SURFACE TOPOGRAPHY RECONSTRUCTION OF VENUS FROM THE MAGELLAN MISSION

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ABSTRACT

NASA's Magellan mission to map planet Venus was an unqualified success. Over 95% of the planet's surface have been imaged, a large portion of that even more than once. The imaging part of the mission ended in 1992; the satellite itself had its life terminated in 1994. The images of the planet represent more than 400 Gbytes of pixels, distributed over more than 5000 individual orbits. These images have been entered into a data base of NASA's Planetary Data System PDS. As the major source of information about Venus, they are being studied now and for many years to come. This paper reports about some studies relating to managing the images and extracting the detailed topographic surface shape. One exploits the overlaps among images taken during different phases or cycles of the mission. Major issues in theses studies are the extent to which terrain features are laid-over at steep look angles off-nadir, the obstruction of analyses by the dissimilarity of images taken from opposite sides, and the sheer size of the data which causes difficulties in the interaction and use of the images.

ZUSAMMENFASSUNG

NASAs Magellan-Mission zum Planeten Venus wurde ein voller Erfolg. Mehr als 95% der Oberfläche des Planeten wurden abgebildet, ein Großteil sogar mehr als einmal. Die bildgebende Phase der Mission dauerte bis 1992, der Satellit beendete seine Existenz aber erst 1994. Die Bilddatenmenge umfaßt etwas mehr als 400 Gbytes an Pixeln und betrifft mehr als 5.000 Umlaufbahnen. Diese Bilder wurden nun in NASAs Planetary Data System (PDS) eingegeben und stehen für die Detailanalyse bereit, welche sich noch weit in die Zukunft dieser primären Informationsquelle des Planeten wird widmen können. Dieses Paper berichtet nun über einige dieser Studien zur Verwaltung dieser Bildmengen und zur Detailanalyse der Oberflächenformen. Es wird die Überlappung zwischen den Bildern genutzt, welche in den verschiedenen Projektphasen entstanden. Wesentliche Sorge dieser Arbeiten ist einerseits der hohe Anteil an topographischen Merkmalen, welche wegen der steilen Beleuchtungsrichtungen in einen sogenannten Layover fallen, weiters die Unähnlichkeit der überlappenden Bilder aus unterschiedlichen Beleuchtungsrichtungen, als auch die große Datenmenge, welche Schwierigkeiten bei der schnellen interaktiven Handhabung zur Folge hat.

1 INTRODUCTION

When the radar imaging system on NASA's Magellan satellite ceased operations in 1992, it had not only already assembled an amazing 400 Gbytes of images, covering more than 97% of the planet's surface, but it had also exhausted NASA's ability to keep the data stream funded. Within the almost polar, but highly elliptical Venus-orbit of the Magellan-probe, imaging periods were about 37 minutes per orbit. Within this time, a swath of about 20km width and 1700km length was to be acquired. Play-back to Earth took place for more than 100 minutes during the more distant section of the orbit, at a transmission rate of 270 Kbits/second. (see Figure 1).

While the mission would already have been considered highly successful had it merely managed, from August 1990 onwards, to produce single images of 70% of the surface, in fact it produced data also during two additional acquisition cycles: Cycle 2 was collecting images at an opposite viewing direction and Cycle 3 provided stereo-coverage in combination with Cycle 1 data by using a steeper inclination angle of the radar beam. Thus, many areas on Venus were imaged at least three times, and a coverage much higher than that specified as a mission goal could be achieved.

