VALIDATION OF THE USGS MAGELLAN SENSOR MODEL FOR TOPOGRAPHIC MAPPING OF VENUS.
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Introduction: The Magellan spacecraft obtained synthetic aperture radar (SAR) same-side stereoimages for about 17% of the venusian surface. The geometric properties of these stereoimages are excellent, resulting in an estimated vertical precision (EP) of ~10 m [1]. Magellan also obtained radar altimetry data at a horizontal resolution of 10x25 km, but photogrammetric analysis of the stereomagery can yield a horizontal resolution more than an order of magnitude superior to that of the altimeter. Digital photogrammetric systems have therefore been developed to stereoscopically derive Magellan digital elevation models (DEMs). After working with two such systems, the Magellan Stereo Toolkit (MST) developed by VEXCEL [2] and the SAIC Digital SAR Workstation-Venus (DSW-V) [3], and finding that neither fully met our needs for map production, we undertook the development of software needed to utilize Magellan stereomagery on our LH Systems DFW 790 digital photogrammetric workstation. The special hardware and SOCET Set ® BAE SYSTEMS software [4,5] of this system can be extended by programming with the SOCET Set Developer’s Toolkit (DEVKIT). For a variety of missions [6,7,8,9], we have written translation software to import planetary images and supporting data from ISIS [10,11,12], which is used for mission-specific data ingestion and calibration steps, into SOCET Set for stereomapping. However, the unique properties of the Magellan SAR data made it necessary to develop both translation software and a sensor model [13].

Magellan SAR Mapping System: We designed our system to be rigorous and flexible. The sensor model (which is based on the sensor model utilized by the SAIC DSW-V) includes all the physics of the Magellan imaging process and accounts for the fact that the images have been partially orthorectified as part of the correlation process. Our system works with any combination of unmosaicked (F-BIDR), mission-mosaicked (F- and C-MIDR), and USGS-mosaicked (FMAP) images. In addition, information about the spacecraft position and velocity can be taken either from the F-BIDRs or from separate NAIF SPICE kernels, letting us take advantage of post-mission improvements to the spacecraft ephemerides without the need to redo SAR correlation or mosaicking. Furthermore, the SOCET Set bundle-adjustment software can be used to estimate corrections to the ephemeris of each orbit. The form of the corrections, offsets and velocity adjustments in three orthogonal directions (along-track, across-track, and radial), suffices to correct the orbits over short arcs and reconcile SAR and altimetry observations.

Initial Test Results: Experimentation on three subsets of Magellan stereo data allowed us to develop effective procedures for operational mapping, but unfortunately also exposed some significant problems. The first test used images of the stereo test area acquired during Cycle 2 of the Magellan mission, which we previously used to test the SAIC DSW-V and the VEXCEL MST systems. The SOCET SET matcher was found to combine the high speed of automatic matching available in MST with high DEM resolution, but some manual editing was necessary in very bland image areas.

Development of procedures for control and stereomatching required a larger dataset, such as the 64 Cycle 1 and 53 Cycle 3 orbits covering FMAP quadrangle 06S066 (Joliot-Curie). We were particularly concerned with the well-known “cliffs,” artifacts in the stereo data caused by discrepancies between the mission ephemeris solutions for successive blocks of orbits. Alex Konopliv of JPL reprocessed the entire set of orbital tracking and navigation data based on the detailed gravity observations from the end of the mission and claimed that errors in the new orbit solutions were decreased 1.5 orders of magnitude (to 50-200 m) in all 3 axes [14]. Our test mapping unfortunately showed that errors of this magnitude north-south interfered with stereomatching, while east-west ephemeris errors resulted in height offsets in the derived stereomodels. To produce seamless elevation data, and maintain good agreement with Magellan altimetry, we found it necessary to collect image-to-image tiepoint measurements and use these to estimate 3-axis corrections to the Konopliv orbits as described above.

A second result of the Joliot-Curie tests was the development of a stereomatching procedure that minimized the need for manual DEM editing. We found that "seeding" the DEMs with a small number of manually collected points on ridge and valley lines greatly improved the success rate of the automatic matching step. With this approach, the need for manual editing was largely limited to bland areas where the matcher failed entirely. In a few areas of intermediate roughness, however, the matcher did not fail but produced artifacts in the form of roughly east-west trending bands superimposed on the real topography. The cause of these artifacts is discussed below.

A third test area covering Maxwell Montes was selected because of the availability of an independent set of improved ephemerides, calculated by Paul Chodas of JPL, based on his own tiepoint measurements [15]. Unfortunately, we were not able to map this area because of an apparent large (several km) offset between Cycle 1 and Cycle 3 images in this region. The consequent misalignment in the stereomages made automatic matching impossible. Although it would be possible to bring the images into alignment by bundle adjustment, we considered it essential to first understand the cause of the large discrepancy.

