Three Dimensional Landmark Templates

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Abstract

Three-dimensional surface templates are being used to identify and locate landmarks on Mars and Phobos. They can be aligned both with images and the MOLA map to help tie these two data types together. The Martian templates form a control network of well-defined and easily identified landmarks For small bodies, templates covering larger areas can be woven together to provide a dense shape model, a single template providing thousands of body-fixed surface vectors.

Since errors exist in estimates of body-fixed landmark location, camera orientation and spacecraft location, there will be residuals between predicted and measured landmark locations. Minimizing the mean square residuals of a single landmark over many images, and possibly the MOLA map, refines the estimate of landmark location. Minimizing the mean square residuals of many landmarks in a single image refines the estimates of camera orientation and spacecraft location.

Each surface template is represented by a pixelized array of heights, surface slopes (height gradients), and albedos, by a local coordinate system, and by a body-fixed vector from the center of the parent body to the origin of the local coordinate system.

The albedo and slope at each map pixel predicts the relative surface brightness for a given illumination and camera angle. Minimizing the mean-square residuals between this prediction and the appropriately projected imaging data over many pictures refines the estimates of slope and relative albedo. The slopes are then integrated, with a sparse set of seed heights from MOLA or surrounding templates, to provide a new set of heights. The new template is again aligned with imaging or MOLA data to begin a new estimation cycle.

Procedure Overview

A landmark is defined by digital elevation and albedo maps relative to a local coordinate system whose origin is located by a vector V in the body-fixed frame.

For a single landmark, V is determined by minimizing weighted squared residuals between:

- **Image projections into the local system and the illuminated landmark map**
- **Overlapping landmark maps or MOLA maps**
- **Landmark map limb projections and observed limb images**

summed over all images and overlapping maps.

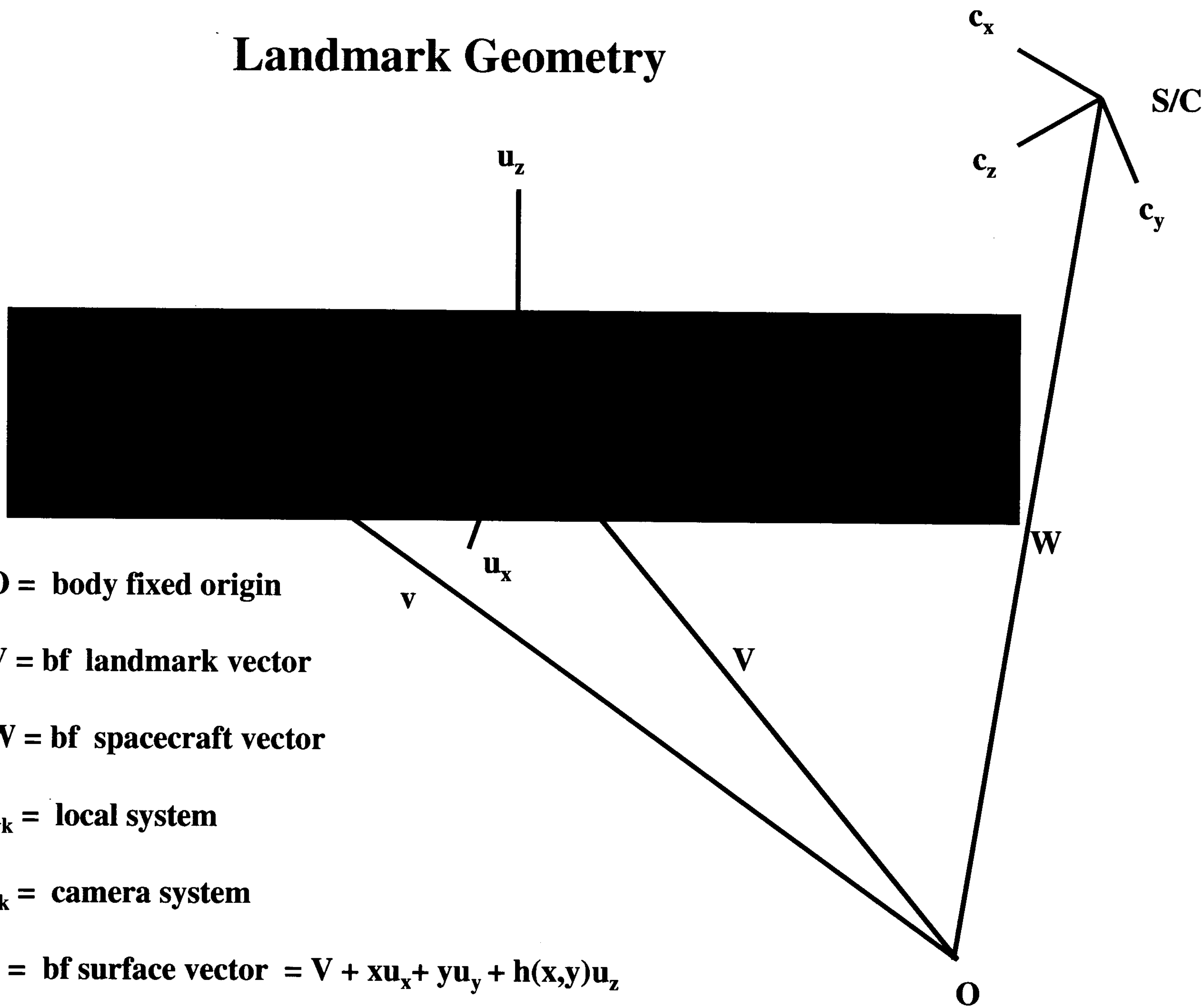
For a single image, camera pointing c_k and spacecraft location W are determined by minimizing weighted squared residuals between:

