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Identification and Evaluation of the Mars Global Surveyor MOLA Profile of the Mars Face

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The method is described by which a Mars Orbiter Laser Altimeter (MOLA) profile was identified for the Face landform at Cydonia. A comparison between the MOLA profile and a profile extracted from a previously constructed shape-from-shading model of the Face is presented. The comparison suggests that the shape-from-shading model is reliable and, indirectly, that the three-dimensional facial features predicted by the model are probably real features of the landform. It is argued that a widely publicized "3D perspective" view that seems to show a landform of very low relief lacking such features is highly inaccurate due, among other reasons, to a very low estimate of the landform's peak height that is not in agreement with the MOLA elevation data.

Introduction

On April 8 th , 2001, the Mars Global Surveyor (MGS) acquired a full image of the "Face" on Mars [1] . The image number was E03-00824. Six weeks later, the image was publicly released. The release of the image was accompanied by the nearly simultaneous posting of a news article on an official NASA web site [2] .

The intent of the article was apparently to render a definitive scientific conclusion that the Face is an unremarkable hill or mesa. The posting of the article on their web site implies that NASA officially endorses the methods and conclusions represented.

To support the expressed opinions, the article presents a "3D perspective" image. This image was constructed by combining the visual image acquired by the MGS high-resolution Mars Orbiter Camera (MOC) with elevation data acquired by the MGS Mars Orbiter Laser Altimeter (MOLA). The elevations of points on the planet surface directly beneath the spacecraft's orbital path are determined based upon the time it takes for laser pulses fired by the instrument to return to the spacecraft after reflection from the surface.

NASA's "3D perspective" view of the Face in Figure 1 shows a landform of very low relief. Apparently, the landform was depicted in this way because the landform's height as measured by the MOLA instrument is very low in proportion to its width as measured on the visual camera image. The article states that "the peak of the mesa-like landform rises 800 feet (240 meters) above the surrounding plain." That distance is less than 10% of the landform's length, which is about 2600 meters. This was a completely unexpected result because previous analyses by Carlotto [3] indicated the landform's height to be 412.5 ± 17.5 meters. Carlotto's figure was supported by two different methods: a simple measurement of the length of the landform's shadow in an earlier Viking Orbiter image and by a more sophisticated shape-from-shading (SFS) analysis of two of the Viking images.

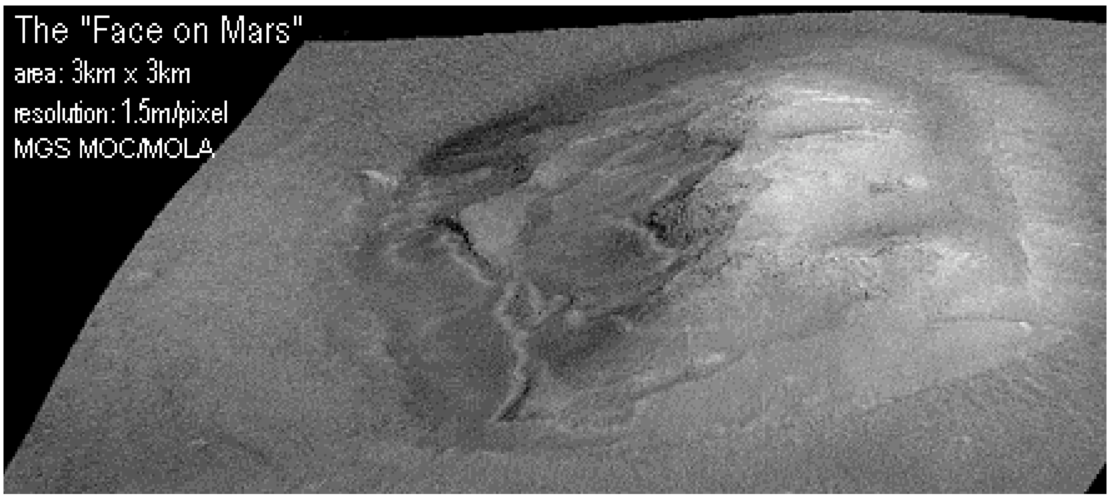

Figure 1 Image from the May 24th, 2001 "Science@NASA" article on the Mars Face. The NASA caption reads in part: "A 3D perspective view of the Face on Mars landform produced by Jim Garvin (NASA) and Jim Frawley (Herring Bay Geophysics) from the latest MOC image (April 8, 2001) and all of the available laser altimeter elevation measurements by MOLA. There is no vertical exaggeration in this ray-traced image" (The landform was presented upside-down relative to its orientation in the Viking images with which most people are familiar.)