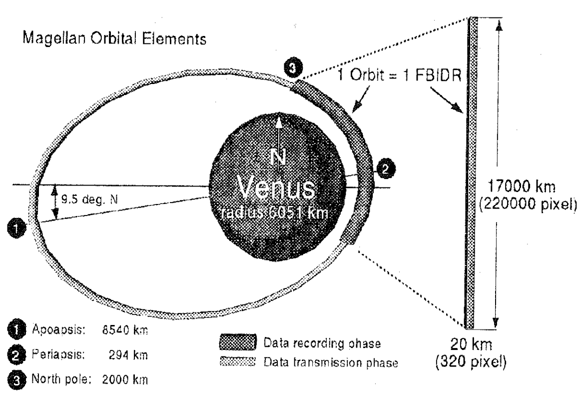

Figure 1: Schematic sketch of image acquisition by Magellan's SAR sensor, including distances to the surface of the planet at distinct points

The US$ 1 billion spent on Magellan primarily served the goal of collecting synthetic aperture radar (SAR) images of the planet's surface, to assemble all images to a mosaicked presentation on film at reduced scale, and to develop other data sets such as from altimetry, radar backscatter and gravity operations.

By the end of the mission, and thus also at the end of the mission's funds, the individual image strips, each up to 220,000 rows of pixels at 300 pixels per row, with each pixel representing an area of 75 m x 75 m on the surface, had been assembled into mosaics. Table 1 summarizes the SAR image products obtained from the mission, Table 2 addresses the range of data products in addition to those derived from the images. It becomes evident that the entire globe is covered by image mosaics at a scale up to 27 times smaller than that at which raw images exist. The full resolution products, however, were only assembled from perhaps 20% of the images, and over 10% of the surface.

F-MIDRs		
Full-Resolution Mosaicked Image Data Records	5° x 5°	75m pixels
C1-MIDRs		
Averaging 3x3 pixels to a reduced resolution Mosaicked Image Data Record	15° x 15°	225m pixels
C2-MIDRs		
Averaging 9 x 9 pixels	45° x 45°	625m pixels
C3-MIDRs		
Averaging 27 x 27 pixels	120° x 120°	2025m pixels
F-MAPs		
Reprocessed Full-Resolution Mosaics		75m pixels

***Table 1**: Summary of the major data products derived from Magellan SAR images. The C1-, C2-, C3-MIDR sets all cover the entire planet, devided into mapsheets of given extent*

Radar Altimetry	
ARCCDR Altimetry and Radiometry Data Records Individual echoes	
G-TDR Global Topography Data Records	5 km grid
G-SDR Global Slope Data Records	5 km grid
Radiometry	
G-REDR Global Reflectivity Data Records	5 km grid
G-EDR Global Emissivity Data Records	5 km grid
Gravity	
High Resolution Gravity Map	

***Table 2**: Summary of other data products obtained from the Magellan mission in addition to the images.*

Magellan challenged the data processing capabilities available during the mission. Still, all the 400 Gbytes of raw images are now available in NASA's planetary data system PDS, being responsible for data from all US planetary missions. After being transferred to an up to date storage media, also the raw radar phase and amplitude signals are planned to be managed by PDS.

Even a few years after completion of the mission itself, the data set is still large enough by contemporary standards to stimulate one's imagination; in addition, the uniform coverage of an entire planet without the concern for national borders helps to provide Magellan's images a function of „role model“ for managing terrestrial remote sensing data sets.

Many of the procedures used during the mission to create image products and information about the planet's surface were, in essence, „quick“, not necessarily most accurate and optimum. Since the mission's pressures and priorities have now faded one can take the time to develop a strategy for producing optimum data products and most accurate descriptions of the surface topography.

We report on ongoing work and will show how laid-over terrain features and dissimilarities between overlapping images are important elements in a strategy to reprocess the raw images. Of course, the sheer size of the data set must itself be a focus of recent work to prepare for an efficient analysis of Magellan imagery.

2 THE PLANETARY DATA SYSTEM

2.1 Organizational Aspects

Extraterrestrial space missions result in data that are being maintained by a NASA-funded organization of 8 research centers, half academic, half governmental. Each represents a functional node of a so-called network denoted as Planetary Data System (PDS). Its headquarter is at the Jet Propulsion Laboratory in California. PDS deals with images, atmospheric, gravity and other data resulting from past missions to other planets and moons, not, however, with data of the Earth. The Magellan images themselves are the responsibility of the so-called „Geosciences Node“ at Washington University (St. Louis). This node in turn manages a European Magellan Data Node at the Technical University in Graz. Magellan images are also being studied at the „Imaging Node“ at the Center for Astrogeology in Flagstaff, Arizona, which is part of the US Geological Survey (USGS). PDS is networked via the Internet. Access is free for anyone on the Internet via the address http:/www.pds.nasa.gov/. PDS maintains an on-line facility for those interested to search a data catalog. Images can be ordered and are being distributed by mail.