- **Image projections into the local system and the illuminated landmark map**
- **Landmark map limb projections and observed limb images**

summed over all landmarks.

Landmark slopes and albedos are found by minimizing weighted summed squared residuals between image projections into the local system and the illuminated landmark at each pixel of the map. Slopes are integrated, constrained by heights from MOLA, limbs, individual landmarks or overlapping maps, to produce a digital elevation map.

Landmark Geometry



O = body fixed origin

V = bf landmark vector

W = bf spacecraft vector

u_k = local system

c_k = camera system

v = bf surface vector $= V + xu_x + yu_y + h(x,y)u_z$

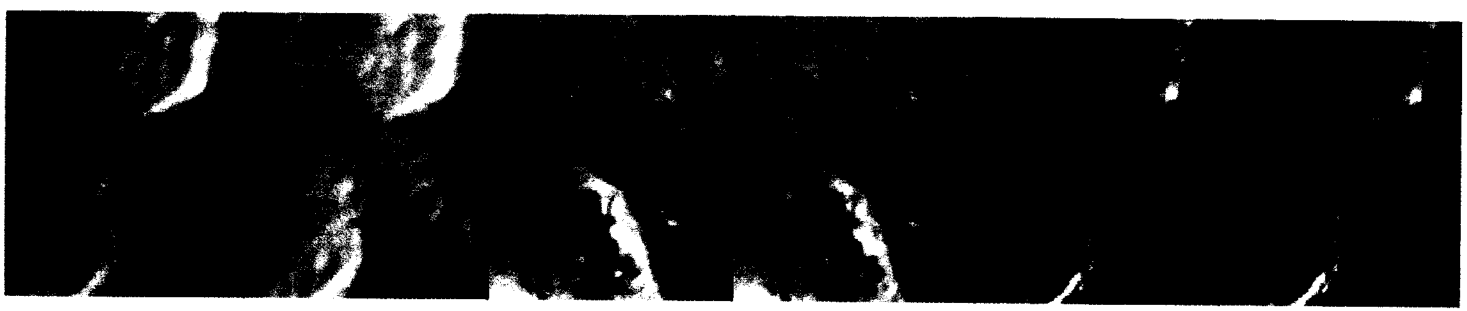
Landmark Image Projection

Landmark point (x,y,h) maps to focal plane location (X,Y) where

$$X = f((V-W)\bullet c_1+M_{11}x+M_{12}y+M_{13}h)/((V-W)\bullet c_3+M_{31}x+M_{32}y+M_{33}h)$$

$$Y = f((V-W)\bullet c_2+M_{21}x+M_{22}y+M_{23}h)/((V-W)\bullet c_3+M_{31}x+M_{32}y+M_{33}h)$$

where f=focal length and $M_{ij}=c_i\bullet u_j$



A different algorithm is used for data extraction from MOC images such as the two on the left.

