Automatic DEM Generation Using Magellan Stereo Data

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ABSTRACT

The Magellan radar instrument collected a large volume of radar stereo images during its two years of operation. In order to make full use of this data an automatic means of generating digital elevation models is required. Because of Magellan's unique orbital geometry and radar image formation algorithm a number of modifications to the standard stereo processing scheme are required, This paper outlines a stereo algorithm suitable for Magellan data.

INTRODUCTION

Subsequent to its insertion into Venus orbit in August of 1990 the Magellan spacecraft collected synthetic aperture radar (SAR) data over 98% of the planet's surface. Because Venus' spin rate is very small, completing one rotation every 243 days (one cycle), Magellan was able to image a large portion of the planet's surface during each of its three mapping cycles. During the third cycle the look angle was adjusted in order to obtain stereo pairs with data collected during the first cycle. Stereo data WLLS collected over approximately 35% of the planet surface. This data is a valuable in a variety of geologic and geophysical investigations such as measurement of extensions and compressions, impact craters, surface processes, backscatter studies, and surface composition studies.

In order to exploit this data set an automated procedure for making digital elevation models (DEM) from the stereo data is required. Stereo processing consists of three primary functions, scene correlation or matching, solving for scatterer position vectors using the matching data (stereo intersection), and regrinding the position vectors to a uniform map grid. This paper focuses on the scatterer position vector determination and regrinding operations leaving the automatic matching to be discussed elsewhere,

MAGELLAN MISSION

The Magellan spacecraft carried only one scientific instrument, a radar consisting of a synthetic aperture radar, altimeter and radiometer with the primary goal of obtaining high resolution SAR imagery of the cloud covered surface of Venus on a global scale. Magellan's orbit about Venus is nearly polar, and prior to aerobraking in May-August 1993, moderately eccentric with a periapsis altitude of 290 km and an apoapsis altitude of 8460 km. Table I contains a summary of Magellan's orbital characteristics. During each of the cycle 1 orbits the radar operated for 37 minutes around periapsis during which time the high gain antenna was pointed toward Venus and radar echo data was collected arid stored using the on board tape recorder, Subsequent to data' collection the spacecraft the high gain was pointed toward earth and the radar data was played back at 1/3 the speed it was recorded,

The radar data acquired on each orbit consists of North-South strips of data 23 to 35 km in width and as long as 15000 km. Venus rotation of .20° from one orbit to the next causes the mapping swath to be displaced to the east of the previous one with a small amount of overlap, Since the amount of linear displacement is largest at the equator, approximately 23.25 km, the amount of overlap increases with higher latitudes. This fact was exploited in cycle one to maximize the latitudinal coverage by mapping from the north pole to 52° South on even orbits and from 54° North to 78° South on odd numbered orbits. No gaps in the coverage resulted from this strategy because the rotation rate was slow enough to allow overlap on alternate orbit pairs for latitudes above 54" North. Due to a transponder problem in cycle 3 which severely lowered the data rate the swath lengths were half the length of those in cycle 1 and the alternating latitude coverage was not used.

Table I. Magellan Orbital Characteristics

Parameter	Value
Periapsis Altitude, km	290
Periapsis Latitude, °N	9.5
Altitude at Pole, km	2000
Inclination, deg	85.5
Period, hr	3.259
Repeat Cycle, days	243

MAGELLAN RADAR SYSTEM

Many of the unique aspects of Magellan stereo processing arc a result of the elliptical nature of Magellan's orbit and the burst mode of operation. The radar was forced to operate in a burst mode, that is sequence of pulses are transmitted and received with interspersed periods of radar inactivity, in order to meet data rate constraints. The number of pulses in each burst varied from approximately 1000 near the pole to 250 pulses near periapsis. The bursts were arranged so as to guarantee that each point was imaged in a minimum of 4 bursts (i.e. the number of looks was at least four). Because of the elliptical geometry of the orbit the look angle and pulse repetition frequency were adjusted up to a 1000 times during each mapping pass.