The NASA height estimate is 42% lower than the earlier estimate. The difference is much too great to attribute to the low (47 meter) resolution of the Viking images employed in the earlier analysis. This is a discrepancy that needs to be resolved and it is the purpose of this paper to do so.

Objections to the NASA Height Estimation Technique

The NASA article cites the very high vertical resolution (30 centimeters) of the MOLA instrument to support the validity of the authors' conclusions as to the height of the Face. However, it incorrectly states that the MOLA's horizontal resolution is 150 meters when in fact the MOLA specifications state a resolution of ~300 meters [4] . Even this lower resolution is highly misleading, because it is the resolution of the instrument only in the "down-track" direction -- the spacing between the laser shots fired by the instrument along the spacecraft's orbital path. The horizontal resolution in the cross-track direction is the spacing of the orbital tracks and is dependent upon the total number of mapping orbits that have been made by the spacecraft.

Toward the end of the mapping phase of the MGS mission, the cross-track resolution was between 1/32 and 1/64, or 700 to 1400 meters at the latitude of Cydonia. The width of the Face landform is approximately 2000 meters in the east-west direction, so no more than two or three profiles were likely to have been made of the Face. Profiles spaced 700 meters apart can yield little information on the 3-dimensional shape of an object that is only 2000 meters wide. Due to random factors affecting the spacecraft's orbit, its path across an object the size of the Face is mostly a matter of chance. The width of the MOLA laser spots on the planet surface is 130 meters [5] . NASA has provided no evidence that it could be ascertained with confidence that the high point of the landform fell within one of these laser spots.

One possibility is that the highest-elevation point on the MOLA profile was matched to what is believed to be the highest point on the Face landform (a point near the centerline of the landform). However, this seems unlikely because the coordinates of the MOC image "footprints" are given to a precision of 1/100, which translates to 590 meters in linear distance on the Martian surface. Even if the accuracy of the footprint coordinates were on the order of their precision, the uncertainty of 580 meters would be too great to determine whether or not any given point in an MOC image falls within the area of a 130 meter-diameter MOLA spot.

It could still be argued, of course, that even if the MOLA missed the high point, it might have measured a height close to the peak height. But as is demonstrated subsequently, examination of the MOLA data itself shows that the 800-foot height assumed in the construction of the NASA 3D perspective view of the Face is not even close to the maximum height of the Face landform measured by the MOLA.

MOLA Database Search and Data Processing Methodology

The MOLA science team has provided an online database of MOLA measurements. The elevation data collected for any area on the surface of Mars may be retrieved with a JAVA application called "molafind." [6]

In the UNIX environment, the data is accessed by executing the commands:

```
% setenv JAVADIR .
% java -classpath $JAVADIR/molafind.jar molafind $* -h
lorentz.caltech.edu min.lat max.lat min.lon max.lon > filename
```

The latitude and longitude arguments define the corners of the area for which the data is to be retrieved. The longitudes must be given in degrees east. Each line written to the local file destination contains the orbit number, the latitude, the longitude, and the elevation in meters.

A program was written to construct a visual gray-scale representation of the MOLA data for the selected area to display the landforms in the region. The image resolution was chosen to be high enough to resolve individual MOLA tracks but low enough that clusters of data points could be identified as landforms. Several tries had to be made before the best size-scaling factor was found.

The brightness of each pixel in the image is scaled to be proportional to the average elevation of the MOLA points that fall within the pixel's area. Pixels containing no MOLA points are filled in with the brightness value corresponding to the average of all the MOLA points in the area covered by the image. A "pure white" pixel represents the highest elevation in the covered region and a pure black pixel represents the lowest elevation. Pixels falling within craters or other depressions thus appear darker than surrounding points while pixels falling within the perimeter of a hill or mountain will appear brighter.

As the two-dimensional pixel array for the visual image is constructed, the program records the orbit numbers for the MOLA data points contributing to the value of each pixel in a second array in a cell at the same indices as those of the pixel. The orbit array can then be used later to retrieve the profile for any orbit passing through a point of interest in the visual image. A second program is used to construct the graph of the elevation profile for any selected orbit. The areocentric coordinates of each data point for the orbit are converted to linear distances, with each degree of latitude equaling 59 kilometers and each degree of longitude equaling 59 kilometers times the cosine of latitude.