Landmark Illumination

Landmark model illuminated in local frame according to

$$I(x,y) = I_0(1+t_3(x,y))F(\cos i,\cos e)+ \Phi$$

$$\cos i = (s_1t_1+s_2t_2+s_3)/\sqrt{(1+t_1^2+t_2^2)},\ \cos e = (e_1t_1+e_2t_2+e_3)/\sqrt{(1+t_1^2+t_2^2)}$$

$t_1 = -\partial h/\partial x$, $t_2 = -\partial h/\partial y$, $1+t_3$ = relative albedo, Φ = background,

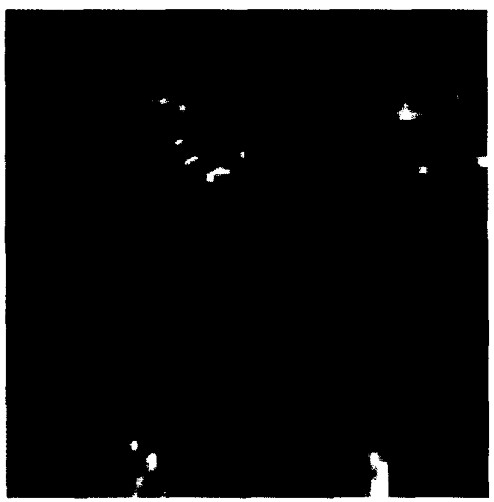
I_0 =normalization, s_k= local sun vector, e_k= local camera vector

The function $F(\cos i,\cos e)=\cos i+2\cos i/(\cos i+\cos e)$ does a good job of reproducing imaging data.

Mutual Landmark Registration

Landmark model is registered to MOLA map or to another overlapping landmark map by correlating gradients

Landmark (250 m) **MOLA**



d/dx

d/dy

Landmark (250 m) **Landmark (500m)**

d/dx

d/dy

Limb Projection

Landmark model is projected into image space and limb residuals are determined

Phobos landmark map (60 m)

Viking Orbiter image 315A11 (cropped)

Stereophotoclinometry

The slopes $-t_1$ and $-t_2$ and the relative albedos $1+t_3$ are determined from the following minimization procedure:

At each location (x,y) of the map, minimize

$$\sum_k \left(E_k(x,y) - I_k(x,y,t) - \delta t \bullet \nabla_t I_k(x,y,t) \right)^2$$

where the sum is over images k and where

E_k = Extracted image data at (x,y)

I_k = Predicted image data at (x,y)

Only relative photometry is used. The normalization factor I_0 and background Φ are solved for based on the large scale topographic variations known from stereo, MOLA, or overlapping map data. Essentially, this provides an interpolation algorithm for topography down to the pixel scale.

Height Determination

The height at each location (x,y) is determined from the neighboring heights, and a possible constraining height h_c from MOLA, stereo, limb or overlapping map data, according to:

$$
\begin{aligned}
h(x,y) = [&w_c h_c(x,y) \\
&+h(x+s,y)+s(t_1(x,y)+t_1(x+s,y))/2 \\
&+h(x-s,y)-s(t_1(x,y)+t_1(x-s,y))/2 \\
&+h(x,y+s)+s(t_2(x,y)+t_2(x,y+s))/2 \\
&+h(x,y-s)-s(t_2(x,y)+t_2(x,y-s))/2]/(w_c+4)
\end{aligned}
$$

where s is the map pixel spacing and w_c is a small constraining weight.

This equation is applied repeatedly to map points chosen at random until a converged solution is reached. If any height does not exist, its term is not included in the average.

Application Overview

A number of applications for landmark templates have been explored or are under study. Among them are:

- **Development of a high precision control network for Mars or other planetary bodies.**
- **Determining the shape and topography of small irregular bodies such as Phobos.**
- **Mosaicking of landmark templates to produce wide area topographic maps at resolutions approaching the best imaging data.**
- **Development of a semi-autonomous navigation and target characterization capability for certain types of small body missions.**

Martian Control Network

A set of landmark templates for Mars is being developed using Viking Orbiter and MOC imagery as well as the 1/64 degree MOLA map. All results are referred to the IAU2000 reference frame. About 1000 landmarks have been cataloged so far.

A file is produced for each image containing camera pointing, spacecraft location, formal uncertainties in these values, landmark names and pixel-space locations. MOC image files contain additional information regarding variations occurring during the exposure interval.

