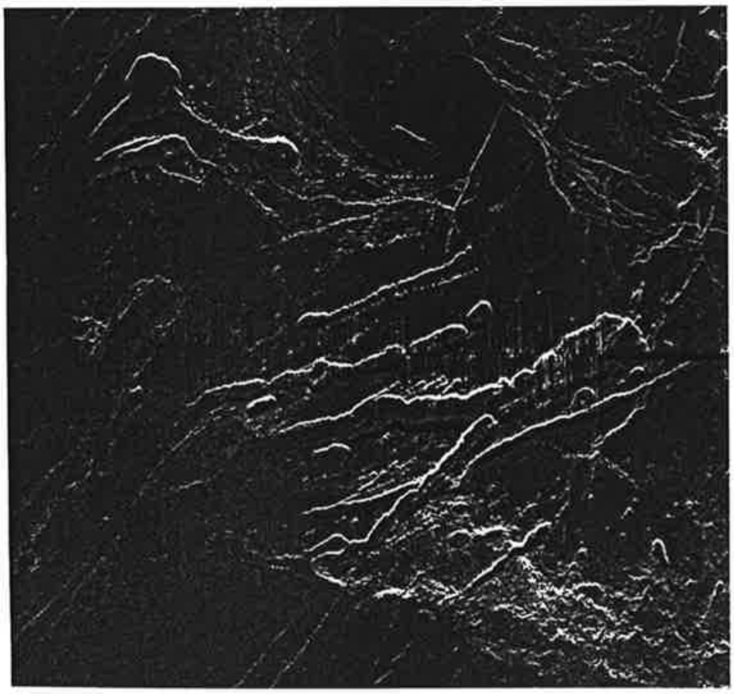

Figure 2: Example of a Venus surface feature exhibiting shadows, and supporting the assumption of symmetry. Area covered is 90 km x 120 km.

determined that the accuracy of such measurements can be rather high, in the range of $\pm$200 m (Leberl et al. 1991).

A *third* approach uses interferometry, whereby two images taken from nearly identical orbits serve to measure the radar energy's phase differences as a result of small variations of topography. In Magellan, such data do not exist, except for a limited area over the North pole. The lateral displacement of orbits from one image to the next is too large (about 18 km at the equator) , as is the particular mode of transmitting /receiving radar bursts, so that phase differences cannot be observed due to a lack of "coherence" between signals in the two images.

The *forth* concept for shape reconstruction is an inversion of image gray values into terrain slopes, and integration of those slopes into elevation differences and terrain elevations. This is "clinometry" or "shape-from-shading" as used in industrial inspection, but adapted to radar (Wildey, 1986; Kirk, 1987; Kirk et al., 1992; Thomas and al., 1991). Since the inversion depends on the knowledge of radar reflection properties of the terrain, and since these properties are generally not known, this concept will not be applicable, except over rather small areas with homogeneous reflection properties. Numerous gray-value/topography inversions have beeen computed from the initial Magellan coverage, accepting the altimetry data as a reference, and merely interpolating elevations in between the widely space altimetry observations. Figure 3 presents an example of a Magellan image set at 83^0 N, and a terrain surface derived from this image using shape-from-shading as discussed by Thomas et al. (1991).

Most shape-from-shading results were not formally published, but were the basis for numerous "visualizations" of Venus terrains in the form of animations. While the local accuracies may be acceptable, the reconstructed terrain will have large errors across several hundred pixels (Leberl et al., 1991). One approach to improve the usefulness of the reconstructed shape measurements is based on multiplte images taken at diffferent incidence angles. However, this requires that multiple images be registered, which in turn must use the topographic terrain shape one is seeking.

The *fifth and last* technique employs conventional stereo photogrammetry, but adapted for radar images taken of terrain from one and the same side, yet under slightly different look angles (same-side stereo). It is the best developed and most widely understood source of topographic data from images. A complete end-to-end capability to develop DEMs exists and has been exercised with Magellan images (Figure 4). However, many questions about this approach remain unanswered, for example the use of image pairs looking at terrain from opposite sides, or the question of how to best employ the gray value diffferences in overlapping images, not as a perturbation in the stereo process, but as an aid to refine the topographic measurements through an integrated stereo/shape-from-shading approach.

