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THE CUSTOMIZATION OF SATELLITE TOOL KIT FOR USE ON THE NEAR MISSION

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The commercial software product, Satellite Tool Kit (STK), has been customized using the STK Programmer's Library to allow for its use in performing certain analysis tasks associated with the NEAR mission. The most challenging aspect of this work was the modeling of the shape of the asteroid 433 Eros. Three models of the shape of the Eros asteroid are investigated. A triaxial ellipsoid model of the shape is shown to be computationally efficient and simple to implement but does not provide all of the information needed to compute accurate access periods to science targets on the surface of the asteroid. A model which describes the surface as a set of flat triangular plates is shown to be more desirable for use with access computations, but is computationally inefficient for the visualization of sensor fields of view. A model which describes the radius of the central body as a truncated series of spherical harmonic is briefly discussed, but is seen to undesirable for this application. A hybrid approach is suggested where the triaxial ellipsoid model is used for the graphical depiction of sensors and the triangular plate model is used for analysis related tasks.

INTRODUCTION

The NEAR mission is being managed by The Johns Hopkins University Applied Physics Laboratory (JHU/APL) and is the first launch of new Discovery Program. The Discovery Program guidelines place tight limits on the development costs and schedule for spacecraft and software development. The Near Earth Asteroid Rendezvous (NEAR) satellite is currently en route to its final destination, in orbit about the asteroid 433 Eros. The spacecraft will spend about one year orbiting Eros and will provide an opportunity for the study of the composition and physical properties of the asteroid. The asteroid is postulated to be a convex hull shaped much like a potato with estimated dimensions of 40.5 by 14.5 by 14.1 kilometers[1] and has a rotational period of approximately 5.27 hours[2]. The shape and dynamics of the asteroid cause the scheduling of data collection to be a more complicated problem than is typically encountered for an Earth orbiting mission.

Recent architectural modifications, to the Commercial Off The Shelf Software (COTS) product, Satellite Tool Kit (STK), have made STK a viable tool for use in support of

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the NEAR mission. Although some of these modifications were driven by the requirements of the NEAR mission, the implementation is generic in nature. Being a long time user of the STK family of products, JHU/APL was interested in using STK to help fulfill its role in managing the NEAR mission while keeping costs and schedule impacts to a minimum. That interest developed into a relationship between and APL and the developers of STK and resulted in the creation of a flexible tool for mission analysis which could be easily adapted to support specialized missions. The specific modifications which benefit missions such as NEAR include the generalization of the central body within STK and the addition of a generic reporting capability.

CENTRAL BODIES WITHIN STK

STK is designed to be an analysis tool for satellites in orbit about a single central body. A large percentage of the functionality within STK is dependent upon the definition of the central body. The definition of a central body within STK includes the central body specific data and the set of functions to be used to perform central body related processing. New central bodies may be added to STK using the STK Programmer's Library (STK/PL). STK/PL is the set of software libraries from which STK is made and may be used to extend the capabilities of STK. The set of central body dependent functions contains some functions which must be explicitly defined and some functions which will work if the required functions are properly specified but may be overridden if a more efficient algorithm is available. In this context, we will only discuss the required functions. Given this set of functions and a minimal set of data associated with the central body, all of the STK analysis capabilities will be available for use with the new central body. Basic capabilities include the generation of satellite ground traces, the computation of lighting and access information and the projection of sensor patterns onto the surface of the central body. There are three distinct parts to the definition of a central body: the dynamics, the shape and the propagation models for the motion of satellites.