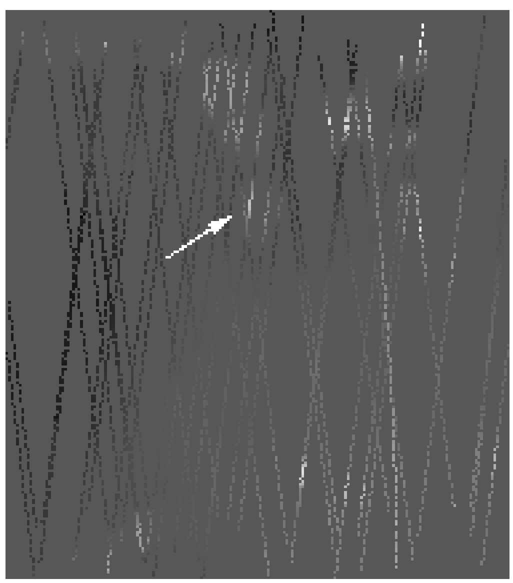

Figure 2 Visual representation of MOLA elevations in an area 40 km wide centered on coordinates 40.99N 350.25E. North is at the top of the image. Arrow indicates feature at 41.11 N, 350.20E at first tentatively identified as the Face landform.

First Tentative Identification of a MOLA Profile for the Face

The coordinates of the southeastern corner of Frame M1600184, a partial image of the Face acquired in June 2000, were chosen as the center of the search area for the first data retrieved from the MOLA database. The resultant visual representation is shown in Figure 2 . The feature indicated by the arrow is the highest-elevation landform on orbital track 10741 within the area shown. It is approximately 2 km from the expected position of the Face relative to the coordinates of the MGS image. This discrepancy did not appear significant because 2 km translates to an error of 0.03 degree in areographic coordinates while image footprint coordinates are given only to a precision of 0.01 degree in the ancillary data.

The profile of Orbit 10741 in Figure 3 shows this feature to be a landform about 240 meters high -- very close to the elevation cited by NASA. Its width is somewhat less than 3 km -- on the order of the length of the Face, which is generally taken to be 2500 and 2600 meters. This seemed at first persuasive evidence that this was, in fact, a MOLA profile of the Face.

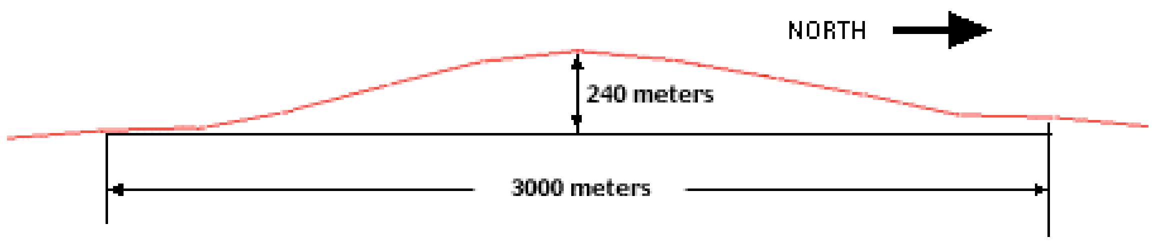

Figure 3 MOLA profile of landform at 41.11N, 350.20E on Orbit 10741

On further consideration, the overall distribution of brightness values in the visual image of the MOLA tracks appeared wrong. In Figure 2 , there is no indication of the "D&M Pyramid" nor of the "City" landforms that should appear as groups of brighter pixels to the southwest (lower left) of the Face. These should appear as regions brighter than the surrounding areas, particularly the D&M, which is one of the highest landforms in Cydonia. While evidence of expected landforms is missing, there is a bright region a short distance above the putative Face corresponding to hilly terrain where none is evident in the Viking images. Whether or not this was the landform used by NASA to construct the perspective image, it is not the Face.