All topographic measurements depend on an accurate knowledge of the spacecraft's position to transform measurements from the spacecraft coordinates into a planetary system. We will address this issue in the next section.

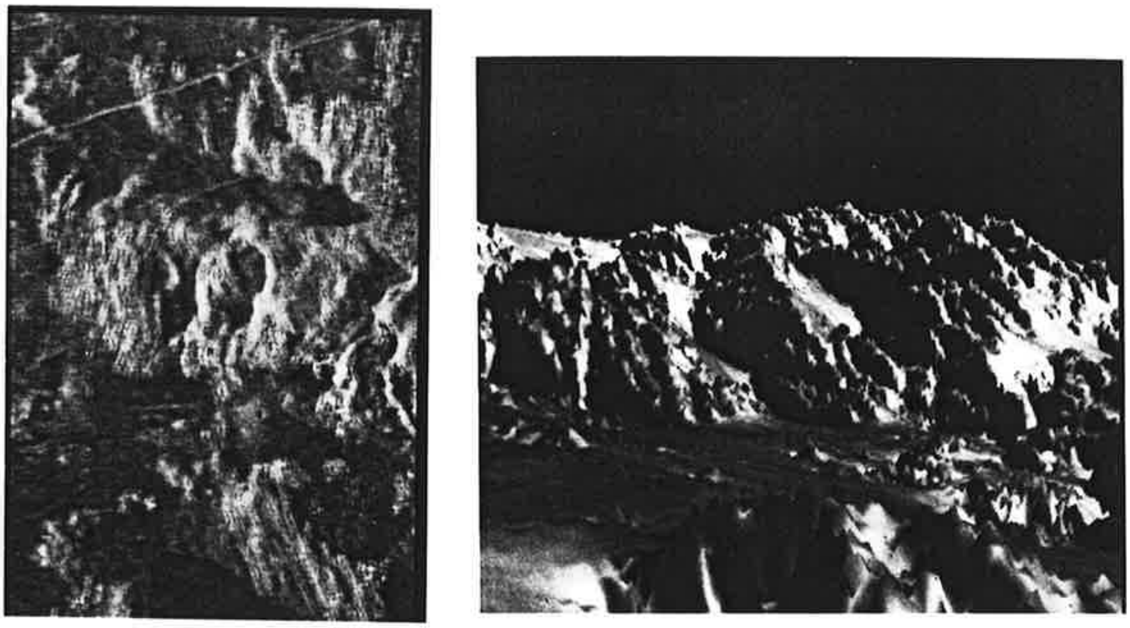

Figure 3: Early Cycle 1 image mosaic from 83^{0}N, and elevation model obtained from shape-from-shading. Note the detail in the elevation map, but also the uncertainty in the accuracy of the low frequency elevations which may be in the kilometer range (from Leberl et al., 1991).