The Magellan radar is an S-band system with an operating frequency of 12,6 cm and a modulation bandwidth of 2.26 Mhz which translates into an effective slant range resolution of 88 m. The ground resolution of the radar was a constant 120 m in the along track direction and the cross track ground resolution varied from 300 m at the pole to 1 IO m at periapsis due to the look angle variation, Each burst of data was then resampled from range/doppler coordinates to sinusoidal projection using a low frequency digital elevation map of Venus by a biquadratic interpolating polynomial, These polynomial coefficients were recorded as ancillary data to the basic image swath enabling the conversion from pixels in the final image back to range and doppler. The data was sampled to a 75 m pixel spacing (that is the images were oversampled by a factor of 2) in the full resolution basic image data record (FBIDR).

STEREO PROCESSING OVERVIEW

Stereo processing of either optical or radar data uses multiple observations of the same scattering element to extract three dimensional scatterer location information. Although the individual images are projections of the three dimensional scene into two dimensions, information on the third dimension can be derived from differences in the relative positions of features in the two images, assuming the viewing directions of the images are different, To

illustrate thi s for radar observations, consider the simplified geometry illustrated in Figure 1.
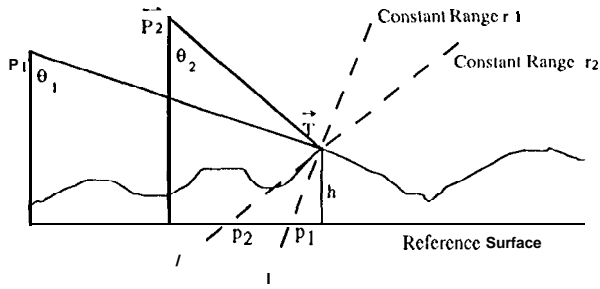

Figure 1. Simplified radar stereo geometry.

Assume for simplicity the radar observation locations denoted by $\vec{P}_1$ and $\vec{P}_2$ and the scatterer location, $\vec{T}$, are all coplanar and that the spacecraft motion is perpendicular to the figure. The radar measures the range (denoted by r_1 and r_2) from each of the observation points to the scatterer. If the ranges are large cornparcd to the features of interest the loci of constant ranges from the spacecraft can be viewed locally as straight lines perpendicular to the line-of-sight vectors, as illustrated by the straight lines in Figure 1. The projection of the scatterer onto the reference surface is the intersection the constant range lines, dashed lines in the figure, with the reference surface denoted by p_1 and p_2 in the figure. The difference in the feature location when projected onto the reference surface, $p_2 - p_1$, is called the parallax and using simple trigonometry the height above the reference surface is seen to be

$$h = \frac{p_2 - p_1}{\cot(\theta_2) - \cot(\theta_1)} \qquad (1)$$

where θ_1 and θ_2 are the angles from the local vertical to the line of sight vector as shown in the figure.

In fact, the above simplified model it not used, instead a more precise formulation using the fundamental radar measurements is employed, This not only allows a more general imaging geometry than discussed above, but permits onc to obtain formal feature location error estimates as will described below.

STEREO INTERSECTION

In a SAR system such as the Magellan radar the fundamental measurements are the range and doppler to each scatterer, A more precise height determination, indeed the full 3 dimensional position vector of the scatterer, can be obtained by relating the observed range and dopplers to the target and platform position vectors. Writing down the equations for the range and doppler from the two observation locations and the scatterer position vector yields the four overdetermined nonlinear equations (the radar stereo equations) given by

$$r_i^2 = \langle \vec{T} - \vec{P}_i, \vec{T} - \vec{P}_i \rangle \qquad i=1,2 \qquad (2)$$

$$f_i = \frac{\langle \vec{T} - \vec{P}_i, \vec{V}_i \rangle}{\lambda r_i} \qquad i=1,2 \qquad (3)$$

where r_i arc the range measurements and f_i are the doppler measurements and λ is the radar wavelength.