2.2 Status of Magellan Data Products

There is currently only one systematic effort going on to process so-called F-MAPs, full-resolution mosaics produced at the USGS Center for Astrogeology, one sheet per 12° x 12°, and created from the original radar image strips. Those images are corrected for the topographic relief known from altimetry. The individual image strips are connected by tie points, but the result is not corrected for detailed topography, even though such information would be available if a stereo effort were undertaken. The entire planet is expected to be covered by 1998. No funding exists at this time to process all 3 imaging cycles of Magellan. Instead a complete coverage of the entire planet is the goal so that each location of the planet is at least available on one F-MAP. This database is meant to replace previous F-MIDRs (see Table 1), the full-resolution mosaicked data records created during the Mission.

Data products suffer from the limitations that exist during a mission, namely insufficiently known topography and the priority of speed over accuracy and quality. Weaknesses in those data products exist:

- The ephemeris on which the image products are based is the predicted one. An ephemeris obtained by post-mission processing of all observations and by consideration of superior gravity data does not exist. To improve the data products, one would have to first reprocess the ephemerides, then reprocess the raw radar echo signals with the improved satellite's ephemeris.

- The image products are not corrected for topographic relief as it resulted from the mission, nor are they corrected for topographic relief as it could be extracted from the images themselves where stereo-overlaps exist (see Leberl, 1993a,b). The individual data products are not terrain corrected and will thus not fit one-another when covering the terrain from opposite sides.

Besides mosaicked image data records there exist other results such as those from the antenna „listening" to the emitted energy from the planet's surface producing temperature maps; or echoes from a radar-altimeter, producing a coarse topographic relief and measures of reflectivity; and finally the gravity observations producing a detailed gravity map (see table 2).

3 MANAGING MAGELLAN'S IMAGES

At Institute for Computer Graphics of the Technical University in Graz, the European Magellan Data Node EMDN has been installed as part of NASA's PDS. Related to the responsibility for supporting Magellan users in Europe, several activities have been started.

3.1 A Venusian Atlas

Since the size of the Magellan data set is to big to distribute it entirely to anyone interested, efforts are undertaken to grant convenient access to the data via an Internet-based image data catalogue. The inspection of the Venusian surface for features or areas of interest so far was done by visual inspection of paper printouts of the digital data. To implement a similiar functionality with the Internet-based retrieval system, a digital map is provided which can be used to explore the Venusian surface at 8 different levels of resolution from 225 m/pixel to about 30 km/pixel. The Venusian Atlas map data were derived from the C1-MIDR (see Table1) data set. To reduce the size of the resulting image data pyramid from about 13 Gbytes down to 500 Mbytes, lossy compression was applied, therefore it can not be used for any further processing. It's main role is to provide interactive access to the Magellan images.

3.2 Interactive Access to Magellan Images

The Interactive Venus atlas can be overlaid with any information available about existing images and other data. One can zoom in and out the digital surface map and define areas of interest using the mouse. The search for the image coverage of a given area becomes a matter of seconds. A color coding scheme helps to identify areas with stereoscopic coverage, where same side images at different inclination angles do exist. Any of the images found during this process can be marked for ordering or downloading depending on their size and the network bandwith available. The system is designed in a way that alows to add any new images or other data like DEMs to the database as they become available.

3.3 Distributed Data and Software

Software and data for Magellan may well be distributed over multiple sites (Rehatschek, 1996; in print; Walcher and Rehatschek, 1995). Access to software and the images should be open to remote locations. Such concepts are currently being tested for PDS / EMDN, but also apply to terrestrial remote sensing, as it is done by EOSDIS in the US, or CEO in Europe.

1) MST is available from Vexcel Corporation by contacting kelly@vexcel.com.
2) P. Chodas, oral communication.