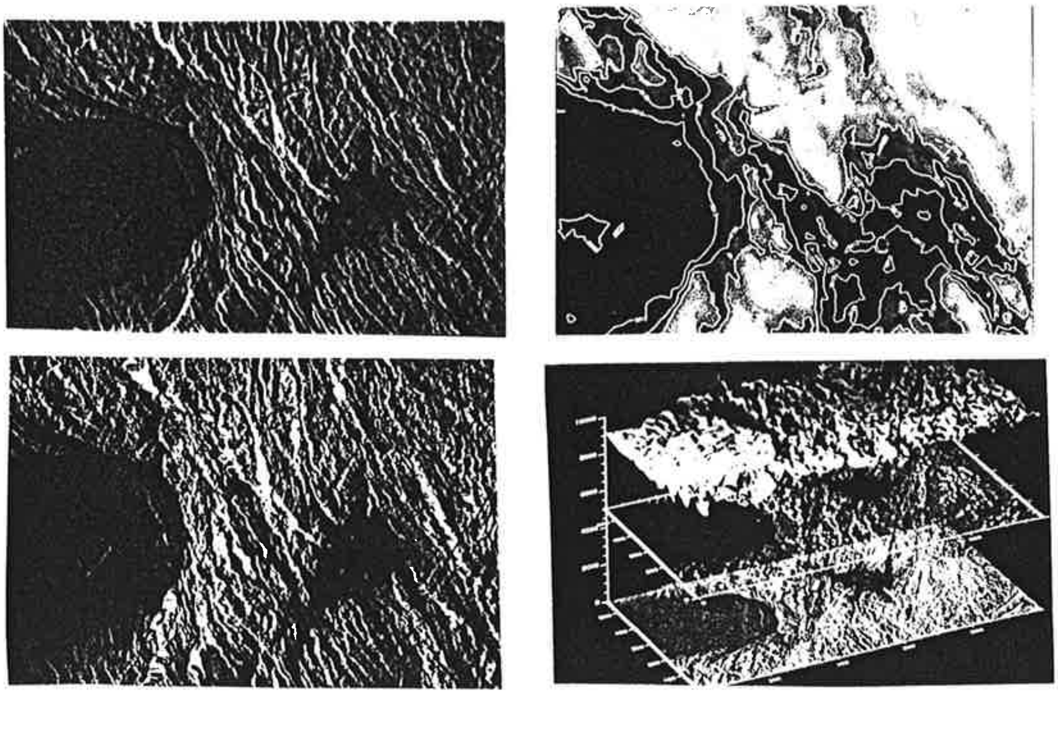

Figure 4: Magellan image mosaic of an area at 8^{0}S, topographic relief extracted with stereoscopy, an orthorectified image and visualization as perspective view (from Leberl et al., 1992b).

3. A Procedure For Topographic Reconstruction Of Surface Shape From Magellan Images

3.1 Ephemeris Adjustment

Figure 5 provides a sketch of an overall flow through overlapping Magellan data to develop a detailed topographic data set. The process begins with a global "ephemeris adjustment" to recompute the spacecraft positions using not only the conventional Doppler and gravity data, but also "landmarks" on overlapping images. Internal reports of the Mission support the expectation that the spacecraft positions can be improved in this manner from the raw ± 1 to ± 2 km errors (and possible worst case errors of 15 km !) to a radius error at $\pm$ 3m, and along- as well as across-track coordinates with accuracies in the $\pm$ 50 m range*) .

The ephemeris adjustment becomes the all-important backbone of any radargrammetric work on Magellan images. To accomplish this work, one needs to identify and measure ground features on overlapping radar images from different Cycles, perhaps at a rate of 10 points along each orbit. Point positions in each image must be measured with the best possible accuracy, and therefore either with the help of visual stereo observations, or with automated image matching.

This task is complicated by the fact that an "orbit" is the fundamental geometric entity, and that images from one Cycle overlap with many images from another Cycle. Therefore this process needs a capability to "stage" large quantities of image data to efficiently identify tie-points (landmarks) in the overlaps of images.

This ephemeris adjustment differs from traditional photogrammetric imag "block adjustments" by using the satellite position measurements as the primary observations, and the image-coordinate measurements as a refinement. The process also is denoted as "navigation solution refinement", to stress its reliance on methods of orbital mechanics.

3.2 Reprocessing Raw Engineering Data Records into Best Quality Images

Rather than starting the topographic reconstruction process from the existing images, it is advisable to improve the images into the best possible quality. The Mission-generated images are the result of fast and preliminary procedures using inaccurate spacecraft positions, preliminary topographic information and often corrupted signal histories. The phase history processing algorithms were changed numerous times along the Mission to respond to new insights and newly discovered data problems. As a result the image data present a rather incoherent data set.

To develop detailed topographic information in a clinometric or "shape-from-shading" effort it would be important to know how the image brightnesses relate to backscatter properties of the surface area producing a pixel. Reprocesssing the EDRs into images promises to obtain a consistent radiometric result.