These equations can bc solved in a variety of ways. First, the simplest solution results by subtracting the two range equations and solving the resulting linear system of equations, This is not viable in the Magellan situation because the solution of this linear system of equations is extremely sensitive to ephemeris errors. This sensitivity to ephemeris errors is a result of the velocity vectors being nearly parallel at the two observation locations. A second, and in fact robust approach is to take the two range equations and one of the doppler equations and solve the resulting set of nonlinear equations which will bc referred to as the nonlinear stereo equations (NSE). A closed form expression for this set of equations exists and provides an efficient means solving equations 2 and 3. By averaging the solutions obtained from using the two doppler equations a solution that nearly satisfies all four equations can be obtained which is very tolerant of ephemeris errors.

The above two methods used only a portion of lhe measured data to obtain solutions, It is natural then to seek a method that will simultaneously use all the provided information and obtain the "best" solution to all of the stereo equations. This suggests using a least squares approach to finding the solution (a generalization of the method described in [Leberl 1990] to nonzero squint is employed). The only complication to using the least squares method in the stereo context is the equations are nonlinear in the parameters to be estimated forcing the use of an iterative scheme to obtain the solution. The number of iterations is reduced significantly by using the solution of the NSE as an initial estimate for the solution to the least squares problem. Additional computational efficiency is achieved when using the nonlinaer least squares approach by blocking the least squares matrix equations appropriately. Doing so reduces the size of the matix that must be inverted to 3x3. Moreover, if error covariance matrices are available for the ephemerides and the range/doppler measurements the covariance matrix of the solution can be obtained providing formal height error estimates, Measurement covariances for the ephemerides are obtained as ancillary information to the navigation solution for the Magellan spacecraft. The range/doppler covariance estimates are obtained from the offset measurement covariance matrices (as described in the scene matching section below) and the range/doppler resampling polynomials.

An important factor not considered thus far is the effect of the very thick Vensuian atmosphere. The atmosphere refracts the radar wave according to Snell's law as it passes through the atmosphere going from the spacecraft to the planet's surface, The apparent or observed range to a scatterer on the surface is greater than the geometric or straight line range due to two effects, first the time delay is increased because the index of refraction is larger than 1 and secondly, the radar path is curved due to the changing index of refraction as a function of altitude. The change in time delay is a much larger effect than the difference in path length due to curvature alone, Also affected is the doppler measurement since the speed of propagation is changirg as the index of refraction changes, (Note that the range and doppler obtained from the polynomial resampling coefficients is the apparent range and doppler.) The aggregate effect if not compensated can cause stereo position errors as large as 600 m. A exponential model of the index of refraction as a function of altitude is used to convert the apparent range and doppler measurements to geometric range and doppler prior to solving the stereo equations, Since the exact position of the scatterer in not known a priori the scatterer location in the original image is to estimate the amount of atmospheric refraction and solve the stereo equations, An iterative process is employed whereby successive stereo derived scatterer locations are used to refine the refraction estimate until the resulting scatterer location fails to change by more than 1 m. Covergence t ypically requires two iterations.

SCENE MATCHING

Implicit in the above discussion of extracting three dimensional scatterer location data using stereo methods is the ability to identify the same scatterer at the subpixel level in multiple SAR image pairs, this is the scene matching or image correlation problem. Since the SAR is a coherent imaging system images contain not only thermal noise but speckle noise. Speckle noise is inherent to the radar signal itself since the received voltage is the result of random interference of the backscattered electric field from the multitudinous facets of the distributed scene within a resolution element whose dimensions are many times greater the radar wavelength, The structure of the speckle noise within a scene changes completely whenever the two observation locations are outside the diffraction pattern of a resolution element (approximately 300 m for Magellan). Thus unlike optical image correlation fine details in the scene texture do not aid in the image correlation process and makes impossible correlation of scenes without features. Another problem is geometric distortions that arise when the same scene is imaged from different viewing angles. These distortions can bc so severe that it is impossible to identify a prominent scatterer that

" is clearly visible in one image when that same scatterer is viewed from a different angle.