Dynamics

The specification of the dynamics must include information on both the translation and rotation of the central body as well as the definition of an inertial coordinate system with origin at the center of mass of the central body. The dynamics of the central body are needed for the computation of the ground traces of satellites, the prediction of lighting conditions on the surface of and in orbit about the central body and to relate the location of the central body to other objects. The position and velocity of the central body must be specified relative to the Solar System Barycenter Inertial (SSBI) coordinate system. The origin of the SSBI coordinate system is at the Solar System barycenter and the axes are oriented along the directions defined by the J2000 coordinate system. The rotational motion of the central body is defined through direction cosine matrices representing the relationship between the Central Body centered Inertial (CBI) and Central Body centered Fixed (CBF) coordinate systems and the angular velocity of the CBF coordinate system relative to the CBI coordinate system. The definition of the CBI coordinate consists of providing a direction cosine matrix representing the relationship between the axis directions of the CBI coordinate system and the SSBI coordinate system. This matrix is assumed to be constant and therefore does not require a functional relationship. The necessary dynamics functions are summarized the table below.

Table 1. CENTRAL BODY DYNAMICS FUNCTIONS

Function	Description
Position and Velocity	Given a time, provide the position and velocity in SSBI coordinates.
Orientation	Given a time, provide the transformation matrix between CBI and CBF coordinates
Angular Velocity	Given a time, provide the angular velocity vector of the CBF coordinate system relative to the CBI coordinate system.

Shape

The specification of the shape of the central body is necessary to compute the intersections of sensor patterns with the central body, for use in access and eclipse computations and for 3D visualization of the central body. To adequately specify the shape of the central body, the functionality summarized in the following table must be provided:

Table 2. CENTRAL BODY SHAPE FUNCTIONS

Function	Description
Local Radius	Given a spherical or body-detic latitude and longitude, provide the local radius.
Surface Normal	Given a spherical or body-detic latitude and longitude, provide the local normal to the surface.
Body-detic	Given a body-detic latitude, longitude and altitude, compute the Cartesian coordinates and the reverse transformation.
Ray Intersection	Given a reference position and direction in CBF coordinates, compute the intersections of a ray along the specified direction with the surface.
Tangent	Given a reference position and a vector normal to the reference position vector in CBF coordinates, compute the tangent points to the surface of the central body which lie in the plane defined by the normal vector.
Elevation Mask	Given a body-detic latitude, longitude and altitude, compute the azimuth-elevation obstruction mask.

The body-detic latitude is defined as the angle between the normal to the surface and the equatorial plane, measured as positive in the direction of the +Z body fixed axis. The body-detic longitude is defined as the angle between the +X body fixed axis and the projection of the normal to the surface in the equatorial plane, measured in a right handed sense about the +Z body fixed axis. The body-detic altitude is defined as the distance from the surface of the central body along the normal to the surface, measured as positive outside of the central body.

The problem of computing the intersections of a ray with the surface of the central body is depicted in Figure 1. The vector, $\vec{r}_o$, is the reference position, $\vec{d}$ is the direction vector and $\vec{r}_{I_1}$ and $\vec{r}_{I_2}$ are vectors to the points of intersection.

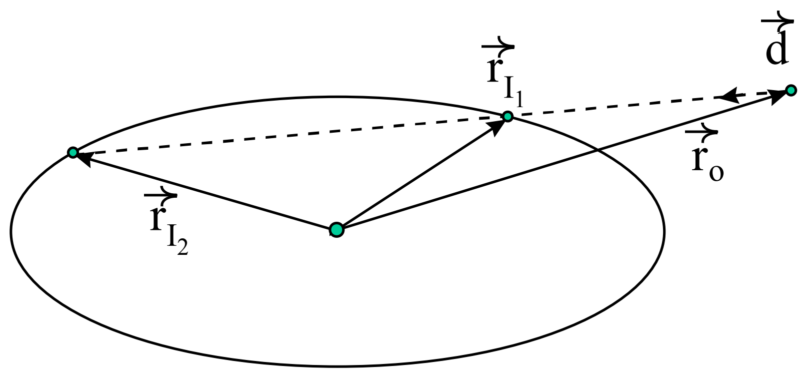

Figure 1. Intersection of a ray with the surface of the central body

The intersection problem may be expressed mathematically as the solution to the following set of equations,

$$\vec{r}_I = \vec{r}_o + \alpha\,\vec{d}, \tag{1}$$

$$S\left(\vec{r}_I\right) = 0, \tag{2}$$

where α is a scalar multiplier to the direction vector and S is a function representing the surface of the central body.