Finally, the new images will be geometrically consistent with the best topographic information now known about Venus. Instead of basing all geometry on old, preliminary Pioneer Venus and Venera altimetry, thereby ignoring Magellan altimetry, one will be able to employ a significantly improved surface model.

---

*) P. Chodas, Jet Propulsion Laboratory, Personal Communication

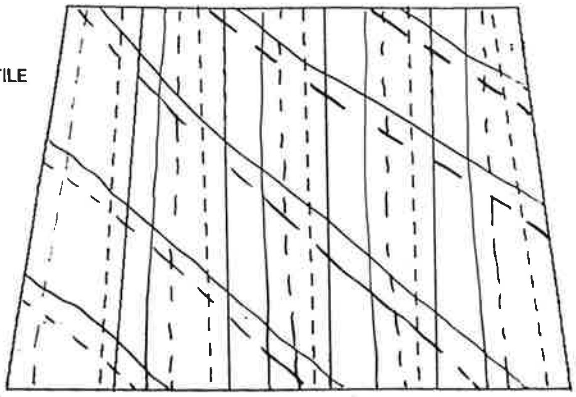

Figure 6: A basic *tile* of an image information system optimized for ease of interactive queries and visualizations in digital form.

Given that the images all exist in a digital format representing a volume of almost 300 Giga-Bytes, it is recommended to not organize the data by orbit, nor to think of image analysis in hardcopy form, but to organize Magellan's images and non-image data into an *information system* for easy interactive queries, display, product generation and automated analysis. An orbit-based image repository is to be converted into an image information system based on geographically coded tiles containing all images and image meta-data as well as non-image results of the mission. Figure 6 sketches the concept.

The information system is to support the user's acccesss to the data, the freedom to choose certain visualizations, scales of representation, data sub-set selections etc. Basic tiles are to be combined into larger units automatically if a query describes an area larger than that of a single tile.

3.4 Detailed Topography from Stereo and Clinometry

A considerable portion of the planet is covered by multiple images for

* straight same-side stereo (Cycles I and III);

* opposite-side images for a yet to be determined methodology of surface shape reconstruction (Cycles I and II, as well as II and III);

* triple overlaps for same-side stereo and opposite-side improvements (Cycles I, II and III).

There are two processes for elevation extraction from overlapping images: stereo and clinometry.

3.4.1 Stereo

Application of the stereo-process to develop detailed topographic relief has been implemented in a Magellan Stereo Tool Kit. Identical points in overlapping images can be identified by hand through a stereo operator, or automatically through image matching methods. This produces sets of image coordinates (x',y', x",y") for each topographic elevation posting, to be converted to slant range r', r", ephemeris positions s', s" and velocity vectors s', s" and furthermore to planetary ϕ, δ and height h.

The possibly random geographic positions of elevation postings must now be interpolated (resampled) into a regular grid in the output coordinate grid.

3.4.2 Clinometry

Refinement of the DEM is now feasible by using the two gray values at each surface location to compute slope values. These are then integrated into elevations,. One may thereby violate the constraint that the resulting surface point must be at the observed slant ranges from the imaging antenna locations. Such constraints must be algorithmically enforced.

3.4.3 Ortho-Recification

In order to use the image gray values in a clinometric DEM refinement, the images must be registered to the DEM and to one another. This requires that the images be resampled to the planetary coordinate system and that the known topographic deformation be removed. Therefore the development of the DEM produces, as a by-product, a set of ortho-rectified images that are now co-registered.

4. Opposite-Side Image Coverages

Currently this author has no knowledge of work performed or reported in the literature that would address the issue of using overlapping radar images from opposite sides of the surface. As a result there now exists a Magellan data set from Cycles I, II and III which cannot be registered since no algorithms exist to accomplish this task.

It will therefore be necessary to perform exploratory work to find ways of reconstructing a topographic surface which is consistent with the slant range measurements taken from two or three orbits, and is also consistent with the gray values in the radar images. Since an object patch (target area) described by an image pixel is at ground position ϕ, δ, h, at a certain set of slant ranges r', r" r"' and at crtain gray values g', g", g"', the meaningful reconstruction of surface shape will not only produce an estimate of local terrain slope, but also of the local backscatter property of the relevant object patch.

