A New Automated Method of Determining Depth, Diameter, and Volume of Craters. S. J. Robbins[1-1] (stuart.robbins@colorado.edu) and B. M. Hynek[2-3], [1]Astrophysical and Planetary Sciences Department, UCB 391, University of Colorado, Boulder, CO 80309; [2]Laboratory of Atmospheric and Space Physics, [3]Geological Science Department, UCB 392, University of Colorado, Boulder, CO 80309.

Introduction: Ever since the first craters were photographed from spacecraft, different techniques have been used to determine the fundamental properties of depth and diameter, which can reveal a wealth of information about surface history, impactor population, and surface age. The first studies involved photoclinometry, an analytic technique involving manual measurements (e.g., [1-3]). With the advent of fast personal computers over the last ~15 years, automatic algorithms have been proposed to locate craters and determine their diameter (e.g., [4-7]). Many of these are based upon visual images, though a few (e.g., [8-9]) are based upon topography. The benefit of using topography to determine crater locations is that the depth can be directly calculated, as well. One of the premier manual catalogs of craters was compiled by Barlow [10] using Viking images of Mars. Because of the plethora of martian data sets created over the past few years and the planet's vast and diverse crater population, manual techniques are quickly becoming too slow and not expandable enough to meet modern needs. They are also prone to subjectivity such that two different people will end up with slightly different catalogue results. Therefore, martian craters are generally seen today as the test-bed for developing crater detection algorithms - besides the utility in studying Martian craters themselves.

The technique described here focuses on finding the rim of a 2-D azimuthally- and radially-binned crater profile. We developed it for use in determining the depth and diameter of craters in the Barlow database [10], so we were not concerned with identifying unknown craters. It works by first assuming that all craters are azimuthally symmetric. It uses this assumption to reduce the 3-D crater topography into a 2-D topographic profile. The algorithm then looks at the 2nd derivative of the profile to determine where the curvature is most negative near the crater's topographic highs, assigning that location as the crater's rim.

Input Data: The algorithm described here is resolution-independent, but it has been created and tested using 1/128°-binned MOLA topographic and count data (~0.5 km spatial resolution), which serve as the main inputs. Also required are two parameters from the Barlow database: The location of the crater's center (latitude and longitude) and an estimate of the crater diameter.

Algorithm: The algorithm first determines the diameter of the crater. Step 1 is to define a square region of interest around the crater, which we have selected to be 150% the crater's diameter on a side. A larger buffer could be necessary if the starting uncertainty in the crater diameter is larger than 25%, though the smaller the buffer the lower the chance of a false rim being found. The buffer is necessary, however, because without a well-defined slope away from the rim there is nothing for the 2nd derivative to lock onto (see Step 5). Step 2 fits a 3-D 2nd-order polynomial to the region and subtracts it from the topographic data to remove long-wavelength structure (e.g., an overall topographic slope that would throw off subsequent steps). It adds back the 0th-order term to keep the relative topographic elevation. Step 3 uses the distance from the crater's center (which requires the center to be known to high precision) to re-bin the data into a 2-D profile, separating it into two azimuthal bins - an "East" and "West" side. The pixels are scaled by the map projection into a physical unit of distance. If the MOLA counts that went into each topographic pixel are below a user-definable threshold, that pixel is omitted (e.g., if set to 1, any pixel with 0 MOLA counts would be omitted).

At this point, the 3-D topography has been reduced to two dimensions. Step 4 takes the crater profile and bins it radially in a user-definable bin size (we used 0.5 km to coincide with MOLA gridded resolution). The bin value is assigned to be the median of the data points contained within that bin. The median is used because the mean is more easily affected by outliers, such as a small overlapping crater that was not masked out beforehand. Step 5 evaluates the 2nd derivative of the binned profile. It then searches for the minimum of the 2nd derivative on both the West and East sides. If the corresponding points in the original binned profile are within a user-definable distance of the maximum topographic height, then it saves those locations as the rim. If not, it goes back and searches for the next-largest minimum. Note that this descretizes the diameter to the bin resolution.

With the rim now located on both sides, the algorithm sums the two and treats that as the crater's diameter. To calculate the depth, it takes the average height of the rim (East and West sides) and subtracts from it the altitude of the lowest bin of the profile. A volume sub-routine has not yet been implemented, but the prototype uses the discrete trapezoidal integration scheme, taking into account that the MOLA data is not on a uniform rectilinear grid once it has been projected from degrees to a physical unit of distance. It uses the original background-subtracted region of interest rather than the binned profile.

Current Limitations: The main limitation at present is that the input to this algorithm requires the crater to have a known center and approximate diameter. Consequently, this algorithm's utility would be greatly increased if it were combined with an automated crater-finding routine (e.g., [7]).

Another limitation is the requisite precision of the crater center. If the center is off slightly, the profile prior to binning will become skewed due to an apparent relative shift of the crater walls. We are working on a routine to partially alleviate this, as discussed below in the section entitled, "Future Improvements."

