PHOENIX LOCATION DETERMINATION USING HIRISE IMAGERY

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ABSTRACT

This investigation looked into determining Phoenix's position using an image taken by the University of Arizona's High Resolution Imaging Science Experiment camera. The objective was to test how accurately a position for the lander could be determined during entry, descent, and landing to provide an alternate means of position determination independent of Phoenix navigation data or Phoenix telemetry in the event of the spacecraft's on-board inertial measurement unit failing or a communications breakdown that prevented the return of the data.

NOMENCLATURE

d	=	24 hour days since J2000 epoch
$J2000$	=	Epoch referring to 12:00 pm (i.e. noon) on 1 January 2000 (JD 2451545.0)
$\mathbf{r}_{AP}$	=	Apparent position of the Phoenix lander from the HiRISE camera's point of view
$\mathbf{r}_{LOS}$	=	Line-of-sight vector from the HiRISE camera to the Phoenix lander
$\mathbf{r}_{MRO}$	=	Position of the Mars Reconnaissance Orbiter at the time the Phoenix Descent Image was taken
$\mathbf{r}_{PHX}$	=	Predicted position of the Phoenix lander at the time the Phoenix Descent Image was taken
T	=	Julian centuries of 36525 days past the J2000 epoch
W	=	Angle between the IAU vector and the Prime Meridian of Mars
Y	=	Pixel-precision ratio
$\hat{\mathbf{z}}_{EME2000}$	=	North pole of the EME2000 coordinate frame
$\hat{\mathbf{z}}_{Mars}$	=	North pole of Mars
α	=	Right ascension of Mars' north pole
β	=	Declination of Mars' north pole
ρ_{HC}	=	Resolution of Heimdal Crater in the Phoenix Descent Image
ρ_{PHX}	=	Resolution of the Phoenix lander in the Phoenix Descent Image

1. INTRODUCTION

The Phoenix Mars mission launched on 4 August 2007 is the first mission of NASA's "Scout" program. The Scout missions are a series of competitively selected, low-cost missions to Mars. Led by principal investigator Peter Smith of the University of Arizona, Phoenix is designed to measure volatiles (especially water) and organic molecules in the ice-rich soil of the Martian arctic. Phoenix inherited a highly-capable spacecraft partially built for the Mars Surveyor Program 2001 lander, as well as some scientific instruments from the Mars Polar Lander. The Phoenix team benefited from lessons learned from the Mars Polar Lander and Mars Surveyor Program 2001 experience, as well as further reliability upgrades and subsystems demonstrated in previously successful space missions. [1]

The High Resolution Imaging Science Experiment (HiRISE) camera is a camera on board the Mars Reconnaissance Orbiter (MRO), which was placed in orbit around Mars in March 2006. [2] The HiRISE camera was built by Ball Aerospace & Technologies Corporation under contract for the University of Arizona's Lunar and Planetary Laboratory. HiRISE is able to image the surface of Mars with a nominal spatial resolution of up to 0.3 m using its 0.5 m reflecting telescope. [3]

The spectacular "Phoenix Descent Image" (Fig. 1) taken by HiRISE [4] as the Phoenix lander descended on its parachute presented an opportunity to apply photogrammetry on Mars to determine the position of the descending

spacecraft. The background of Heimdal Crater provides the necessary topographic reference, while the known position of the HiRISE camera (i.e. Mars Reconnaissance Orbiter) provides a second reference for position anchoring.

Fig. 1. *Phoenix Descent Image*. The inset shows the lander descending on its parachute, while still enclosed in the backshell. Heimdal Crater is in the background.

2. METHOD

Determining the position of the Phoenix lander from the Phoenix Descent Image (Fig. 1) required four steps:

1) Determining the location of the HiRISE camera (i.e. MRO's position in its orbit),
2) Anchoring the Phoenix Descent Image to the topography of Mars,
3) Calculating the line-of-sight along which the Phoenix lander appeared, as well as its position on the surface of Mars as it appeared to the HiRISE camera,
4) Using the resolution of the image to calculate where along this line-of-sight vector the Phoenix lander was positioned.