Matching is performed on the FBIDR where the geometry, ephemeris, and the range/doppler resampling polynomial information is readily available. The algorithm uses a hierarchical approach based on a two dimensional normalized correlation function to determine the offsets. Matching is performed on successively finer scales down to a final resolution of 4x4 image pixels (gives DEM samples every 300 m). For each match the Hessian of the correlation function coupled with a local scene noise estimate is used to estimate the formal covariance matrix for the offset measurement. These covarinace estimates are used to filter out bad matches and greatly reduces the effects of noise on the results. Moreover, the local offsets arc optimally combined using the covariance estimates to determine a local polynomial warping function between the stereo image pair which is used to predict offsets at the next level. This significantly reduces the size of the search window that needs to be used in determining the offsets at the next level as well as avoiding bad matches.

REGRIDDING

After solving for the feature position vectors the data arc inherently not uniformly distributed in the plane and there arc often large gaps in the data where scene matching was not possible. Thus to get the data sampled to a specified grid requires regrinding or interpolating of the data. First a sigma type filter is performed to remove shot noise "from the resulting height values. A variant of the Aikima interpolator [Aikima, 1978] is used to resample the data. The Aikima interpolator has a number of nice properties among them it passes through the given data points and secondly, it tries to interpolate the data so as to preserve the intergrability of the surface (i.e. the second order cross partial derivatives are equal).

MEASUREMENT ACCURACY

The accuracy of stereo derived scatterer position data is a function of the spacecraft ephemeris accuracy and tile scene matcher's ability to identify the same scatterer in both scenes. I'able 11 shows the absolute and relative target position errors for some typical ephemeris errors. Clearly, much greater ephemeris errors can be tolerated if only relative position data is, desired, However, in order to mosaic multiple orbit data and to compare topography from different regions of the planet quantitatively requires good absolute accuracy, Standard processing of the navigation data has ephemeris errors as large as 10 km making them unacceptable for stereo work. By using tiepoints obtained from the SAR imagery the ephemeris accuracy can be improved to better than 100 m [Chodas 1993]. With improved orbit ephemeredes tile dominant error source is scene matching errors. For example a .5 pixel matching error in the Maxwell region on Venus translates into a 120 m height error. Comparison of stereo height measurements of the same scatterer found in multiple stereo orbit pairs in the Maxwell region yielded a standard deviation of 150 m consistent with the formal height error covariance estimates.

Table II. Sample Target Location Errors

Orbital Element Errors	Target Location Errors					
	Absolute (m)			Relative (m)		
	AT	CT	H	AT	CT	H
$\Delta a = .1km$	-100	-480	60	-1	-1	4
$\Delta e = 1e-6$	**-lo**	30	3	0	0	.7
Ai = .005°	250	2000	250	2	25	-20
$\Delta\Omega = .01°$	100	2000	600	-lo	-7	-lo
A(I) -.010	-480	-400	-loo	-1	-1	2
$\Delta\tau = 1.cg.$	-250	1700	500	2	2	10

CONCLUSION

In this paper an algorithm for producing digital elevation models from Magellan stereo data was described. The three main aspects of stereo processing, scene matching, stereo intersection, and regrinding were discussed. Scene matching is done via an hierarchical approach and gives a formal covariance estimate for each offset measurement. The range/doppler based stereo intersection algorithm employed accounts for Venus atmospheric refraction, the local topographic model, and generates formal height error estimates from the matching and ephemeris covariance matrices. Finally, the data is regridded to a specified map projection. Stereo height errors are a function of ephemeris errors, matching errors, atmospheric model errors, and the imaging geometry. The dominant error source is scene matching errors and the resulting height estimation accuracy are between 150 m and 200 m

REFERENCES

Aikima, II. "Bivariate Interpolation and Smooth Surface Fitting for Irregular Distributed Data Points", ACM Transactions on Mathematical Software, Vol. 4, No. 2, June 1978.

Chodas, P. W., Lewicki, S. A., Hensley, S., Masters, W. C., "nigh Precision Magellan Orbit Determination for Stereo Data", AAS/AAJA Astrodynanmics Specialist Conference, August 1993.

Lebrel, F., Radargrammetric Image Processing, Artech House, 1990