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Topographic/F) hotometric Model of Small Bodies

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ABSTRACT

Developing image acquisition requirements is a major part of the Autonomous Feature and Star Tracking (AFAST) project's work in advancing sensor technologies for planetary exploration. Sensing and detecting desired planetary features also involve topographic and photometric characterization of celestial bodies. The photometric study can provide felicitous designs of optics, focal plane array, and processing pertaining to feature extraction and tracking. In this paper, we present the results based on our preliminary study and implementation of photometric modeling on the AFAST's SGI- based 31) graphics testbed. Specifically, a computer-generated topographical model of Phobos is used since the photometry of Phobos have been studied in great details, The photometric function derived is mapped onto the computer-generated topographic model. Using the photometric model and specific camera parameters, an accurate CC]) pixel response to target irradiance can then be calculated. This pixel information can be used by the feature tracking algorithm, and sensitivity to signal-to-noise ratio can then be determined.

Keywords: topography) photometric modeling, CCD camera, feature tracking

1 INTRODUCTION

High-fidelity images of small bodies are essential to the dcr ivation of J1'1,-developed Autonomous Feature And Star Tracking (A FAST) solutions to permit visually-guided, autonomous spacecraft.[1] Actual images of small bodies are rare compared to images of planets and icy satel lites. Only comet Halley, Phobos, Deimos, Gaspra, and Ida have been captured by planetary spacecraft, and the only image data available for a complete 3D-shape and photometric characterization is that of Phobos. Because computer-generated images of small bodies can accurately predict image detector (CCD) responses to various illumination, shading, and camera characteristics, a wide range of synthetic target bodies can be simulated and supply the necessary test images for evaluating AFAST solutions in absence of real data. Thus, the topographic. and photometric model of a body must be represented in a numerical or analytical form. In addition to providing valuable test images for AFAST processing, representative surface-photometry also permits reliable assessments of various camera designs for the spacecraft celestial sensing system.

in this paper, we describe the necessary processes required to synthesize a small body. Phobos was selected because of the complete topographic/photometric characterization based on image data collected by the Viking and Soviet's 1'110110S spacecraft. Results of the computer-generated images of Phobos based on the described models employing a SGI GL^{TM} platform are also presented. in the next century, planetary spacecraft will totally rely on visual cucs contained in celestial scenes to maneuver and navigate their way through the Solar System, and the ability to provide the focal plane simulation for any type of target bodies for any orientation and lighting condition will become a necessity in developing the required celestial sensing system for various exploratory missions.

2 PHOTOMETRIC MODELING OF PHOBOS

Phobos (moon of Mars) was chosen as our target body for this study because both the 3D geometric model and photometric properties were readily available. The polygonal model was generated by T.C. Duxbury and his research team at JPL based on images returned by the Viking spacecraft.[3,4] The photometric information of Phobos was derived by Klaasen, Duxbury, and Vervcka[5] based on images returned by the Viking spacecraft. This information was integrated into AFAST's 3D Visualization Testbed[2] to demonstrate the results of photometric modeling in a dynamic spacecraft flyby scenario. In this section, the photometric modeling of Phobos is briefly reviewed,