A third limitation lies in the assumption that all craters are perfectly circular, which is in reality rarely the case. This assumption is made inherently by the binning process, converting a 3-D irregular shape into a 2-D profile. In doing this, we effectively lose an entire dimension of information, which in this case contains any knowledge of eccentricity and other non-azimuthally symmetric features. This is both a blessing and a curse: While we lose subtle information about the crater by doing this, what we gain is an assumption of simplicity that allows us to model the crater as perfectly circular, giving us the ability to increase the number of data points used in defining the rim, allowing for greater confidence in the "average" diameter of the crater.

Application and Advantages: We are currently employing this algorithm to determine the depths and diameters of 8562 craters in Arabia Terra and the neighboring region of the Southern Highlands, looking for highly eroded craters as evidence for massive erosion of Arabia Terra (i.e., [11]). Preliminary results show two distinct crater populations in the region, as shown in the depth-diameter plot in Figure 1.

This is just one application of this algorithm. It also has global applications, since it could be easily set up to calculate depth, diameter, and volume from a global catalogue of craters to create one large planetary database. Once the craters have been catalogued with depth and diameter, subsets can be used to create cumulative crater counts of regions for dating purposes. Another application is depth-diameter plots can be created, comparing craters in different regions such as the Northern Plains and Southern Highlands of Mars or the lunar mare vs. highlands, or, as for our application, Arabia Terra and the adjacent Southern Highlands.

It is also a fast algorithm. Once it has read in the MOLA data (approx. 75 seconds on the test machine; this speed is limited mainly by disk I/O), it can determine the depth and diameter of ~2000 craters ranging in size from 5-500 km in approx. 150 seconds while running on a single CPU. Most subroutines in the algorithm are readily expandable to support multi-threading, including the most time-intensive part of converting to a 2-D profile (since the algorithm is written in Java which has native multi-threading capability, it would run on any machine that has a Java compiler and not need add-ons as would be required with C++). Note that the test machine is a Mac Pro running two dual cores at 2.0 GHz.

The algorithm is also planet- and resolution-independent. It has been developed using MOLA 1/128°-gridded data, but it can easily be set to use higher-resolution data (e.g., if Mars Express DEMs become publicly available). It should also be able to be used on the Moon and Mercury once topography maps of those bodies become available (from LOLA and MLA, respectively) with little or no modification. Another benefit of this algorithm is that it mathematically defines the crater diameter and depth in a uniform manner, without subjectivity, as suggested by [12]. This global crater morphometry analysis may prove invaluable to understanding the global crater populations of terrestrial bodies. This will result in an improved understanding of the impact process (including gravity effects) and subsequent modification of crater populations.

Future Improvements: One of the foremost improvements - which we are currently working on - is a decrease in the accuracy needed for the crater's central location. The subroutine we are working on to alleviate this burden would define a search box around the supplied crater center. The subroutine would create binned profiles using all of the possible centers within that box, and it would select the one with the smallest standard deviation of the binned data points. It is assumed that the smallest average of the standard deviations is the "best" crater profile because it indicates the least spread of the raw data points within each bin. This small spread implies that the crater is the most azimuthally symmetric about that center. It would then move on to Step 5 as described in the "Algorithm" section.

Besides this and finishing implementation of the volume integration, we plan to work on making the algorithm more robust by studying the specific cases in which it fails to locate the crater rim, and we also plan on further speed optimizations, including expansion to multi-threading to allow the code to take advantage of modern multi-processor machines. We also may implement the ability to do a second pass, using the already-derived diameters and centers to create a mask to remove pixels interfering craters, allowing for a more precise rim determination of the crater of interest.

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Acknowledgements: MOLA data are freely available online from NASA's Planetary Data Service. This work has been supported in part by NASA MDAP grant NNX06AE08G. This work has also been supported in part by NASA Goddard NESSF grant NNX07AU85H.

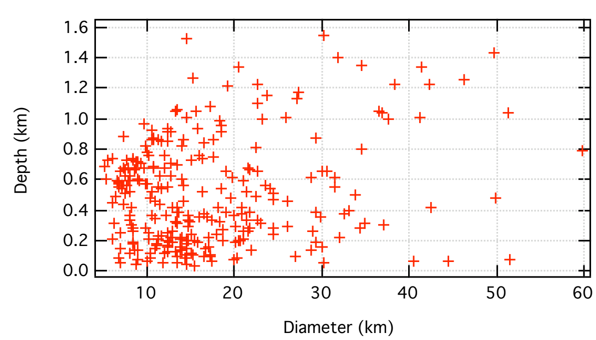

Figure 1: Depth-diameter plot of a random 10% of the craters in Arabia Terra and the neighboring Southern highlands. This shows two distinct populations, and we are presently analyzing the data clusters to infer their histories.