The problem of computing the points of tangency is depicted in Figure 2. The vector, $\vec{r}_o$, is the reference position and the normal vector, $\vec{n}$, may be considered to be out of the plane of the paper. $\vec{r}_{T_1}$ and $\vec{r}_{T_2}$ are the vectors to the tangent points. The $\vec{n}_{S_1}$ and $\vec{n}_{S_2}$ vectors are normal to the surface at the points of tangency.

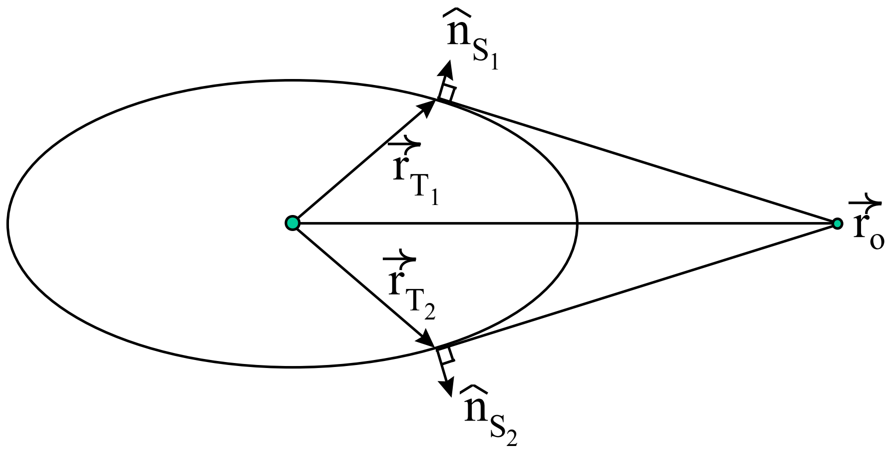

Figure 2. Projection of tangents to surface of central body

The tangent problem may be expressed as the solution to the following set of equations,

$$\vec{\nabla} S(\vec{r}_T) \bullet (\vec{r}_T - \vec{r}_o) = 0, \tag{3}$$

$$\vec{n} \bullet \vec{r}_T = 0, \tag{4}$$

$$S(\vec{r}_T) = 0, \tag{5}$$

where $\vec{n}$ is defined such that

$$\vec{n} \bullet \vec{r}_o = 0, \tag{6}$$

The elevation mask is a list of azimuth-elevation pairs associated with a specific location on the surface of the central body. An azimuth-elevation pair may be interpreted as meaning that at the specified azimuth, the elevation value represents the lowest possible non-obstructed viewing angle relative to the local horizon.

Orbit Propagation Models

The final set of information needed to describe the central body supports the computation of the trajectories of satellites in orbit about the central body. Since the ephemeris for the NEAR satellite is being provided by the Jet Propulsion Laboratory (JPL) Navigation Team, no Eros specific models were developed for use in STK.

MODELING THE ASTEROID 433 EROS

Software was designed and coded at APL to provide the necessary dynamics and shape related functions for the asteroid 433 Eros to be implemented as a central body within STK[3]. The final integration of these functions with STK was performed at Analytical Graphics.