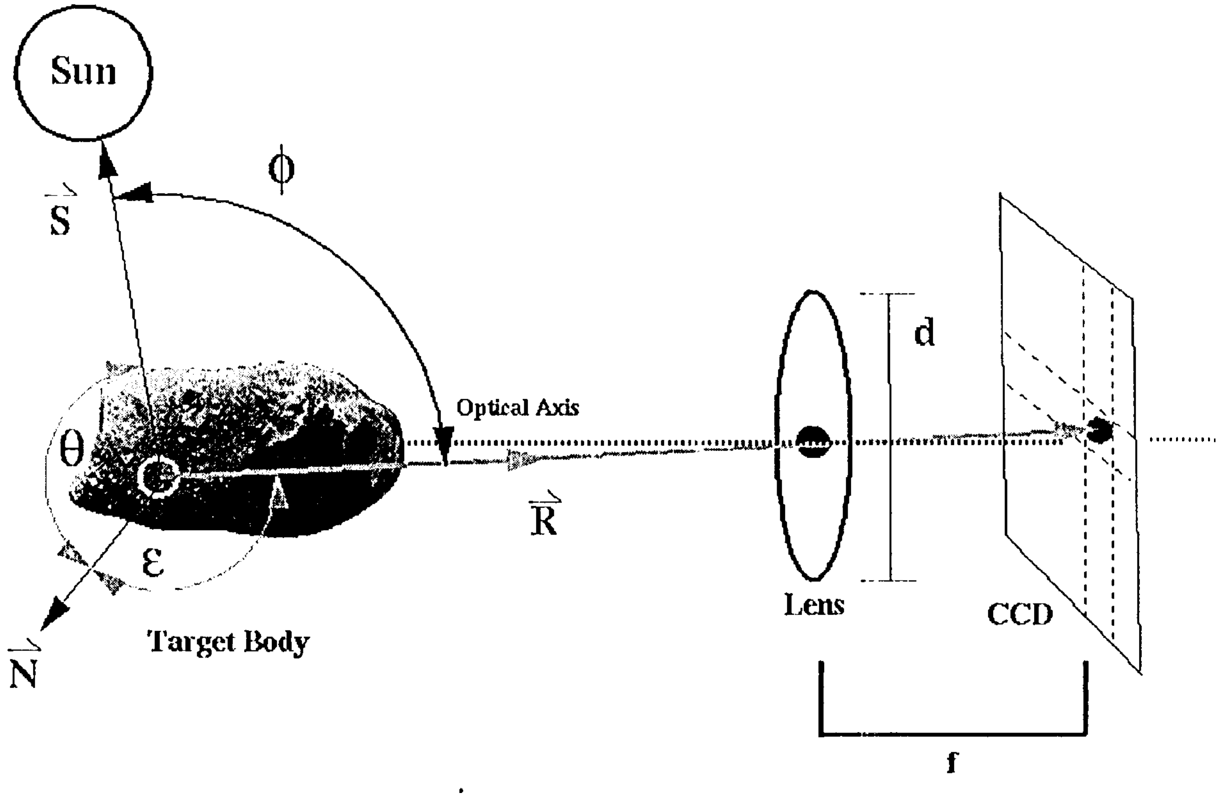

Figure 1 The sun, camera, and target body camera geometry

Given any point on the surface of the target body as shown in Figure 1, we define the following 3 vectors:

$\vec{R}$ = the unit vector from the surface point to the spacecraft,

$\vec{S}$ = the unit vector from the surface point to the sun, and

$\vec{N}$ = the normal vector at the surface point.

The corresponding incidence (θ), emission (ϵ), and phase (ϕ) angle are defined as

$\theta = cos^{-1}(\vec{S} \bullet \vec{N})$

$\epsilon = cos^{-1}(\vec{R} \bullet \vec{N})$, and

$\phi = cos^{-1}(\vec{R} \bullet \vec{S})$, respectively.

The photometric function in astronomical applications is generally written as

$$\frac{I(\theta, \epsilon, \phi)}{H} = \frac{cos\theta}{cos\theta + cos\epsilon} \rho_0 F(\theta, \epsilon, \phi) \quad (1)$$

where I is the intensity of the scattered light, H is the solar irradiance incident on the reflecting surface, and ρ_o is the normal reflectance.

For surface with low normal reflectance (i.e., ρ_o <0.3, such as Phobos), it has been demonstrated[6] that Eq. (1) can he simplified as

$$\frac{I(\theta, \epsilon, \phi)}{H} = \frac{cos\theta}{cos\theta + cos\epsilon} \rho_0 F(\phi). \quad (2)$$

For our implementation, a closed-form representation for the phase function $\rho_o F(\phi)$ is desired. For this study, the following parameterized exponential function of a 4^{th} order polynomial[5] is used:

$$\rho_o F(\phi) = exp(A + B\phi + C\phi^2 + D\phi^3 + E\phi^4). \quad (3)$$

Using photometric data[5] derived from images taken by Viking, the values for the parameters are estimated using the least-squares curve fitting method which are listed in the following table:

Parameter	Estimated Value
A	-2.0101e+00
B	-4.7470e-02
C	5.3663e-04
D	-4.1893e-06
E	1.2212e-08

The data and the result of least-squares curve fitting is shown in Figure 2. This estimated phase function is then used to compute the intensity (subject to a scale factor) based on the phase angle derived from the geometry of tile spacecraft, target, and the sun.