2.1 Location of the HiRISE Camera

Mars missions express the position of spacecraft in different coordinate systems depending on the type of information needed. In this investigation, it was found that MRO's position could be easily determined in any of the frames from its orbital determination state vector. However, Heimdal Crater's location, as well as other Martian planetary locations could only be found in a body-fixed system. Thus, all position information had to be transformed into one consistent frame. These coordinate frames can be categorized into two broad groups: inertial non-rotating frames, and non-inertial, body fixed frames. Primarily, four coordinate frames were considered. These are listed below:

1) *Earth Mean Equator and Equinox of J2000 (EME2000)* [5]

This is the most fundamental coordinate system where the reference direction (i.e. x-axis) is the vernal equinox of J2000 and the reference plane (plane normal to the z-axis) is the Earth mean equator of J2000. The frame can be centered on any body, and for a Mars mission it is normally centered on Mars itself. Since both the reference plane and the reference direction are fixed to epoch J2000 (which corresponds to 12:00 pm (i.e. noon) on 1 January 2000), this is an inertial frame and a reference frame for coordinate transformation. Refer to Fig. 2 for a visual representation of the coordinate system.

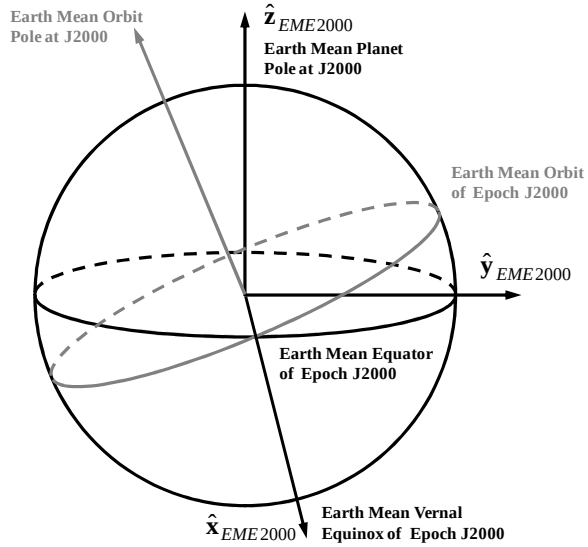

Fig. 2. *Earth Mean Equator and Equinox of J2000*. The x-axis is defined as the vernal equinox of J2000 epoch and the z-axis is the normal to the Earth mean equator at J2000. The y-axis is defined appropriately to complete the right-hand rule. [5]

2) *Mars-centered, Mars Mean Equator and IAU Vector of J2000* [5]

This is another inertial coordinate system centered on Mars with J2000 as the epoch. However, unlike the EME2000 frame, the reference plane is the Mars mean equator and the reference direction is the International Astronomical Union (IAU) vector. The change in the reference plane means that a transformation has to occur around the x-axis to move from the Earth mean equator to the Mars mean equator. Also, the reference direction is defined by a vector defined by IAU as the intersection of the Mars mean equator of J2000 plane and the Earth mean equator of J2000 plane, and is positive in the direction of the ascending node of the Mars mean equator of date on the Earth mean equator of J2000. This means that a transformation has to occur around the z-axis to rotate from the equinox of J2000 to the IAU vector of J2000.

Moreover, it must be noted that the IAU vector can be calculated by the cross product of the EME2000 pole (which is normal to the Earth mean equator) and the Mars pole of J2000 (which is

normal to the Mars mean equator). The EME2000 pole is given in Eq. 1 in Cartesian coordinates.

$$\hat{\mathbf{z}}_{EME\,2000} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{1}$$

The Martian pole is determined by calculating the right ascension (α) of the IAU vector and declination (β) of Mars' North Pole with reference to the EME2000 mean equator at the given time. These angles can be computed with Eqs. 2-3

$$\alpha = 317.68143 - 0.1061T \text{ (degrees)} \tag{2}$$

$$\beta = 52.8865 - 0.0609T \text{ (degrees)} \tag{3}$$

where T is the number of Julian centuries of 36525 days past the J2000 epoch (which is JD 2451545.0).