Dynamics

The modeling of the dynamics of Eros is being done through the Navigation Ancillary Information Facility (NAIF) at JPL. The data describing the dynamics of the asteroid is provided in the form of SPICE kernels. In the SPICE kernel format, the variables specifying the dynamics of the asteroid are represented as functions based on coefficients of Chebyshev (or Tschebysheff) Polynomials of the First Kind[4]. For each variable, a function F applies over a specific time interval from $t_0 - \tau$ to $t_0 + \tau$ (all times are relative to an initial epoch defined in the data file, expressed as ephemeris time (ET) or barycentric dynamical time (TDB)). Coefficients $a_i^{[quantity]}$ (i = 1, 2, 3, ... N; usually N = 10), specific to each of the stored quantities, are provided from the data file. Multiple sets of coefficients are included, as required, to span the entire date/time interval encompassed by a particular data file. In summary, the value of an arbitrary variable is computed as

$$\xi(t) = F\left(t, t_o, \tau, a_o^{[\xi]}, a_1^{[\xi]}, a_2^{[\xi]}, \ldots, a_N^{[\xi]}\right). \tag{7}$$

The function F has the same form regardless of whether ephemeris or attitude information is being specified.

The position, velocity and orientation information obtained from the SPICE kernel files is converted to ASCII tables of time ordered position and velocity and time ordered asteroid attitude data to be read by STK. This is accomplished using an external utility, supported by SPICE libraries and the leap seconds kernel provided by the NAIF at JPL. The Eros specific functions for the asteroid dynamics which are inside of STK need only interpolate the data which was read in at initialization. The Asteroid Centered Inertial (ACI) coordinate system is defined with the axes oriented along the directions defined by the J2000 coordinate system so the transformation between the ACI and SSBI coordinate system is identity.

Shape

Three models were constructed to model the shape of Eros: as a triaxial ellipsoid, as a set of triangular plates which form a closed surface and as a surface defined by the coefficients of a truncated series of spherical harmonic functions. To simplify the shape model for Eros, the definition of body-detic latitude and longitude is changed to be the same as the corresponding spherical coordinates. This simplification means that only one function each needs to be provided for the computation of the local radius and surface normal. The definition of the body-detic altitude is changed to be the distance from the surface of the central body along the radius vector instead of along the surface normal. This greatly simplifies the conversion from radius to altitude. These new definitions, which are used for all of the shape models, are illustrated in Figure 3.