4 DIGITAL ELEVATION DATA

4.1 Stereo Matching and the MST

The mission originally did not plan to acquire overlapping stereoscopic radar images at different incindence angles from the same side. It was only in the „extendend mission", when the so-called Cycle 2 images were collected at opposite viewing direction (1991), that it was shown in an eight orbit imaging sequence that useful stereo observations could be made (Leberl et al., 1992). This led to the initiative (as an „on the fly decision") of a third imaging cycle for obtaining a stereo coverage in combination with Cycle 1 data. Such, about a third of the planet was covered when the radar sytsem ceased to function. While the stereo coverage exists, funds are insufficient to actually systematically extract stereo information. Funding was available, however, to develop software to support individual researchers in the production of digital (Leberl, 1993; MST, the Magellan Stereo Tolkit)[1]

A number of stereo experiments were performed at NASA's Jet Propulsion Laboratory, at the Center for Astrogeology of the US Geological Survey, at Vexcel Corporation and elsewhere to verify the ability of extracting a digital elevation model with predictable and useful accuracy. Leberl et al. (1992) and others report that the accuracy may be in the range of better than 1 pixel for image matching, resulting in an elevation accuracy of about 2 pixels or 150 meters. This is an optimistic assessment that assumes that the ephemeris of the spacecraft is known at great accuracy. In fact the ephemeris can have large errors of up to 10 - 15 km when considering image pairs taken several months apart. Unfortunately, this is most likely the case when data from different acquisition cycles have to be combined for stereo restitution.

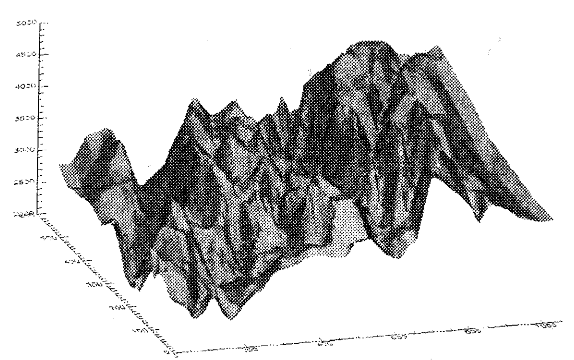

***Figure 2**: Stereo-derived DEM of an area at 2°S, 74°E. Area covered is 75 km x 45 km.*

Figure 2 respresents a digital elevation model of an area obtained close to the equator with differences in altitude of up to 5000m. In that case an improved ephemeris was computed for a limited set of orbits. The Jet Propulsion Laboratory has shown that such improvement is possible within about ± 30 m[2]. However, the ephemerides of the entire Mission will still have to be processed with that technique. The result in Figure 2 is a demonstration of a prototype suite of stereo processing algorithms that have been implemented in MST in a preliminary fashion.

4.2 Coping with Layover

Since the polar orbit of Magellan was highly elliptical, the probe was much closer to the planet when passing the equator than over the poles. To obtain image-strips along the meridians, the inclination of the radar-beam was adjusted during image acquisition. So, the initial Cycle 1 had images taken at 45° off-nadir near the equator and about 11° near the poles. The same applies to Cycle 2 images, taken in similar way from the opposite direction. The stereo partners to the initial coverage were acquired with Cycle 3 and had look-angles ranging between 25° off-nadir at the equator to 7° off-nadir near the pole. This resulted in stereo-intersection angles between 20° and 4°. While these angles are fairly small and represent a limitation to the accuracy at which a DEM can be extracted from the SAR images, there is another issue caused by the steep look-angles: layover. In topographically accentuated terrain a very large portion of the slopes may be laid over. As shown in Figure 3, such layover areas do not lend themselves easily to the reconstruction of surface slopes and elevations. Connors (1994) has shown that it is in principle possible to employ overlapping stereo coverage to determinate whether a layover situation exists or not. There is an ambiguity which of two possible slopes may cause a particular image situation. The ambiguity can be resolved with the third opposite coverage. Gelautz et al. (1996, in print) are working on automating the process used by Connors (1994) in a manual manner. This would lead first to an identification of layover areas in all of Magellan's coverage; and it would secondly use the layover to improve the slope measurement of the terrain that is giving raise to the laid-over images.