Thus, in Cartesian coordinates, the normalized Martian pole would be given by Eq. 4.

$$\hat{\mathbf{z}}_{Mars} = \begin{bmatrix} \cos\beta\cos\alpha \\ \cos\beta\sin\alpha \\ \sin\beta \end{bmatrix} \tag{4}$$

3) *Mars-centered, Mars Mean Equator and IAU Vector of Date* [5]

This is a non-inertial coordinate system as the reference plane and direction are both referred to the date of interest, not a fixed epoch. Therefore, the reference plane and the direction must be rotated around the x-axis (using β) and the z-axis (using α) in order to transform to the inertial coordinate systems.

4) *Mars-centered, Mars Mean Equator and Prime Meridian of Date* [5]

Similar to the IAU Vector of Date frame above, this non-inertial coordinate system has to be rotated around the x- and z-axes to transform to the inertial coordinate systems. However, the reference direction in this case is the Prime Meridian of Mars, which has been set as a longitude that goes through the Airy-0 Crater. Thus, a rotation around the z-axis has to be made in order to rotate between the IAU Vector of Date and the Prime Meridian of Date. These two reference directions are related by the angle W. The angle (W) between them can be calculated using Eq. 5.

$$W = 176.630 - 350.89198226d \text{ (degrees)} \tag{5}$$

where d is defined as the number of 24 hour days since the J2000 epoch. Fig. 3 shows the relationship between IAU vector and Prime Meridian.

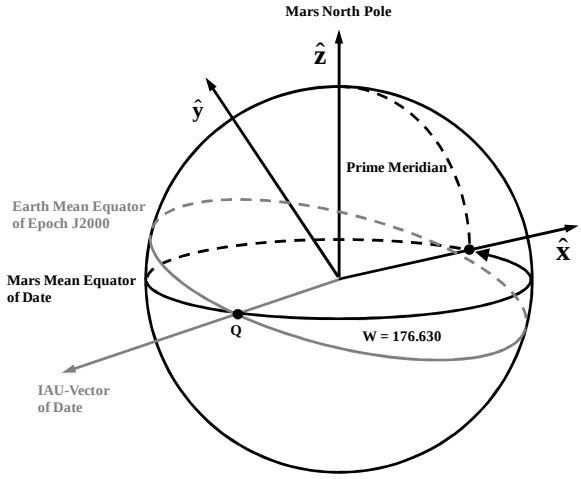

Fig. 3. *Mars Mean Equator and Prime Meridian Vector of Date*. The IAU Vector of Date and the Prime Meridian of Date both lie on the same reference plane (i.e. Mars Mean Equator of Date) and so they are related to each other by a rotation about the z-axis by the angle W, which is defined in the figure for the J2000 epoch. [5]

For this investigation, the Mars-centered, Mars Mean Equator and Prime Meridian of Date frame was chosen as the coordinate system in which to report results. The choice was based upon the fact that entry, descent, and landing reconstruction was being done in this frame, and the Heimdal Crater's location with respect to the Prime Meridian was well known.

The position of MRO and also the HiRISE camera in the Mars-centered, Mars Mean Equator and Prime Meridian of Date frame is given by Eqs. 6-7 (in both spherical and cartesian coordinates) at the time the Phoenix Descent Image was taken.

$$\mathbf{r}_{MRO} = \begin{bmatrix} 62.2561625\,^{\circ}\text{N} \\ 210.5146848\,^{\circ}\text{E} \\ 3690.245998\,\text{km} \end{bmatrix} \tag{6}$$

$$\mathbf{r}_{MRO} = \begin{bmatrix} -1479.952723 \\ -872.2697741 \\ 3266.006875 \end{bmatrix} \text{km} \tag{7}$$

2.2 Anchoring the Phoenix Descent Image to the Martian Topography

Since the location of Heimdal Crater on Mars is known, four reference points were chosen around the edge of the crater in the original Phoenix Descent Image as shown in Fig. 4 such that the Phoenix lander was placed at the intersection of the horizontal and vertical lines. The two horizontal line reference points are labeled H-H1 and H-H2. The two vertical line reference points are labeled

H-V1 and H-V2. These points were used to measure the resolution of the image and provide a scale with which to measure the size of the Phoenix lander on the parachute.