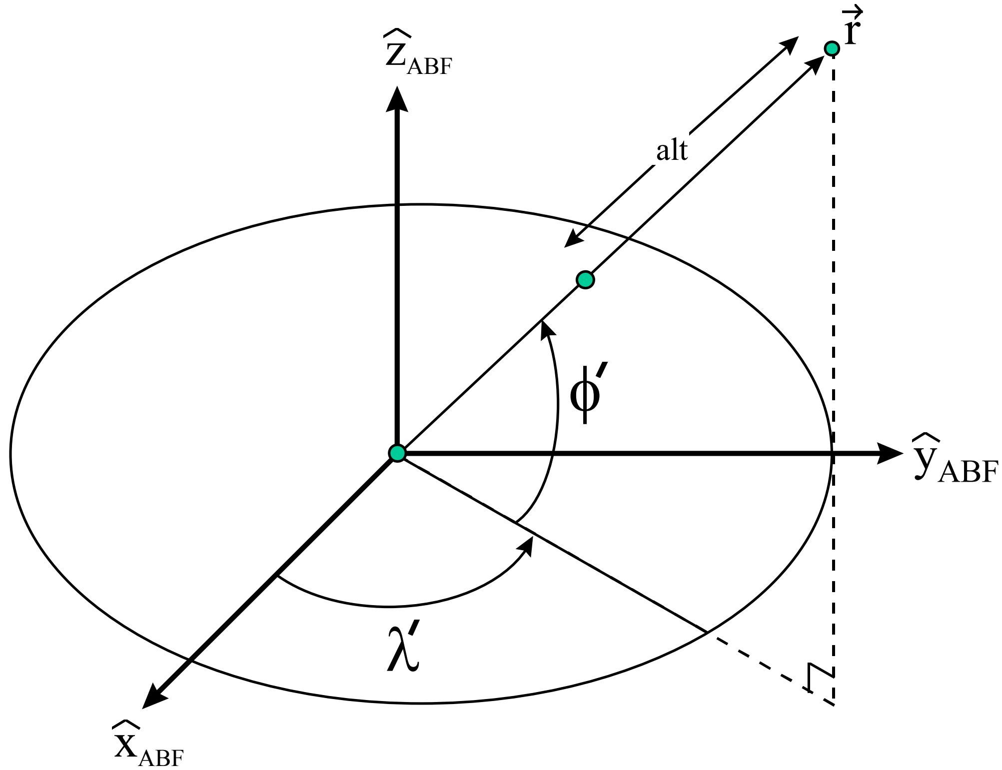

Figure 3. Asteroid-detic coordinates

The conversion between body-detic and Cartesian coordinates is now,

$$r = r_s(\Phi', \lambda') + alt, \tag{8}$$

$$\vec{r} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = r_s \begin{bmatrix} \cos\lambda' \cos\Phi' \\ \sin\lambda' \cos\Phi' \\ \sin\Phi' \end{bmatrix}, \tag{9}$$

where Φ' is the spherical latitude, λ' is the spherical longitude and alt is the altitude. Associated velocities are estimated from first differences with respect to time for the derived positions. Conversely, body-detic coordinates are derived from Cartesian position as follows:

$$r = |\vec{r}| = \sqrt{x^2 + y^2 + z^2}, \tag{10}$$

$$\Phi' = \sin^{-1}\left[\frac{z}{r}\right], \tag{11}$$

$$\lambda' = \tan^{-1}\left[\frac{y}{x}\right], \tag{12}$$

$$alt = r - r_s(\Phi', \lambda'). \tag{13}$$

Associated rates are estimated from first differences with respect to time for the derived latitudes and longitudes.

Triaxial Ellipsoid

The simplest of the shape models is a triaxial ellipsoid, described by the equation:

$$S = \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} - 1 = 0, \tag{14}$$

where a, b and c are the principal semi-axial lengths and x, y and z are coordinates specifying the location of a point on the surface in Asteroid Body Fixed (ABF) coordinates.

The triaxial ellipsoid is the most computationally efficient model of the three. This model is intended for use during the initial approach and rendezvous with the asteroid. The triaxial ellipsoid model will be based initially on the estimate of Ostro et al.[1] and may be refined by the NEAR project in the early stages of rendezvous with and orbit about Eros.

For a *triaxial ellipsoid,* the radial distance from the center to a point on the surface at spherical latitude Φ' and longitude λ' is:

$$r = \left[\left(\frac{\cos^2 \lambda'}{a^2} + \frac{\sin^2 \lambda'}{b^2} \right) \cos^2 \Phi' + \frac{\sin^2 \Phi'}{c^2} \right]^{-1/2}, \tag{15}$$

The surface normal for the triaxial ellipsoid may be computed as:

$$\vec{n}_{surface} = \frac{\vec{\nabla} S}{\left| \vec{\nabla} S \right|}, \tag{16}$$

where,

$$\vec{\nabla} S = \frac{x}{a^2} \vec{i} + \frac{y}{b^2} \vec{j} + \frac{z}{c^2} \vec{k}. \tag{17}$$

and $\vec{i}$, $\vec{j}$ and $\vec{k}$ represent the unit axes in the ABF coordinate system. The Cartesian surface location, $\vec{r}$, needed for computation of the gradient is obtained by using the local radius function at the specified latitude and longitude, then performing a conversion from spherical to Cartesian coordinates.

The ray intersection problem for the triaxial ellipsoid may be solved by first transforming to a space where the ellipsoid is a unit sphere. This is done using the mapping,

$$\vec{r}' = \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} x/a \\ y/b \\ z/c \end{bmatrix} \tag{18}$$

so that Eq.(1)-(2) may be written as,

$$\vec{r}_I' = \vec{r}_o' + \alpha\, \vec{d}', \tag{19}$$

$$S\left(\vec{r}_I'\right) = x_I'^2 + y_I'^2 + z_I'^2 - 1 = 0. \tag{20}$$

Equations (19)-(20) may be solved for α to yield,

$$\alpha = \frac{-B \pm \sqrt{B - AC}}{A}, \tag{21}$$

where,

$$A = \left| \vec{d} \right|^2,$$
$$B = \vec{r}' \bullet \vec{d}',$$
$$C = \left| \vec{r}' \right|^2 - 1.$$

There may be zero, one or two solutions to Eq.(21) depending the value of the quantity $(B - AC)$. If two solutions exist, the ray passes through the interior of the ellipsoid. If one solution exists, the ray is tangent to the ellipsoid and if no solutions exist, the ray does not intersect the ellipsoid.