A file is produced for each landmark containing the landmark vector, its formal uncertainties, images containing the landmark and its pixel-space locations.

A file is produced for each landmark containing the landmark vector, unit vectors defining the local coordinate system, and the heights and albedos of each pixel in the landmark template.

Landmark Template Examples

Stereophotoclinometry interpolates the topography down to the pixel scale.

DK0002 Lt=11.55N Ln=140.65W Rd=3393.55 Sz= 25 km

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A landmark can be any distinctive feature, not just a crater.

DL0009 Lt=22.91N Ln=135.34W Rd=3398.63 Sz= 99 km

DN0005 Lt=13.92N Ln= 92.10W Rd=3398.97 Sz= 25 km

Fine-Scale Topography

Higher resolution templates can be tied to enveloping lower resolution ones to produce a nested set of increasing detail. Note however that the locations of these small scale maps are as uncertain as the large scale ones unless many peripheral stereo points and/or overlapping maps are included in the solution.

MOLA Map

FI0018 Lt=15.83S Ln=184.20W Rd=3392.45 Sz= 99 km

1000 m

FI0018 Lt=15.84S Ln=184.20W Rd=3392.56 Sz= 99 km

500 m

FI0030 Lt=15.95S Ln=184.01W Rd=3392.72 Sz= 50 km

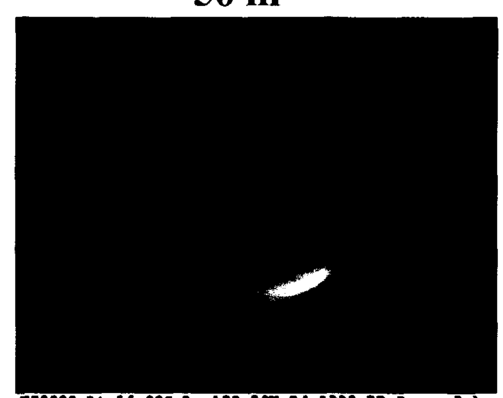
250 m

FI0031 Lt=15.95S Ln=184.01W Rd=3392.74 Sz= 25 km

100 m

FI0032 Lt=16.00S Ln=183.93W Rd=3392.89 Sz= 10 km

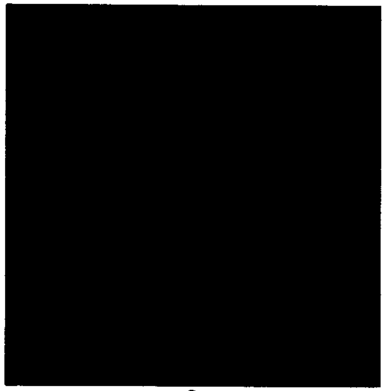
50 m



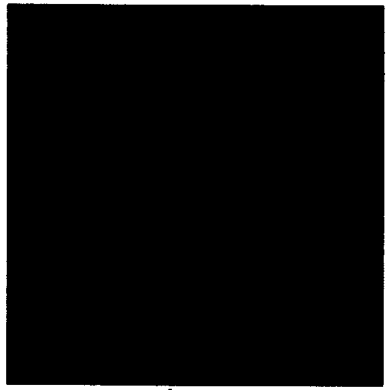
FI0033 Lt=16.02S Ln=183.90W Rd=3392.77 Sz= 5 km

Small Body Shapes

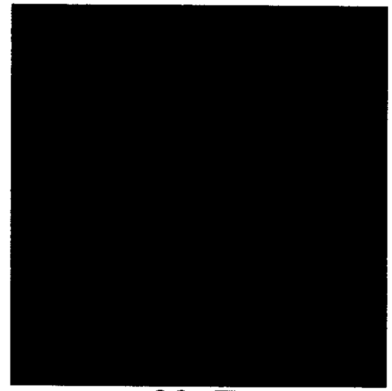
After aligning the images to a set of landmarks, the body is tiled with a set of larger templates called maps. In the case of Phobos, 146 overlapping maps are used, each containing about 10,000 vectors. A coarser shape model is constructed from these maps.