After choosing the reference points, the Phoenix Descent Image was projected onto the surface using a polar stereographic projection as shown in Fig. 5. As can be seen in Fig. 6, the Phoenix lander is no longer at the intersection of the two lines. This proved not to be problematic, as once the Phoenix Descent Image was projected onto the surface of Mars, the location of Phoenix on the surface as it appeared from the HiRISE camera was easily found. The latitude and longitude of the reference points, as well as the Phoenix lander's apparent position on the surface, are given in Table 1. The final projected image resolution was 0.792382 m/pixel.

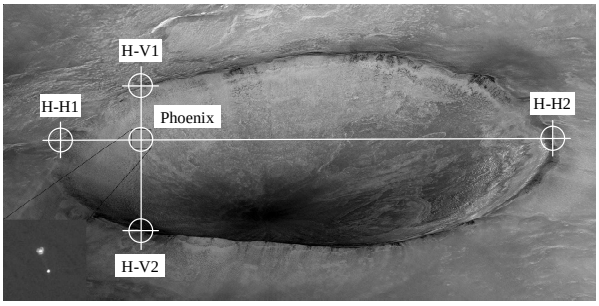

Fig. 4. *Heimdal Crater Reference Points.* The reference points are shown as chosen based on the non-projected Phoenix Descent Image.

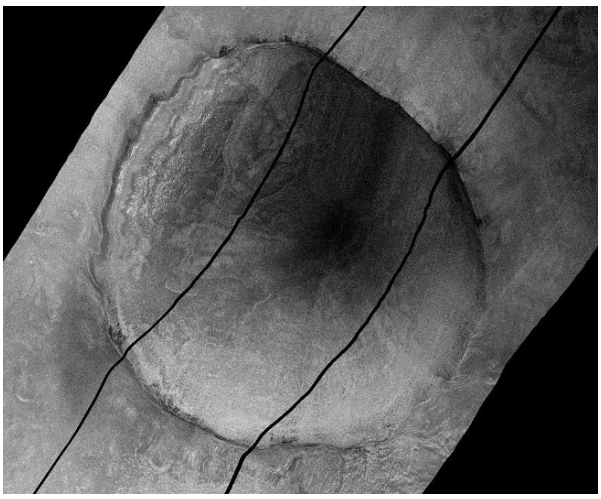

Fig. 5. Polar stereographic projection of Heimdal Crater onto the surface of Mars.

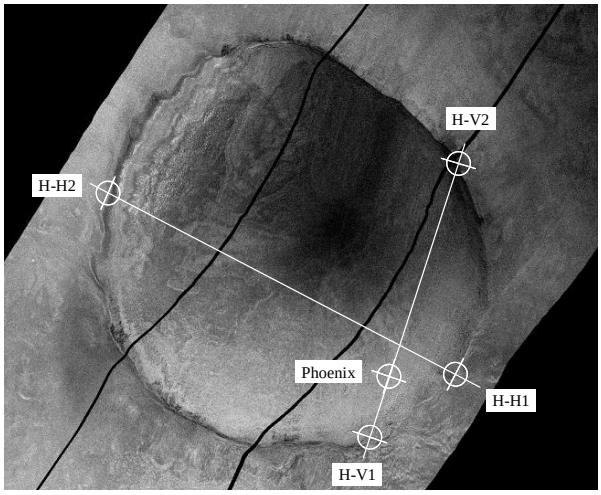

Fig. 6. Polar stereographic projection of the Heimdal Crater reference points onto the surface of Mars.

Table 1: Reference Points in the Phoenix Descent Image.

Point	Areocentric Latitude (°N)	Longitude (°E)
H-H1	68.4164272	235.4314185
H-H2	68.2411781	235.5089667
H-V1	68.3992828	235.5632454
H-H2	68.3643413	235.2257889
Phoenix Lander's Apparent Position	68.3909730	235.4741291
Phoenix's Actual Landing Site	68.21894	234.2487

Table 2: Local Radii for the Reference Points in the Phoenix Descent Image.