The tangent problem may be solved by first applying the mapping described by Eq.(18) to the tangency condition of Eq.(3) which is simplified into a linear equation by this substitution. The resulting system of equations to be solved is,

$$\vec{r}_o'' \bullet \vec{r}_T = 1, \tag{22}$$
$$\vec{m} \bullet \vec{r}_T = 0, \tag{23}$$
$$S\left(\vec{r}_T\right) = \frac{x_T^2}{a^2} + \frac{y_T^2}{b^2} + \frac{z_T^2}{c^2} - 1 = 0, \tag{24}$$

where,

$$m = \begin{bmatrix} 1/a^2 \\ 1/b^2 \\ 1/c^2 \end{bmatrix},$$

$$\vec{r}'' = \begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix} = \begin{bmatrix} xm_1 \\ ym_2 \\ zm_3 \end{bmatrix}.$$

We also define the intermediary quantity

$$(\det) = \vec{n} \times \vec{r}'' . \tag{25}$$

The largest component of (det) in absolute value determines the coordinate index k in the equations below; i and j are the remaining components which are selected to preserve right-handedness of the coordinates (when k = 3, i = 1 and j = 2; when k = 2, i = 3 and j = 1; when k = 1, i = 2 and j = 3). This rotation of indices is performed to avoid numerical problems with may be associated with dividing by a component of the (det) vector. We note that the (det) vector is actually the set of possible determinants of the linear system of Eq.(22)-(23). The solution to the full set of equations may now be written as

$$\left(r_T\right)_k = \frac{-B \pm \sqrt{B^2 - AC}}{A}, \tag{26}$$

$$\left(r_T\right)_i = \frac{-n_j + \left(r_T\right)_k (\det)_i}{(\det)_k}, \tag{27}$$

$$\left(r_T\right)_j = \frac{-n_i + \left(r_T\right)_k (\det)_j}{(\det)_k}, \tag{28}$$

where,

$$A = m_i (\det)_i^2 + m_j (\det)_j^2 + m_k (\det)_k^2 ,$$
$$B = m_j n_i (\det)_j - m_i n_j (\det)_i ,$$
$$C = m_j n_i^2 + m_i n_j^2 + (\det)_k^2 .$$

Since the triaxial ellipsoid is everywhere convex in shape, no elevation mask can be computed for locations on the surface based upon the definition of the shape of the central body.

Triangular Plate Model

The most useful shape model in general to support access calculations is a triangular plate model. This model is defined by N vertices and 2N-4 associated plates forming a completely enclosed surface. The geometry of each triangular plate is shown in Figure 4. Each plate j forms the base of a prism whose apex is at the origin of the ABF frame and has three associated vertices (denote by indices i = j1, j2 and j3). There are no overhanging plates (i.e., no plates for which the outward normal vector has a negative radial component with respect to the body center).