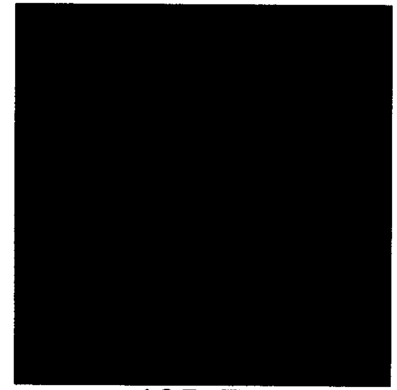
0°



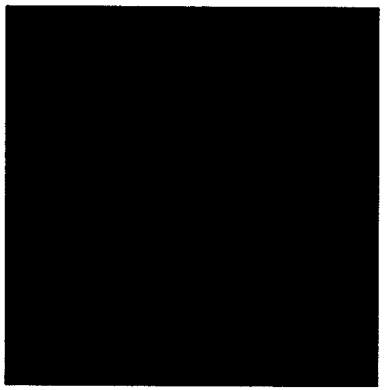
45° E



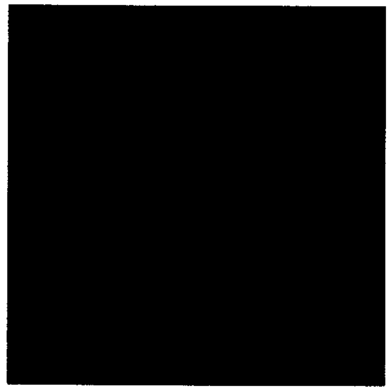
90° E



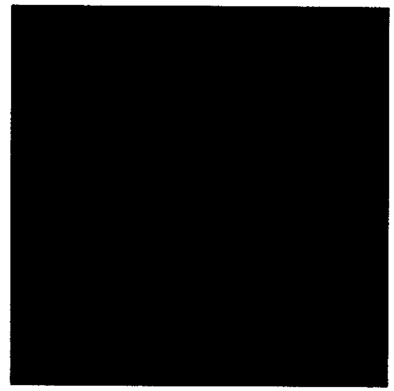
135° E



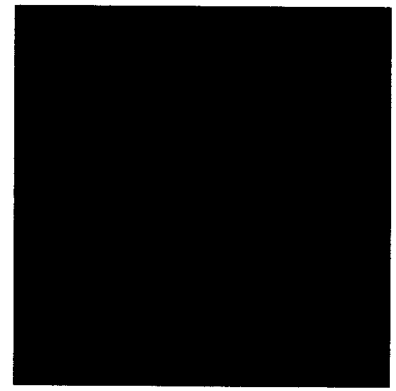
180° E



225° E



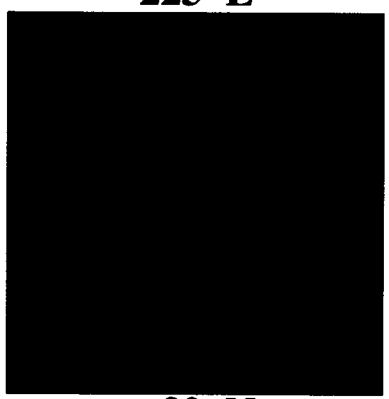
270° E



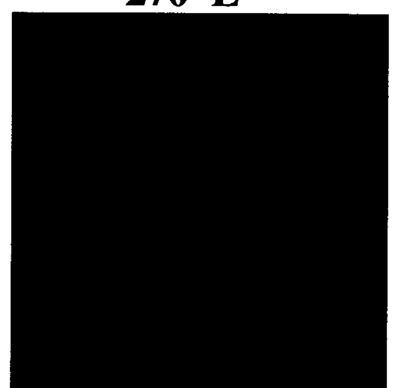
315° E

Phobos Results

Preliminary 25,000 vector model averaged from 1.4 million



90° N



90° S

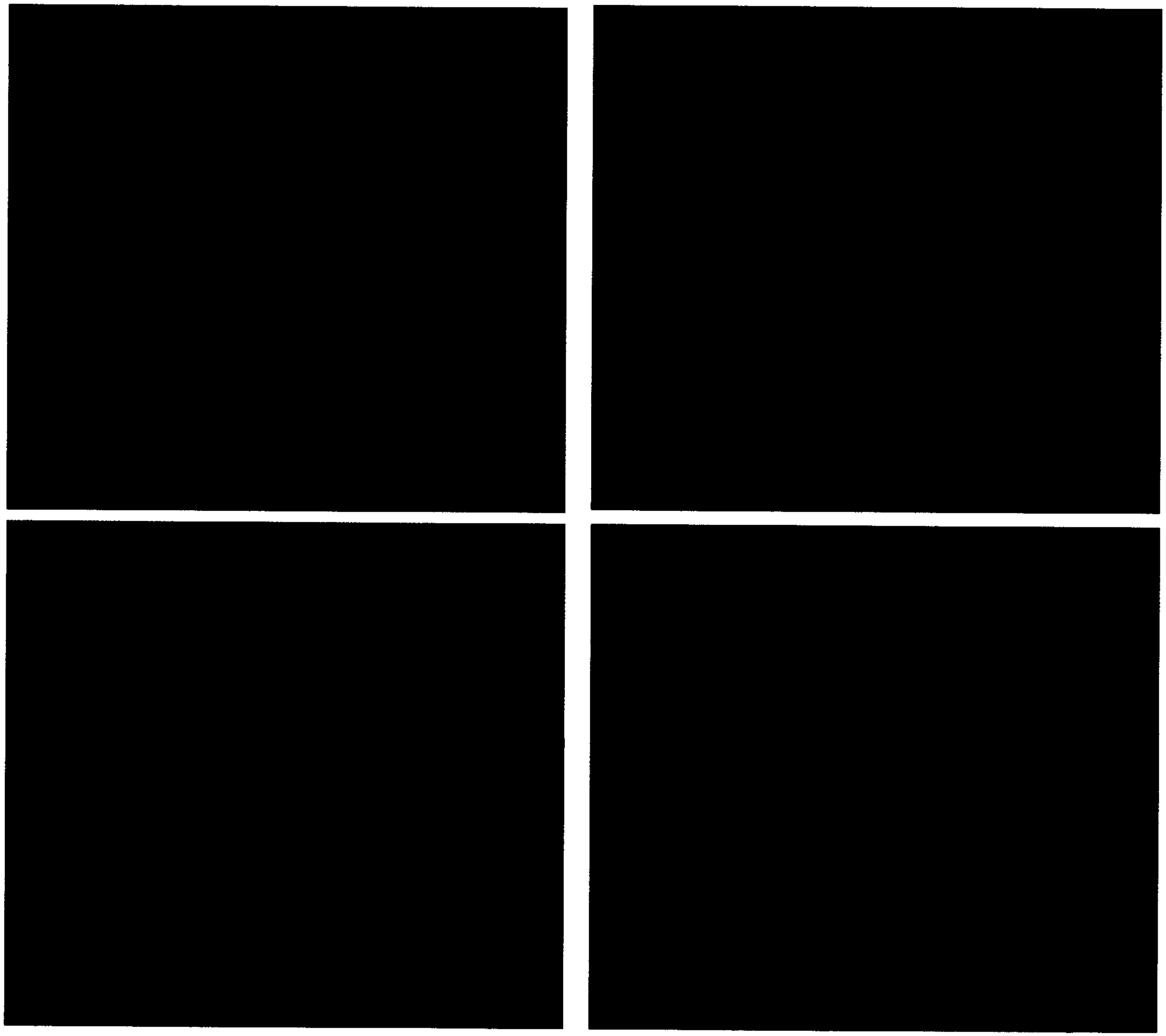
Volume = 5755 km^3

I_{xx}/M = 43.8 km^2

I_{yy}/M = 51.4 km^2

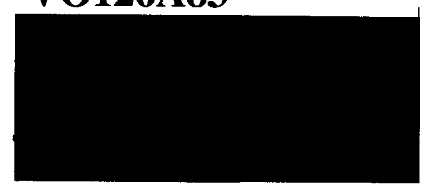