A Positive Identification of the Face MOLA Profile

After recognizing that the wrong suspect had been apprehended, a wider net was cast around the coordinates at which the Face had been expected. The discovery of the MOLA traces of a unique group of three craters also visible in an earlier MGS wide-angle camera image provided the key for identifying all other prominent landforms in the area, including the Mars Face. Both the MOLA and camera images are shown in Figure 4 . The MOC image has been orthorectified and adjusted in size and orientation to match the MOLA image. The labels identify common features in both images as follows:

1. C1, C2, and C3 - group of three craters that provided the key for locating other features;
2. A - hill or mesa originally misidentified as the Mars Face
3. B - Mars Face
4. D - D&M Pyramid
5. E - City landforms

The match between the two images of the length and orientation of a line connecting any two of the labeled features is virtually exact. A close correspondence between other patches of bright pixels in the MOLA image with prominent hills or mountains in the MOC image can be seen throughout area. There seems little reason to doubt that Feature "B" is the Mars Face; there is no other elevated feature for several kilometers in any direction.

The true position of the Face is 20 kilometers from the position indicated by the coordinates for the visual MOC images. This large discrepancy (a third of a degree) may seem to imply a serious error in the coordinate systems used by the either the MOC team or the MOLA team. But that is not the case, as the following statements in MGS documentation makes clear:

The MOLA instrument documentation states:

> "Map coordinates are areocentric with east positive longitude. Areocentric locations will not correspond exactly with areographic coordinates." [7]

While the MOC documentation states:

> "Latitude is given in areographic form using the IAU 1994 definition of the Martian equatorial and polar radii (3397.0 and 3375.0 km, respectively)." [8]

The coordinates given in the ancillary data for the MOC visual images are based on the areographic coordinate system rather than the areocentric system used by the MOLA team. The difference between the two coordinate systems arises because Mars is not a perfect sphere. The departure from spherical symmetry is reflected primarily in a north-south displacement of latitude between the two systems while the longitudes are more similar. As can be seen by comparing the Face's true position at point "B" in Figure 4 and the position of the feature at point "A" that was at first misidentified during this investigation as the Face, most of the displacement is in the north-south direction. While the displacement in latitude is large, the longitude for the position of the Face is in closer agreement between the two coordinate systems. From measurements on an orthorectified version of the MOC image of the Face in April 1998, the coordinates of the central point on the landform should be near areographic coordinates 41.08N, 350.18E while the highest point on the MOLA profile of the landform are at areocentric coordinates 40.748N, 350.299W.