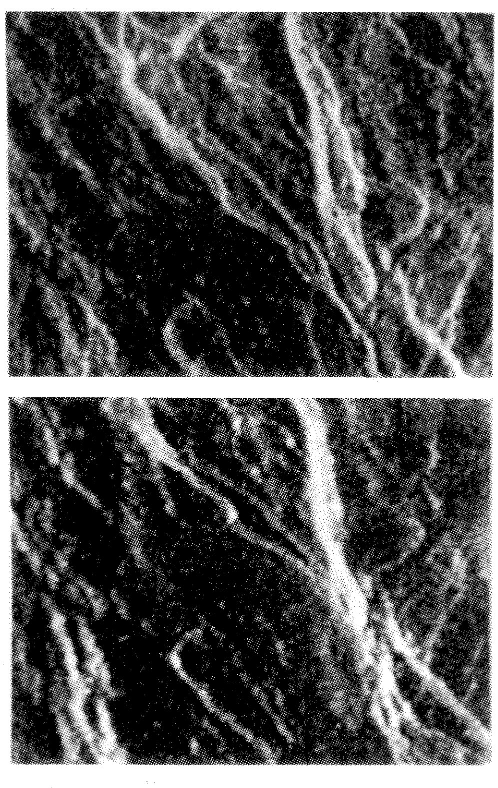

Figure 3: Example of laid-over terrain features in Magellan images taken at 11° look-angle off-nadir. Area covered is 15 km x 2 km.

4.3 A System for Reprocessing Stereo Data

The use of the Magellan Stereo Toolkit, the elevation and slope errors caused by erroneous ephemerides and the problems arising from laid-over features cause us to suggest that extraction of a detailed topographic relief from Magellan images should be based on a complete processing chain. It should begin at the raw signal histories received at the ground receiving stations on Earth from the satellite. We describe a sequence of procedures to accomplish an optimum extraction of topographic relief.

(a) The ephemerides need to be reprocessed in the manner described by Chodas et al. (1992). A total of about 5,000 orbits are at issue. For each orbit a number of tie-points needs to be identified between an image of a particular orbit and images from other cycles. Perhaps 10 to 20 tie-points would be needed per orbit. The improvement of the ephemerides can also take advantage of the most recent gravity model of the planet. Its quality was vastly improved when the orbit was circularized just prior to the satellite dipped into the atmosphere and perished. That accuracy may be sufficient to obtain an ephemeris as accurate as that which could be obtained with tie-points in a type of photogrammetric block adjustment.

(b) Reprocessing raw signal histories can be based on the improved ephemeris and produces full-resolution image strips. These will not be corrected for topographic relief obtained from altimetry.

(c) Stereo matching uses new images as each orbit of Cycle 1 crosses over orbits of Cycle 3. Such stereo matches should have errors in the range of open 0.6 to 2 pixels depending on the type of features and the dissimilarity between the images (Leberl et al., 1993). Various authors have argued that image matching should be performed on the mosaics that are currently being processed in the form of F-MAPs. Match points in each image could then be converted to time, Doppler frequency and range which could then be attached to the improved ephemeris. This proposal would skip step (b) until such time that the stereo-derived topographic relief has become available. But in that event one would not use the best and highest resolution images for matching. Given current parallel processing technologies one could argue that going through all signal history records and creating a new intermediate set of 5,000 full-resolution images is no longer the monumental task it was during the Mission.

(d) Intersecting surface XYZ-values is based on the Doppler frequency and range measurements of homologue features in Cycles 1 and 3. This produces surface locations in XYZ at an accuracy of the ephemeris. In areas where no stereo observations can be made one can employ the altimetry data that were independently obtained from a vertical looking antenna (Ford et al., 1994).

(e) Gridding converts the stereo-derived surface points at irregularly spaced position into a regular grid. This is based on interpolations; such points are regularly spaced in latitude/longitude or in a map projection. Elevations obtained in this way can also be resampled to be attached to the individual image pixels.