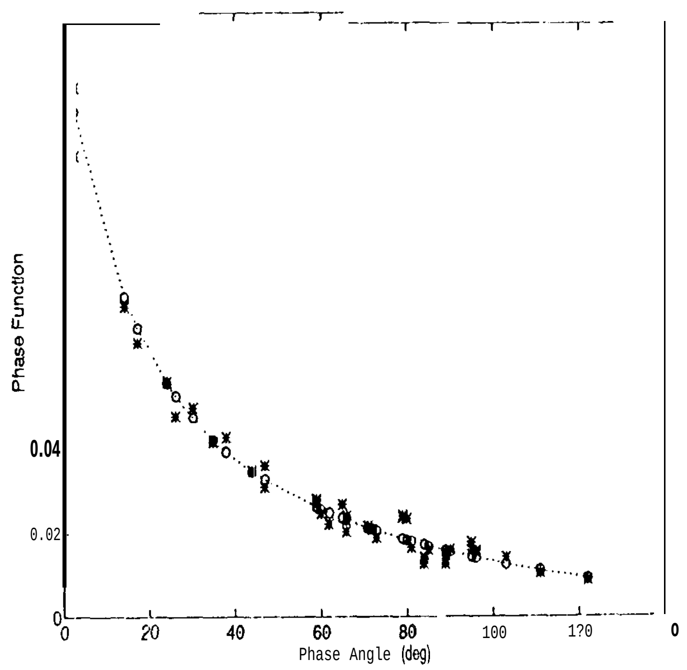

Figure 2. Curve-fitting results of Phobo's phase function $\rho_o F(\Phi)$

In our simulation, we recompute the surface brightness of each polygon vertex at each simulation time step, and usc the SGI's hardware Gouraud shading[7] capability to fill in the intensity for the pixels at the interior of each polygon. The pixel intensities arc then scaled from O to 255 to aid in visualizing the photometric effects. For comparison, a Lambert shading[8] is also implemented where the information of the camera position with respect to the target body and the sun was not considered. The simulation results of the photometric and Lambert shading arc shown in Figure 3 and 4 respectively.