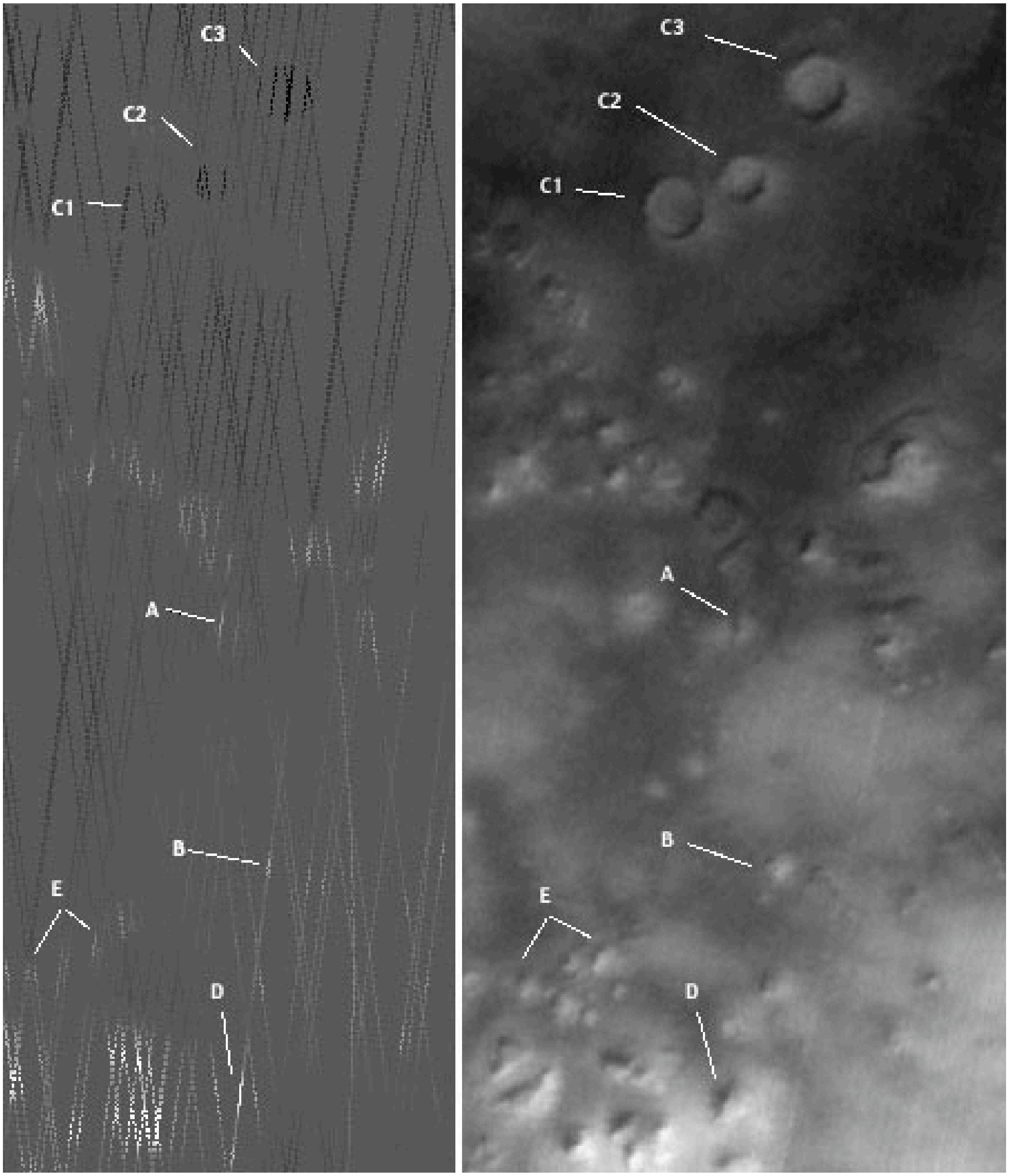

Figure 4 Left: Visual representation of MOLA data over an area 40 km wide and 103 km long centered on the expected coordinates of the Face. Right: Section of wide-angle MOC SP125801, the third Cydonia image taken in April 1998. Positions are labeled in the two images to show the correspondence of their positions. The feature at position "B" is the Face.

Fortuitously, two nearly congruent orbital tracks crossed the Face: 10062 and 16677. These have been combined into a single profile to improve the profile resolution somewhat above the more typical 300 meters. The result is shown in Figure 5 . A line has been drawn on the graph to indicate the distance of 240 meters that the NASA article stated is the height of the landform at its peak. It can be seen that the length of this line falls noticeably short of the distance from the maximum height of this profile to the surrounding plain. The true height of the Face through the cross section shown is about 330 meters. The Face is at least 90 meters higher than the value given in the NASA article.

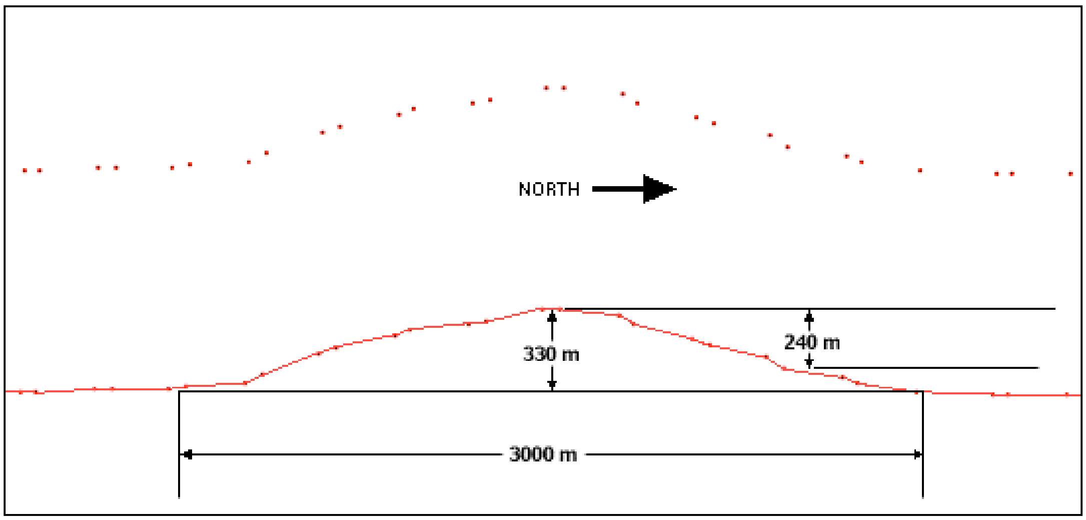

Figure 5 Top: Plot of data points across the Mars Face for Orbits 10062 and 16677. Bottom: Same graph with points connected by straight-line segments and labeled with dimensions. Heights have not been exaggerated. The highest point on the profile is at 40.74813N 350.29864E in areocentric coordinates.