(f) Terrain-corrected ortho images derive from the raw images, resampled to the proper terrain geometry. One will obtain geocoded ortho-rectified radar images from each of the 3 cycles. An individual surface point may thus be shown on different images. Due to Magellan's quasi-polar orbit, near to the pole a location may have been imaged tens to hundreds of times.

(g) Shape-from-shading models how a human observer would interpret brightness and shadows in the radar image, which roughly appears like an oblique illumination of the terrain. Unjustified, this process is assuming uniform backscatter-properties for the whole surface of the planet and accuracies are much dependent on the look-direction of the sensor. Still, a shape-from-shading approach applied to geocoded images is beneficial to refine details of the digital terrain elevation beyond what can be extracted from the geometric disparities in stereo pairs.

(h) An image and data stack may consist of an optimum digital elevation model and a set of overlapping geocoded and ortho-rectified images from multiple cycles. One may organize the material into an image data base as discussed in Section 3.

5 COPING WITH DISSIMILARITY

5.1 Opposite Side Images

Subsection 4.3 assumed that all the 3 Cycles of Magellan images can be geocoded using terrain elevations extracted from stereo or from altimetry. This is only true if the images from the third non-stereo („opposite-side") Cycle can successfully be processed with the elevation data.

5.2 Experiments with Image Simulation

One software tool for this task is simulation. The opposite-side image can be synthesized using the topographic relief available from altimetry, stereoscopy or from shape-from-shading. Figure 4 illustrates the problem of an opposite-side Magellan pair and relates this to a DEM obtained by stereo. Simulating the opposite-side image produces an intermediate product that may be matched with the actual opposite-side image by conventional methods. So, one can verify if and where the two images are geometrically identical. If not, then the digital elevation model needs to be corrected so that identity between the simulated and real image is accomplished. This problem domain is the subject of ongoing work (Kellerer-Pirklbauer, in print).

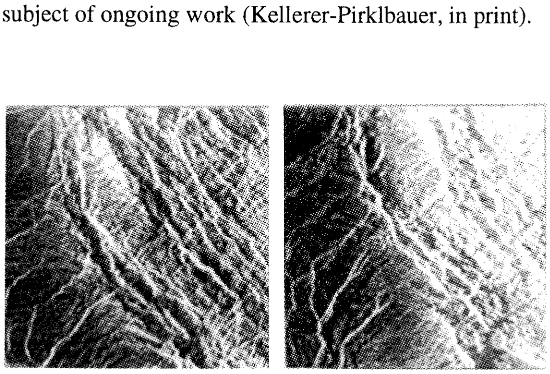

Figure 4: *Opposite-side Magellan images of accentuated terrain. Look-angles are 43° East and 25° West. Location at 2°S. Area covered is 30 km x 30 km.*

6 CONCLUSIONS AND OUTLOOK

We have described geometric processing of Magellan radar images. The Internet provides access to the images in the Planetary Data System PDS. A systematic effort currently converts the full resolution original image strips into a final image product, the F-MAP. However, those images still are affected by the errors of the preliminary ephemerides obtained during the Mission, and they just corrected using the poor DEM obtained from altimetry.

We have proposed and are actively pursuing the development of a suite of modules that would represent an alternative system for reprocessing the raw phase histories. We work towards a final image data base of ortho-rectified and geocoded images. The DEM would be produced from stereo, taking into account also the opposite-side imagery.

We are addressing a number of individual problems such as the database issues of managing the large 400 Gbyte images from Venus; the difficulty one faces because of the excessive layover in topographically accentuated terrain which occurs because of the very steep look-angles of Magellan; the matching of opposite-side image using the topographic elevations obtained from stereo; the use of shape-from-shading and of image simulation that should alleviate the concerns resulting from layover and dissimilarities in opposite-side images. We are also concerned about computing times and therefore have embarked on an effort to parallelize key algorithms such as shape-from-shading, image matching, surface point gridding, and perspective rendering for quality control (Goller et al., in print; Goller, in print).