Point	Local Radius (km)
H-H1	3378.884399
H-H2	3378.926095
H-V1	3378.888466
H-H2	3378.896763
Phoenix Lander's Apparent Position	3378.890438
Phoenix's Actual Landing Site	-

2.3 The Line-of-Sight Vector

As discussed above, the position of MRO is given by the Mars-Centered Mars Fixed vector (in both spherical and cartesian coordinates) in Eqs. 6-7. And the apparent position of the Phoenix lander on the surface of Mars is given by Eqs. 8-9.

$$\mathbf{r}_{AP} = \begin{bmatrix} 68.39097306\,^{\circ}\mathrm{N} \\ 235.4741291\,^{\circ}\mathrm{E} \\ 3378.890438\,\mathrm{km} \end{bmatrix} \tag{8}$$

$$\mathbf{r}_{AP} = \begin{bmatrix} -705.2691464 \\ -1025.180995 \\ 3141.41687 \end{bmatrix} \text{km} \tag{9}$$

Subtracting the position of MRO from the apparent position of Phoenix as shown in Eqs. 10-11, we can obtain the line-of-sight vector along which the HiRISE camera was looking when the Phoenix Descent Image was taken. It is along this vector that the Phoenix lander lies.

$$\mathbf{r}_{LOS} = \mathbf{r}_{AP} - \mathbf{r}_{MRO} \tag{10}$$

$$= \begin{bmatrix} -705.2691464 \\ -1025.180995 \\ 3141.41687 \end{bmatrix} \text{km} - \begin{bmatrix} -1479.952723 \\ -872.2697741 \\ 3266.006875 \end{bmatrix} \text{km}$$

$$\mathbf{r}_{LOS} = \begin{bmatrix} 774.6835764 \\ -152.911221 \\ -124.590005 \end{bmatrix} \text{km} \tag{11}$$

2.4 Image Resolution

The position of the Phoenix lander can be found using the resolution of the Phoenix Descent Image. As stated above, the projected image resolution for Heimdal Crater is 0.792382 m/pixel. Since the Phoenix lander lies in front of Heimdal Crater in space, it should be imaged with a higher resolution. Therefore, if the distance between the lander and the top of the parachute, for example, is known, the resolution at which the Phoenix lander was imaged can be found. The ratio (Y) of the Heimdal Crater resolution(ρ_{HC}) to the Phoenix lander resolution (ρ_{PHX}), as given in Eq. 12, can then be used to determine how far along the line-of-sight vector Phoenix lies in space. Adding this scaled line-of-sight-vector to the position of MRO (Eq. 13), we have the actual position of Phoenix when the Phoenix Descent Image was taken.

$$Y = \frac{\rho_{PHX}}{\rho_{HC}} \tag{12}$$

$$\mathbf{r}_{PHX} = \mathbf{r}_{MRO} + Y\mathbf{r}_{LOS} \tag{13}$$

The diameter of Phoenix's parachute is approximately 11.8 m. [6] Using this distance as a baseline, the distance between the lander and the maximum diameter of the parachute can be estimated to be 31.5 m. However, since Phoenix is not hanging vertically in the plane of the image, the resolution of the image must be determined using the foreshortened distance between the lander and the parachute.

From Fig. 7, the Phoenix lander on its parachute is rotated approximately 22.13° counterclockwise in the plane of the image. Out of the plane of the image, the Phoenix lander on its parachute is rotated approximately 32.28° such that the parachute is closer to the viewer than the lander.

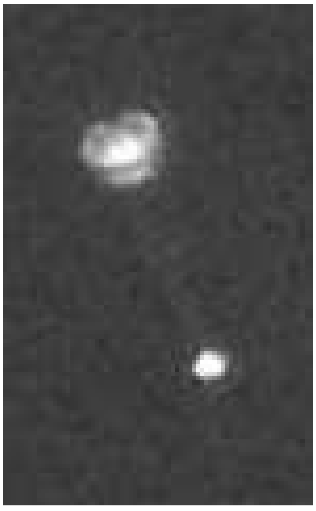

Fig. 7. Phoenix on its parachute as shown in the Phoenix Descent Image.