A height of 330 meters is also about 65 meters short of the estimate made by Carlotto. However, the previously stated objections to assuming that a single profile (or two nearly congruent profiles) would be likely to capture the peak of the landform apply to this profile as well.

Also, the extremely level terrain a few hundred meters to either side of the Face in Figure 5 makes it seem less likely that there is a significant slope down from the Face landform in any other direction. Such a downward slope in the direction of the sun azimuth in the Viking images would have caused the landform to cast a shadow longer than it would have been on level terrain, leading to an overestimate of its height based on the shadow length. This profile, then, provides support for the validity of Carlotto's shadow-length estimate.

Comparison of MOLA and Shape-From-Shading Profiles

In any scientific inquiry, of major interest is the assessment of the accuracy of past predictions in light of more recent data. Obviously, then, a comparison is warranted between the MGS MOLA profile of the Face and a profile extracted from Carlotto's shape-from-shading model. Carlotto constructed the elevation map shown in Figure 6 from the Viking SFS model. The relationship between pixel brightness in the elevation map and the corresponding elevation of the SFS model is linear, just as it was for the visual representation of the MOLA elevation data of Figure 4 .

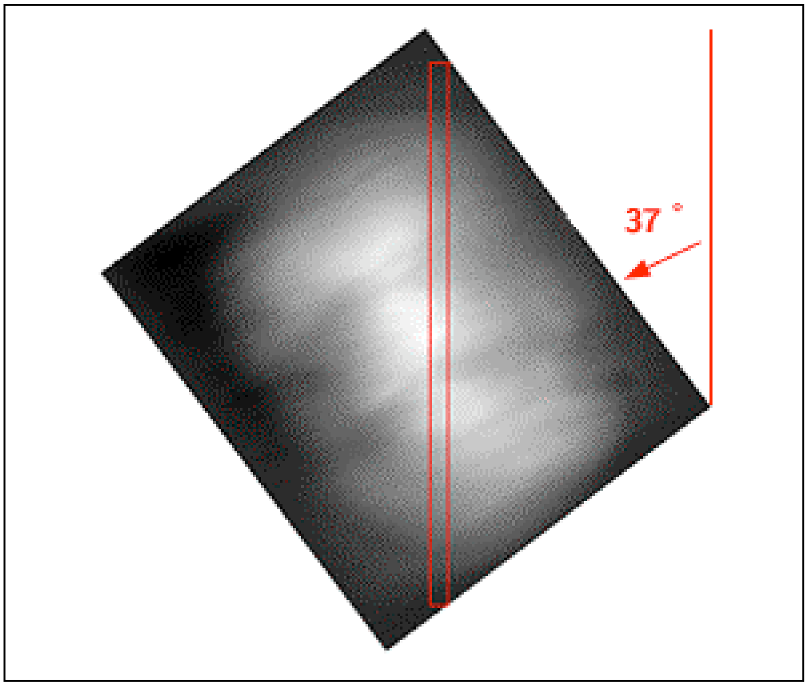

Figure 6 Elevation map generated from the Viking shape-from-shading model courtesy of Mark Carlotto. The red box outlines the section used to generate a profile comparable to the MGS MOLA profile. The MGS orbital track was oriented at an angle of approximately 37 to the long axis of the Face landform as shown.

Extraction of a profile from the elevation map is simply a matter of converting the average brightness for each row of pixels in a narrow column representing the MOLA track to a vertical distance plotted against the horizontal position of the row in the column. The spatial scale of the elevation map is approximately 11 meters per pixel, so a column width of 10 pixels, or 110 meters, was chosen to approximate the 130 meter width of the MOLA laser spots for construction of SFS profiles.