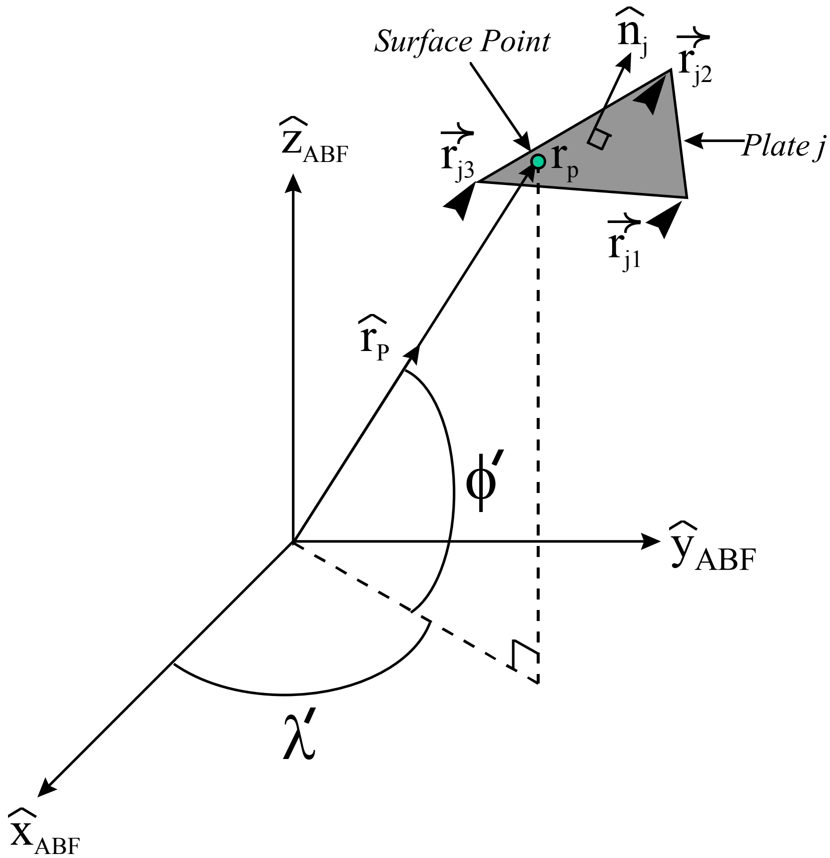

Figure 4. Geometry of a flat triangular plate

The plate model parameters will be provided via the Asteroid Shape File by the Jet Propulsion Laboratory (JPL) Navigation Team in conjunction with various Science Teams. New shape files will be supplied periodically throughout the NEAR mission to reflect new knowledge of asteroid topography derived from imaging and laser range finding.

Initially, a set of vertices and plates will be selected which approximates the aforementioned triaxial ellipsoid. The process of refining this model will begin with the orbit phase of the NEAR mission. Over time the model will be "sculpted", as more knowledge of asteroid shape is accumulated from images. This sculpting process will entail stretching or shrinking the radii of established vertices and, if needed, subdividing plates by addition of new vertices with appropriate lengths.

For the triangular plate model, the problems of computing the local radius of the central body and computing the local surface normal begin with determining on which plate the point of interest lies. Let $\hat{r}_p$ represent the unit vector, pointing in the direction of the surface point. There will be one and only one plate whose associated prism encloses the pointing direction as indicated by $\hat{r}_p$. Searching for this plate can be facilitated by storing the vertices of the plates according to their location on the surface of the body and applying simple filters to minimize the number of plates which need to be checked in detail. One simple method of filtering is to eliminate plates whose vertices satisfy the condition $\hat{r}_{ji} \bullet \hat{r}_P < \cos\delta\theta$ for i = 1, 2 and 3. The critical angle, $\delta\theta$, must be large enough such that the enclosing plate is not unintentionally eliminated (e.g., $\delta\theta \cong 10°$). Consider normal vectors for the sides of a prism:

$$\vec{n}_{j12} = \vec{r}_{j1} \times \vec{r}_{j2}, \tag{29}$$

$$\vec{n}_{j23} = \vec{r}_{j2} \times \vec{r}_{j3}, \tag{30}$$

$$\vec{n}_{j31} = \vec{r}_{j3} \times \vec{r}_{j1}. \tag{31}$$

The following conditions must hold such that $\hat{r}_P$ is enclosed in the prism corresponding to plate j:

$$sign\left(\vec{n}_{j12} \bullet \hat{r}_P\right) = sign\left(\vec{n}_{j12} \bullet \vec{r}_{j3}\right), \tag{32}$$

$$sign\left(\vec{n}_{j23} \bullet \hat{r}_P\right) = sign\left(\vec{n}_{j23} \bullet \vec{r}_{j1}\right), \tag{33}$$

$$sign\left(\vec{n}_{j31} \bullet \hat{r}_P\right) = sign\left(\vec{n}_{j31} \bullet \vec{r}_{j2}\right). \tag{34}$$