These two angles define a cuboid which has two faces parallel to the plane of the image, and whose main diagonal is equal to 31.5 m.

Therefore, in the plane of the image, the distance between the Phoenix lander and the maximum diameter of its parachute is approximately 27.19 m. This gives the resolution of the Phoenix lander (ρ_{PHX}) to be 0.767 m/pixel as given in Eq. 14.

$$\rho_{PHX} = \frac{27.19\,\text{m}}{35.46\,\text{pixels}} = 0.767\,\frac{\text{m}}{\text{pixel}} \tag{14}$$

where 35.46 pixels is an average pixel distance based several measurements from the Phoenix lander to its parachute.

3. RESULTS

3.1 Final Position Determination

Having found the Heimdal Crater resolution and the Phoenix lander resolution, their ratio is given in Eq. 15.

$$Y = \frac{\rho_{PHX}}{\rho_{HC}} = \frac{0.767\,\frac{\text{m}}{\text{pixel}}}{0.792382\,\frac{\text{m}}{\text{pixel}}} \tag{15}$$

$$Y = 0.9675$$

Using the result of Eq. 15, the position of the Phoenix lander is given in Eq. 16 in cartesian coordinates

$$\begin{aligned}\mathbf{r}_{PHX} &= \mathbf{r}_{MRO} + Y\mathbf{r}_{LOS} \\ &= \begin{bmatrix}-1479.952723\\-872.2697741\\3266.006875\end{bmatrix}\text{km} + 0.9675\begin{bmatrix}774.6835764\\-152.911221\\-124.590005\end{bmatrix}\text{km} \\ \mathbf{r}_{PHX} &= \begin{bmatrix}-730.4531853\\-1020.210034\\3145.467142\end{bmatrix}\text{km}\end{aligned} \quad (16)$$

and in terms of latitude and longitude by Eq. 17.

$$\mathbf{r}_{PHX} = \begin{bmatrix}68.25262446\,^{\circ}\text{N}\\234.397975\,^{\circ}\text{E}\\3386.495816\,\text{km}\end{bmatrix} \quad (17)$$

This position places the Phoenix lander approximately 773 km from MRO and approximately 26 km in front of its apparent position in Heimdal Crater from HiRISE's viewpoint at the time the Phoenix Descent Image was taken. Phoenix's altitude was approximately 10.2 km above the surrounding terrain, and the overland distance from the landing site was approximately 3.8 km. The predicted position of Phoenix is plotted in Fig. 8.

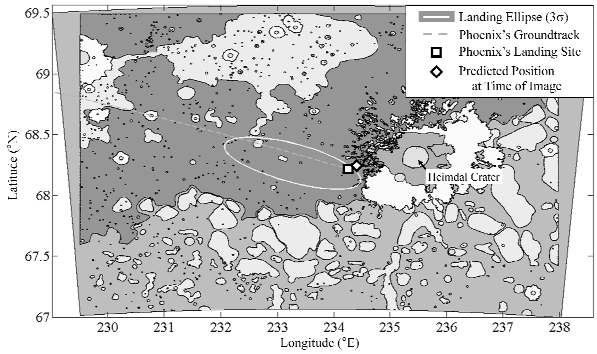

Fig. 8. The Phoenix lander's predicted position.

3.2 Error Considerations

Several sources of error are apparent in determining the position of the Phoenix lander from the Phoenix Descent Image. These sources of error include:

1) Uncertainty in the position of MRO at the time the Phoenix Descent Image was taken,
2) Distortion effects from image compilation and projection onto the topography of Mars,
3) Uncertainty in the distance between the lander and the maximum diameter of the parachute, and
4) Uncertainty in determining the resolution of the images of Heimdal Crater and the Phoenix lander (from previous two sources of error).

The uncertainties in the position of MRO at the time the Phoenix Descent Image was taken are shown in Table 3. These uncertainties translate to a maximum uncertainty in the position of the Phoenix lander of 0.22 m. Therefore, the uncertainties in the position of MRO were not seen as a significant source of error in calculating the position of the Phoenix lander using the Phoenix Descent Image.