The average gray scale number of each row in the chosen column of the elevation map was multiplied by a constant factor to convert from brightness to a height in meters. Carlotto estimated the maximum height of the Face as between 395 and 430 meters. Therefore, the maximum gray scale number of 255 was assumed to correspond to a height of 400 meters -- an elevation near the low end of the range of the peak height of the Face estimated from the SFS model. The gray scale values in the region at the base of the Face on the elevation map are around 30. The conversion factor in meters per gray scale number was therefore taken to be 400/(255 - 30), or 1.78 meters of elevation per gray scale number.

Because of the previously described sources of uncertainties, the precise position of the MOLA track relative to the elevation map cannot be determined. However, the known inclination of the MOLA track to the long axis of the Face is sufficiently great to put strong constraints on the range of possible positions. The long axis of the Face is oriented approximately 30 west of north while the MOLA track is oriented 7 east of north. The MOLA track therefore crossed the Face on a diagonal line ~37 clockwise from a parallel orientation to the long axis of the landform. The MOLA track had to pass close to the landform's central point. Had it crossed the Face at a position very far off to either the left or right of the position of the column shown in Figure 6 , the MOLA profile would have been considerably narrower than its actual width. As shown in Figure 5 , the width of the profile is somewhat less than 3000 meters while the length of the long axis of the landform is about 2600 meters as measured on MGS and Viking images.

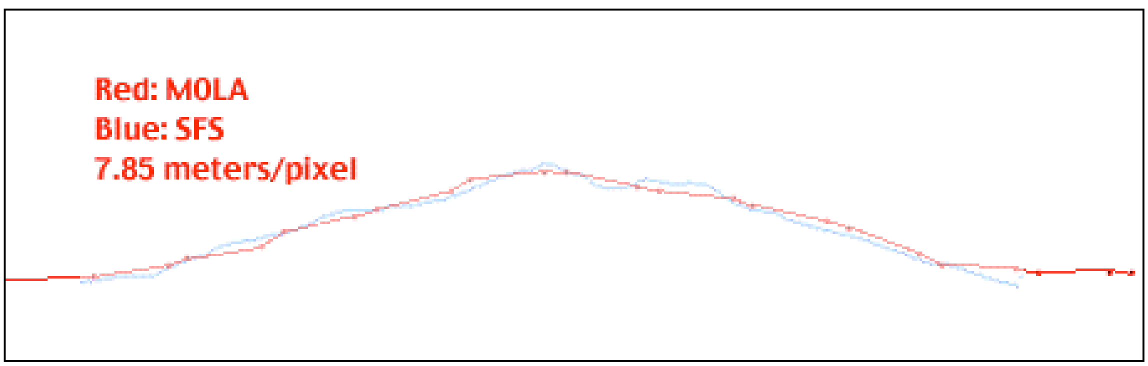

Figure 7 SFS Profile (blue) for the strip of the elevation map indicated in Figure 6 superimposed on the actual MOLA profile (red) of Figure 5.

Profiles were created for several 10-pixel wide strips to either side of the central point on the elevation map. Each sample strip was parallel to the orientation of the MOLA track. Differences in height and shape from the actual MOLA profile precluded all but the one shown on the elevation map in Figure 6 . It can be seen in Figure 7 that the match is very close. The lack of the higher-frequency contours on the MOLA profile that are present in the SFS profile could be attributed to the lower resolution of the MOLA instrument relative to that of the SFS map (the MOLA spots are spaced slightly less than 300 meters apart while the resolution of the Viking images on which the SFS model is based was ~50 meters).

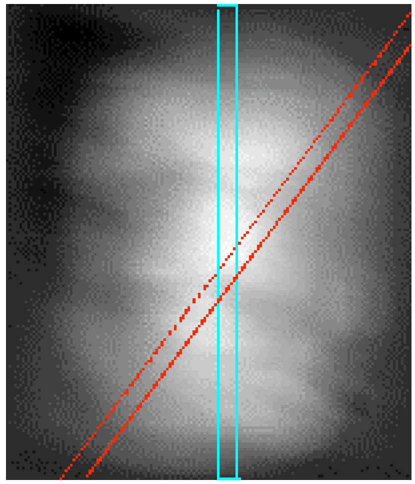

Figure 8 SFS Elevation Map showing strip through centerline of Face (blue) and its relationship to a plausible path of the MOLA across the Face.