I_{zz}/M = 60.2 km^2

Phobos Model vs. Imaging Data



VO436A43

VO126A83



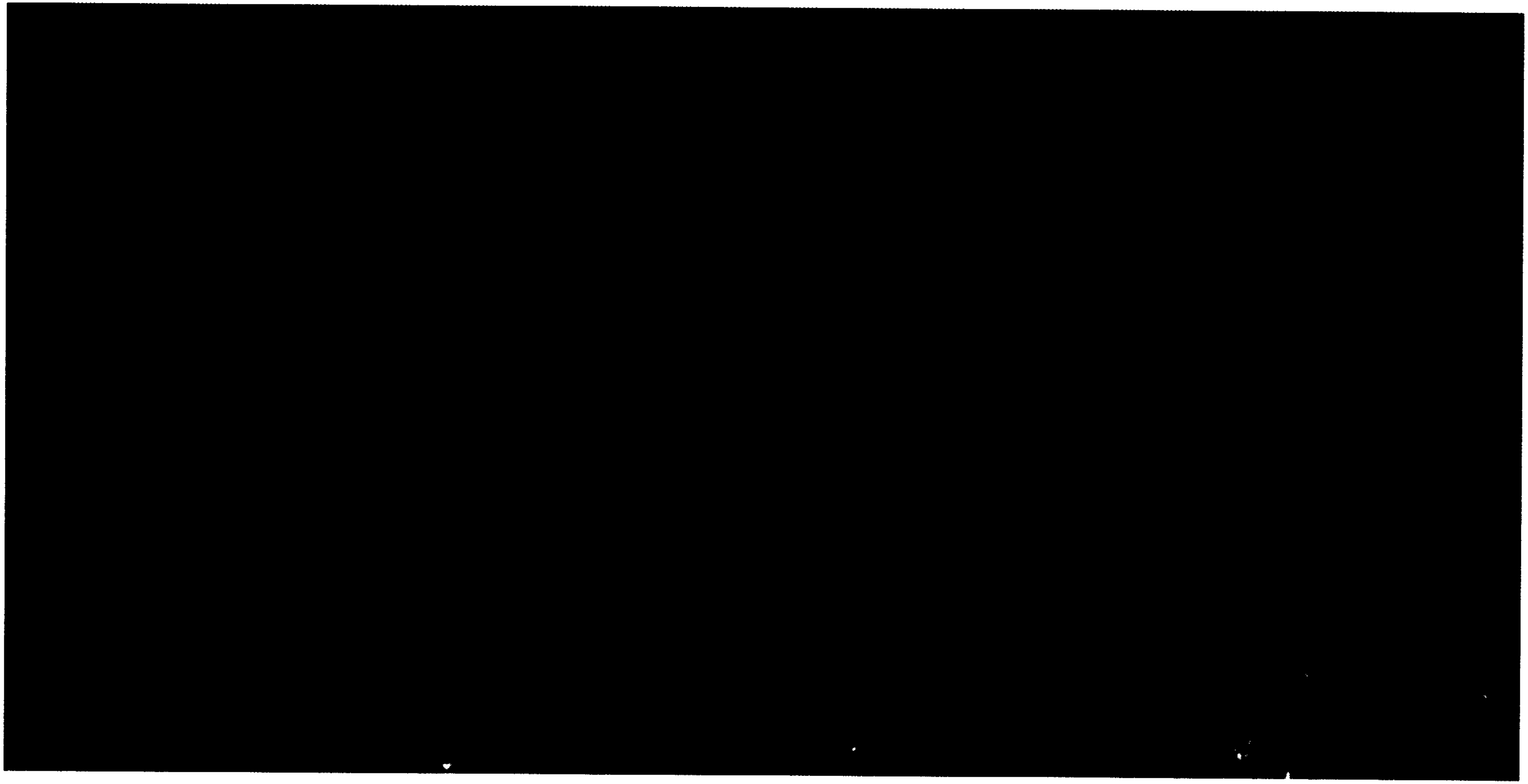
VO149B22

VO203A32

VO405A05

VO458A05

Wide Area Topographic Maps



This shows two views of a mosaicked topographic map of the area around the Pathfinder landing site. Maps for potential MER landing sites are currently being constructed.

Application to Spacecraft Navigation

For orbital missions such as NEAR or for return missions to a previously studied body, landmark templates can be used for autonomous spacecraft navigation.

• Templates are constructed on the ground using data from previous missions or from approach or higher orbits for a NEAR like mission. For small body missions the large scale shape and topography is determined.

• Map files are uploaded to the spacecraft. These are about 28 Kb uncompressed for 100 x 100 pixel maps.

• Using the nominal spacecraft location and orientation, predicted map images are constructed on board, and imaging data is projected and correlated with the predictions. Residuals imply updates to spacecraft location and orientation.

• Camera characteristics and computing needs are under study, but the latter should be modest.

Poster Layout