The Magellan mission was terminated in 1994; the imaging portion of the mission ended already two years earlier in 1992, after the imaging radar had operated for 3 years. Since the end of the Mission the data analysis has become a coordinated but modest effort, much reduced from that which existed during the Mission. It is through the Planetary Data System and its participating 12 institutions that the data are being processed at the rate which funding supports. We hope that radargrammetric processing will evolve into a complete suite of software elements to produce an accurate DEM and associated ortho-rectified images. The basic prerequisite is an improved ephemeris which is outside the scope of the radargrammetric work. It will be the pivotal element to make the geometric reprocessing effort worthwhile.

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REFERENCES

Connor C. (1994) *Determing Heights and Shapes of Fault Scarps and Other Surfaces on Venus Using Magellan Stereo Radar.* Manuscript, Princeton Univ. Dept. of Geological Sciences.

Ford Pl, G. Pettengill (1992) *Venus Topography and Kilometer-Scale Shapes.* J. Geographical Research, Vol. 97, pp.13103-13318.

Gelautz M., F. Weinbergmair, F.W. Leberl (in print) *On the Detection and Exploitation of Layover in Magellan Imagery.* 18th ISPRS Congress, Vienna/Austria, July'96.

Gelautz M., F.W. Leberl, W. Kellerer-Pirklbauer (1996) *Image Enhancement and Evaluation: SAR Layover and Shadow.* EUSAR'96, Königswinter, Germany, 26-28 March 1996, published by VDE, pp.71-77.

Gelautz M., G. Jakob, G. Paar, F.W. Leberl, S. Hensley (in print) *Automated Matching Experiments with Different Kinds of SAR Imagery.* Proceedings of the IGARSS, Nebraska, May'96, published by IEEE.

Goller A. (in print) *Concurrent Radar Image Shape-from-Shading on High-Performance Computers.* ICPR, Vienna, August'96.

Goller A., M. Gelautz M., F.W. Leberl (1995) *Parallelization Experiments for Radar Image Shape-from-Shading.* In F.Solina, W.G.Kropatsch Franc (Eds.): Pattern Recognition 1995 - Proceedings of 19th ÖAGM and 1st SRDV-Workshop, Maribor/Slovenia, May'95. Oldenburg Wien München, pp.41-49.

Kellerer-Pirklbauer W. (in print) *Automated Geocoding of Satellite Radar Images using Radar Image Geometry Simulation.* 20th ÖAGM, Seggau, May'96.

Leberl F.W., J. Thomas, K. Maurice (1992) *Initial Results from the Magellan Stereo-Experiment.* J. Geophysical Research, Vol. 97, pp.13675-13681.

Leberl, F.W. (1993a) *Development of a Stereo Analysis and Visualization Tool Kit for Planetary Radar Images,* International Workshop on Image Analysis and Synthesis, Graz, published by Oldenbourg-Wien, pp.45-56.

Leberl, F.W. (1993b) *How To Extract Venus Topographic Information From Magellan Radar Images,* SPIE Proceedings Vol. 1943.

Leberl, F. W., K. Maurice, J. Thomas, M. Millot (1994) *Automated Radar Image Matching Experiment,* ISPRS J. of Photogrammetry and Remote Sensing, Vol. 49, No. 3, pp.19-33.

Rehatschek H. (1996) *The Design of a Distributed Remote Sensing Planetary Data Archive based on an ATM Network.* Proceedings of Visual '96 - Architecture of Visual Information Systems, Melbourne, Feb.'96, pp.68-78.

Rehatschek H. (in print) *A Concept for a Network based Distributed Image Data Archive.* 18th ISPRS Congress, Vienna/Austria, July'96.

Walcher W. (in print) *Visual Interaction with Very Large Spatial Data Sets.* 18th ISPRS Congress, Vienna/Austria, July'96.

Walcher, W., H. Rehatschek (1995) *Design of a Distributed Database for the Magellan Data Set from Planet Venus,* Proceedings of the IGARSS, Florence, Italy, July 1995, IEEE'95, pp.1610-1612.