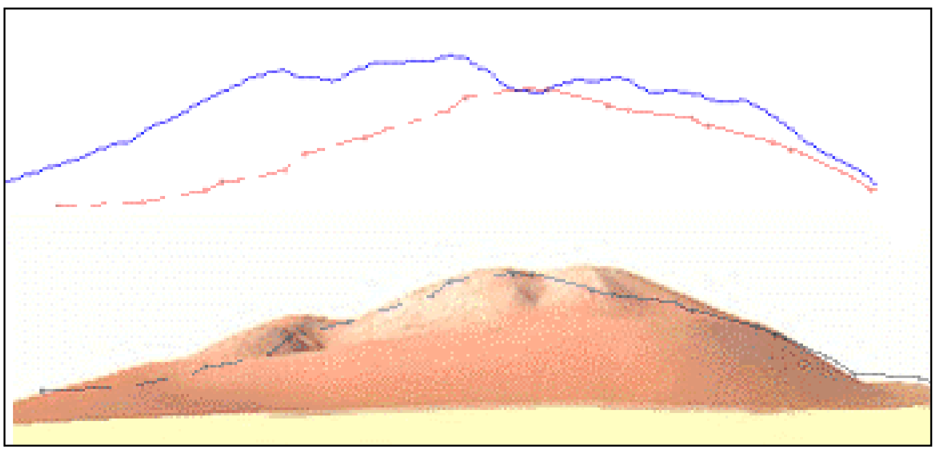

Figure 9 Top: MOLA profile (red) superimposed on a profile (blue) from the SFS elevation map along the centerline of the Face. Bottom: MOLA track (black) superimposed on an artistic depiction of a side view of the Face (courtesy Kynthia). The broken line segments indicate those parts of the MOLA track on surfaces not visible from this perspective, which is a view from the west looking east (north is to the left). The MOLA profile was reduced in width to 79.9% of its original size to produce the shape it should have from this perspective.

To provide another perspective for the MOLA profile, it was compared to a different SFS profile taken along the centerline of the Face that includes the highest point on the elevation map. In other words, this SFS profile is a side view to which the word "profile" most commonly refers in the context of a description of a face. The relationship between this SFS profile and the plausible position of the MOLA track on the elevation map is shown in Figure 8 . The resulting SFS profile is shown in Figure 9 superimposed on the MOLA profile. Because the orientation of the MOLA track is about 37 out of the plane of the side view of this graphic, the MOLA profile has been reduced in width by the cosine of 37 to give it the shape it would have when viewed from this perspective.

For greater visual substance, the MOLA profile is also shown superimposed on a side view of the Face created by the artist Kynthia. For over a decade, Kynthia has applied her skills as a sculptor to translate the 2-dimensional images from Viking and MGS into her interpretation of the 3-dimensional form. While there are differences between the computer-generated SFS profile and the artistic rendering, the general contours are the same. The MOLA profile fits both nearly equally well.

Conclusion

The May 24 th NASA article quotes James Garvin, chief scientist for NASA's Mars Exploration Program as stating:

> "We took hundreds of altitude measurements of the mesa-like features around Cydonia, including the Face. The height of the Face, its volume and aspect ratio -- all of its dimensions, in fact -- are similar to the other mesas. It's not exotic in any way."

That the two low-resolution profiles of the Face reveal nothing "exotic" cannot be disputed, but nothing exotic about the shape revealed by this data would have been anticipated based on Carlotto's previous work. The profiles do, however, reveal that the NASA 3-dimensional reconstructions of the landform based on the MOLA data are in serious error. They may, conceivably, have even been based on a MOLA profile of the wrong landform. Perhaps a mistake was made in the haste of preparing the public relations material for the article in time for its release to coincide with that of the MOC image. This is a matter of conjecture since no details of the reconstruction process were given in the article. Queries made to the article's author and to the web page curator have not been answered. Regardless of the cause of the error, the landform is, at a minimum, 37% higher than the estimate made by NASA. All conclusions presented in the NASA article based upon the MOLA data are therefore invalid.

The MOLA profile is not only consistent with Carlotto's height estimates but conforms in shape as well. The close match provides grounds for increased confidence in the validity of the SFS model. The NASA article cited the MOLA data to support the assertion that features resembling those of a face do not really exist as three-dimensional contours on this landform. To the contrary, the conformity of the MOLA data to the SFS model supports the reality of the unusual features predicted by the model.

Acknowledgements

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[8] URL: http://ida.wr.usgs.gov/corrections/dataset.cat

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