Table 3: Uncertainties in the position of MRO.

Direction	Uncertainty (km)
Radial	6.3634884×10^{-5}
Downtrack	6.7224984×10^{-3}
Crosstrack	3.2557641×10^{-5}

The distortion effects from image compilation and projection onto the topography of Mars are much more difficult to quantify due to their nonlinear nature. The HiRISE camera has a series of charge-coupled device (CCD) arrays that are arranged in a staggered grid. These CCD arrays provide an effective swath width of approximately 20,000 pixels for red images. This results in a swath width of approximately 6 km from an altitude of 300 km when the camera is pointed straight down at the surface of Mars. [3] (Though this usual geometry of a HiRISE image does not apply here. The Phoenix Descent Image was taken from an oblique angle, and MRO was slewing to avoid smearing the image.) However, distortion effects are not expected to be a significant source of error compared to the uncertainty in the distance between the lander and the maximum diameter of the parachute.

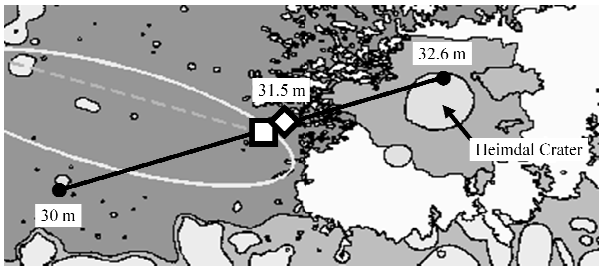

Fig. 9. The distance between the lander and the maximum diameter of the parachute was the largest source of uncertainty. Shown in the figure is the change in predicted position resulting from setting this distance to 30 m, to 31.5 m, and to 32.6 m.

The uncertainty in the distance between the lander and the maximum diameter of the parachute is the largest source of error in determining the position of the Phoenix lander from the Phoenix Descent Image. The apparent distance between the lander and the maximum diameter of the parachute in the image could be changed up to approximately one meter by extreme wrist mode oscillations, for

example. If the distance between the lander and the maximum diameter of the parachute at the time of image capture is, for example, 30 m instead of the estimated 31.5 m (a change of only 1.5 m), the position of the Phoenix lander changes by approximately 35 km. Note that for the Phoenix lander to be at its apparent position in Heimdal Crater, the distance between the lander and the maximum diameter of the parachute would have to have been approximately 32.6 m (only 1.1 m greater than estimated). The effect of changing the distance between the lander and the maximum diameter of the parachute is depicted in Fig. 9.

4. CONCLUSION

This investigation demonstrated that determining Phoenix's position using the Phoenix Descent Image was possible. The position of the Phoenix lander could have been determined independently of Phoenix navigation data or Phoenix telemetry in the event of the spacecraft's on-board inertial measurement unit failing or a communications breakdown that prevented the return of the data. However, position accuracy was affected considerably by knowledge of the orientation and dynamics of the Phoenix lander on its parachute. Using photogrammetry to accurately predict the position of planetary probes during descent could be improved with higher resolution images. Multiple images taken by two of more orbiting spacecraft would also improve position determination. Multiple images might also eliminate the need for both higher resolution images and precise knowledge of the dynamics of a planetary probe descending on its parachute.

5. CONCLUSION

The authors would like to thank Dolan Highsmith of the Jet Propulsion Laboratory for providing the position and the uncertainties in position of the Mars Reconnaissance Orbiter at the time the Phoenix Descent Image was taken by the HiRISE camera. We would also like to thank him for his help with understanding the coordinate systems used for Mars missions. We would like to thank Eugene Bonfiglio of the Jet Propulsion Laboratory for providing the location of Phoenix's landing site, as well as Phoenix's landing ellipse and the terrain map of the region around Phoenix's landing site. We would also like to thank Tim Parker of the Jet Propulsion Laboratory for providing a contoured relief map of the region around Phoenix's landing site.

6. REFERENCES

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