Coordinate Errors Resolved: Investigation of the offset discovered in the Maxwell images yielded some puzzling clues. We found that the C1 (north-south) coordinates of radar-burst centerpoints computed in our software differed from the values stored in the F-BIDR headers and that this discrepancy varied in a smooth but complex way along each orbit. The pattern of small discrepancies at low latitudes and larger (up to 2 km, or 15 pixels) discrepancies at high latitudes explained our success in mapping Joliot-Curie and failure near Maxwell. We eventually found the main cause to be a simple bug in the sensor model code (inherited from the SAIC DSW-V): doppler frequencies were being computed based on the nominal radar wavelength of 12.6 cm instead of the exact wavelength of 12.56991 cm. Using the correct wavelength reduced the maximum coordinate discrepancies at high latitudes to <2 pixels (0.15 km) and eliminated the previously mentioned east-west artifacts in the low latitude DEMs. The remaining discrepancy in C1 coordinates was traced to the difference between implementations of the atmospheric refraction correction in our software and in the Magellan SAR processor that produced the F-BIDRs. Both packages use a simple empirical function fit to numerical calculations of atmospheric refraction. It seems likely that the SAIC/USGS calculation, which uses a rational function of
ground point elevation, spacecraft elevation, and their horizontal separation, is slightly more accurate than the SAR processor code, which uses a polynomial in spacecraft elevation and horizontal separation only. Nevertheless, we have adopted the Magellan SAR processor refraction code in our sensor model in order to insure that our DEMs are positionally consistent with the mission-produced images.

Validation of Control Procedures: The bundle-adjustment takes as input both the coordinates of selected features (pass-points) in the images and interpolated altimetry data; the resulting corrections to the ephemerides are intended not only to make the overlapping same-cycle images align seamlessly, but to make the elevations of pass-points calculated from stereo agree with the elevations from altimetry. Elevations of individual altimeter footprints can be in error by several kilometers at high-contrast boundaries in the surface scattering function. The question therefore arose: would the control process yield stereo DEMs that are similarly in error? This seemed unlikely in principle, because the adjustable parameters allow each image to be translated and rotated as a whole, but not to be "warped" to fit erroneous altimetry data. We nevertheless sought an external check for the reliability of our stereo DEMs.

Better Mapping Through Chemistry: The most direct verification of our results would be a comparison of our DEMs with independent, non-Magellan derived elevation data. Unfortunately, the best Earth-based elevation dataset for Venus, derived from Goldstone radar observations [16], had inadequate resolution and signal-to-noise ratio to address the potential errors inherited from Magellan altimetry. A more indirect approach to validating our results was therefore needed. The temperature- and therefore elevation-dependence of radar backscatter properties on Venus provide such a check. Low-reflectivity lowlands give way to extensive bright highlands, with a few of the highest elevations once again radar-dark. The lower transition occurs over a relatively broad range of elevations locally and at a height that varies by several kilometers globally. The upper transition is noticeably sharper and was therefore selected for test mapping. In particular, we mapped the portion of central Ovda Regio from 88-98E, longitude, 8-5S, latitude, which contains several high-elevation dark regions. One of the dark regions on the eastern side of the study area has previously been described by Arvidson et al. [17] who constructed DEMs of a portion of it from the same Magellan stereo data we used, but with different mapping software. An important result of their mapping was that the transition in emissivity and reflectivity takes place over an elevation range of 500 m or less. We therefore mapped the same area and did a quantitative statistical comparison.

Images (F-BIDRs) used for our mapping came from 47 Cycle-1 orbits in the range 0947-0994 and 34 Cycle-3 orbits in the range 4536 to 4582. Control points, 212 in all, were interactively measured. Elevations of the pass-points were constrained based on the Magellan altimetry, and a least-squares bundle-block adjustment of the spacecraft ephemerides was performed to minimize the image-to-image and control-to-altimetric-elevation discrepancies. Altimetric elevations inconsistent with the remainder of the altimetry data and the stereomography were readily identifiable and were eliminated from the final control solution. Where possible, they were replaced by points nearby for which elevation residuals were found to be acceptable. After a satisfactory control solution was obtained, a DEM was collected by automatic stereomatching, and a bare minimum of interactive editing was done to correct spikes in a few areas where the automatic matcher failed.

We find that the elevation of the bright-dark transition varies up to 500 m across the entire region we mapped, and ~200 m across the region also mapped by Arvidson et al. [17]. This leads us to speculate that the 500-m height range that they reported for the transition might have been inflated because of the low spatial resolution of the emissivity measurements they used.

In contrast to both our stereo-derived DEM and those of Arvidson et al. [17], the Magellan altimetry for this area shows a series of apparent "pits" 20-50 km wide and typically 3 km deep. A chain of such pits runs through the dark areas; if the altimetry were correct, some of the dark material would have to lie 3 km below the majority of the transition boundary. Furthermore, local slopes of as much as 15 degrees would be implied; there is no morphologic evidence for such slopes in the images or for any visible peculiarity spatially associated with the altimetry lows. We conclude that these low elevations are artifacts resulting from noisy or incorrectly interpreted altimeter echoes. Fortunately, the vast majority of the altimetry data are not subject to such severe errors, so it is possible to constrain the stereogrammetric control solution to follow the altimetric DEM where it is valid and robustly exclude bad altimetry datapoints from the control solution.

Conclusion: The most important conclusion of our comparison between the USGS and Arvidson et al. DEMs is that neither shows any sign of the multi-kilometer depressions seen in the altimetric DEM for the area mapped. We are easily able to detect, during our bundle-adjustment process, altimetric elevations in the apparent depressions that are inconsistent with the remainder of the data and therefore do not use these elevations as constraints in the calculation. The result of the software and procedures we have developed are high-resolution stereo DEMs that agree well with the altimetry in the regions of uniform reflectivity, where the altimetry is reliable, yet not distorted by altimetry artifacts where there are strong reflectivity contrasts. We have now started systematic mapping of the areas that combine high scientific interest with the most complete stereo coverage.