One procedure may be developed for the case where a same-side stereo coverage combines with a third opposite-side image: the stero-based DEM may serve to co-register the third image to fit with the stereo-pair.

Another problem is given when only an opposite side pair exists. A search for a surface shape that is consistent with the geometric and radiometric constraints from the images needs to be found. Since no work has been reported on this problem in the past, new ground needs to be broken to solve this issue.

It is only after such work has been completed that a meaningful recommendation can be given regarding global processing of Magellan images. However, it seems reasonable at this time to plan for an approach where basic data base tiles get post-processed with the DEMs if and when they become available.

This will require that the original image pixels get resampled after the image pixels were created from the EDRs; were the DEM known at the time of EDR procesing, the final image records could be created in a single pass through the data.

5. Accuracy Of Topography

Altimetric accuracies depend on the surface topography itself, and errors may rather large (in the kilometer range) when rough topography exist.

Stereo data accuracy is limited by three factors:

* the accuracy of the spacecraft ephemeris;

* the ability to find match points and avoid mismatches;

* the slant range resolution and imaging geometry.

Experimental work with small sample data lead us to speculate that the compound elevation accuracy may be in the range of $\pm$ 200 meters. This is as much a result of residual errors in knowing the stereo base (difference of perhaps $\pm$30 to $\pm$50 meters between the two spacecraft positions of a stereo pair), as it is of matching ($\pm$2 pixels?) and of propagating the range measurement uncertainty into an elevation uncertainty.

6. Outlook

Magellan's images are a unique and challenging data set that is larger than all previous planetary data sets combined. They represent an investment in the range of almost US$ 1 Billion. Processing this set into useable products has only been preliminary and under the pressure of a planetary flight mision.

The systematic and careful analysis of this data set lies yet ahead. It should build on a re-processed data set that goes back to the original engineering data records (EDRs) and develops from there a new and optimized data set with the goal of building a true image information system for interactive computerized use by planetary scientists.

The Magellan data are also a test case for global imaging -- in a coherent fashion -- that may be of relevance to future Earth Observing System (EOS) efforts. Magellan clearly is a "discipline data set", the discipline being geology. Therefore the resulting global image information system is a "discipline" case study, with a worldwide community of data users and a long term value to the data since it is not to be expected that another mission will be launched in the next few decades to map the planet's surface.

References

Kirk R. (1987) A Fast Finite Element Algorithm for Two-Dimensional Photoclinometry, Ph.D.Thesis, California Institute of Technology, USA.

Kirk R., L Soderblom, E. Lee (1992) Enhanced Visualization for Interpretation of Magellan Radar Data: Supplement to the Magellan Special Issue, *J. of Geophysical Research*, Vol. 97, (E10), pp. 16,371-16,380.

Leberl F., K. Maurice, J. Thomas, W. Kober (1991) Radargrammetric Measurements from the Initial Magellan Coverage of the Planet Venus, *Photogrammetric Engineering and Remote Sensing,* Vol.57 (12),pp. 1561-1570.

Leberl F., K. Maurice, J. Thomas, C. Leff, S. Wall (1992a) Images and Topographic Relief at the North Pole of Venus, *J. of Geophysical Research*, Vol. 97, (E8), pp. 13,667-13,674.

Leberl F., J. Thomas, K. Maurice (1992b) Initial Results from the Magellan Stereo Experiment, *J. Geophysical Research*, Vol. 97, (E8), pp. 13,675-13,689

Thomas J., W. Kober, F. Leberl (1991) Multiple Image SAR Shape-from-Shading, *Photogrammetric Engineering and Remote Sensing,* Vol.57 (1),pp. 51-59.

Ford P., G. Pettengrill (1992) Venus Topography and Kilometer-Scale Slopes. *J. of Geophysical Research*, Vol. 97 (E8), pp. 13,103-13,114.

Wildey R. (1986) Radarclinometry for the Venus Radar Mapper, *Photogrammetric Engineering and Remote Sensing,* Vol 52 (1), pp. 41-50.