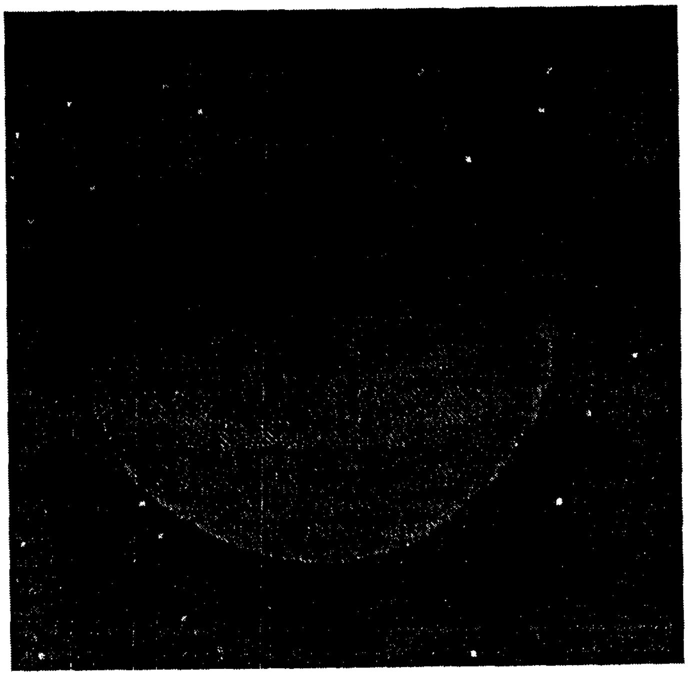

Figure 3. Photometric modeling of Phobos

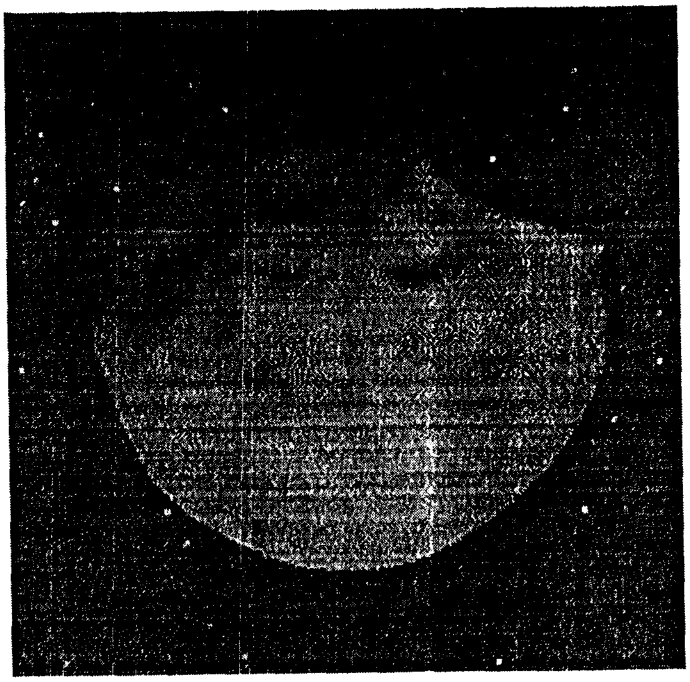

Figure 4. Lambert shading of Phobos

3 CCD CAMERA EMULATION

To enhance the realism of our Phobos simulation, we integrated a CCD camera model into our graphics testbed.[2] To simulate the CCD (intensity) response for a given location on the target body, the following formula was used:

$$DN = Flux * Gain * Exposure\_Time + Dark\_Current\_Count$$

where $Flux = \Phi * A * PO * 10^{\cdot 25}$ (in pe⁻/see)

Φ = phase angle dependent photometric coefficients (Eq. (2)),

A = effective aperture (in mm^2),

P_0 = camera constant corresponding to O Mv and O BV (in pe^- /see/mm^2),

$m_i = M_{V_1} + \alpha * BV + \beta$ (instrument magnitude)

$M_{V_1} = M_{V_0}$ +- $5log(\frac{d_0}{d_1})$,

M_{V_0} = measured visual magnitude

d_0 = distance to the body where M_{V_0} is measured (in Km)

$d_1 = \frac{R}{tan(\frac{FOV}{2N})}$ = distance to the body where the targeted body subtends 1 CCD pixel (in Km).

R = radius of the targeted body (in Km)

FOV = field-of-view of the CCD camera (in radians)

N = CCD resolution

BV = color information,

α = camera parameter,

β = camera parameter.

A representative CCD pixel responses is shown in Figure 5 where the target body is assumed to have an equivalent radius of 1150 Km and located be located 31 A.U. away from the Earth with a visual magnitude of 14.

It is also assumed that a CCD camera with the following parameters is used:

Parameter	Unit	Value
A	(mm^2)	900
FOV	$(^\circ)$	8
N		1024
P_0	$(pe^-/sec/mm^2)$	5350
α		0.04
β		0.08
$Gain$	(DN/pe^-)	3×10^{-4}
$Dark\_Current\_Count$		10 ± 1

An one-second exposure time was used in this simulation. Again, the SGI's hardware shading was used to compute pixel values for polygon interior pixels.

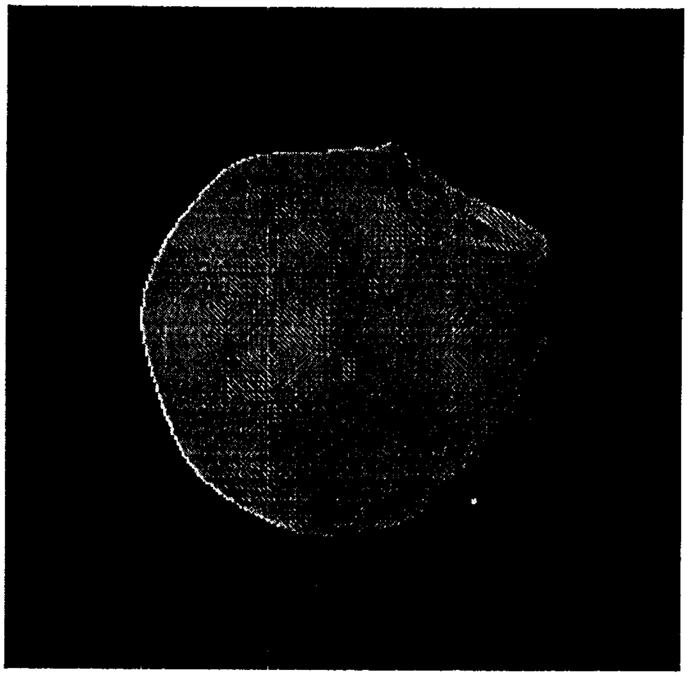

Figure 5. CCD pixel responses

4 CONCLUSIONS

By developing a 3D graphics testbed that incorporates topographic and photometric planetary models in conjunction with CCD camera modeling, we have a tool that allows us to develop and test our feature tracking software. In addition, because a variety of CCD camera parameter sets can be tested, a proper design of CCD-based celestial sensors can be realized for specific flight missions.

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