Once plate j has been determined, the radial distance $\left|\vec{r}_P\right|$ from the origin to the surface point located at latitude Φ' and longitude λ' can be expressed in terms of the plate normal $\hat{n}_j$ (derived from the normal function), the surface point direction $\hat{r}_P$ and any one of the three vertex locations ($\vec{r}_{jk}$ where k = 1, 2 or 3):

$$\left|\vec{r}_P\right| = \frac{\hat{n}_j \bullet \vec{r}_{jk}}{\hat{n}_j \bullet \hat{r}_P}. \tag{35}$$

The surface normal, $\hat{n}_j$, is compute as

$$\hat{n}_j = \pm \frac{\left[\vec{r}_{j2} - \vec{r}_{j1}\right] \times \left[\vec{r}_{j3} - \vec{r}_{j2}\right]}{\left|\left[\vec{r}_{j2} - \vec{r}_{j1}\right] \times \left[\vec{r}_{j3} - \vec{r}_{j2}\right]\right|}, \tag{36}$$

where the sign is chosen to satisfy the condition that $\hat{n}_j \bullet \vec{r}_{j1} > 0$.

For the ray intersection problem, the methodology for determining the correct plate for the local radius computation can also be applied. That is, for an observer at a point other than the body center, an observed location on the asteroid surface can be determined by first translating the plate model into observer-centered coordinates and then applying the same algorithm for the local radius function, which calls for searching through some reasonable subset of candidate plates to identify the plate which is intersected. However, unlike the body -centered geometry, more than one plate can be included along a given line of sight. Of course, the relevant point on the observed plate is the one for which $\left|\vec{r}_P\right|$ is minimized. A secondary intercept point is not calculated in the case of the plate model. It is also possible that a line of sight may not intercept any plate, in which case no intersection has occurred.

The computation of tangent points using the triangular plate model begins with initial estimates of $\vec{r}_T$ based on the ellipsoid model. A pointing direction relative to the location of the observer, $\vec{r}_o$, is then defined as

$$\vec{r}_{look} = \frac{a\vec{r}_T - \vec{r}_o}{\left| a\vec{r}_T - \vec{r}_o \right|} \tag{37}$$

for use with the ray intersection function described above, where the scaling parameter a is initially set to 1. A binary search algorithm is then employed with Δa set to some initial value (e.g., $\Delta a = 0.1\,a$). The ray intersection function is invoked repeatedly with $a_{new} = a + \Delta a$ until the limb location is determined from the ray intersection within a certain threshold. When a particular pointing does not intersect the asteroid after previously intersecting it or a particular pointing does intersect the asteroid after previously not intersecting it , then Δa becomes $\Delta a_{new} = \Delta a / 2$ prior to the next adjustment of the scaling parameter a.

An elevation mask, specifying the minimum elevation for a range of azimuths for each plate and vertex, can be retrieved for a specified surface location, based on the triangular plate shape model for the asteroid. Elevation mask information supports access determination relative to a specific surface location on the asteroid. For the NEAR mission, JPL Navigation will periodically provide a file specifying the latest asteroid shape model. This file must be read and processed using an external utility to regenerate the elevation mask for each plate and vertex. The Programmer's Library function will select the appropriate elevation mask based on the associated plate and proximity to a vertex. The vertex elevation mask is used whenever the position specified is close to a vertex; otherwise, the elevation mask associated with the plate center is chosen.

Spherical Harmonics

A shape model based on spherical harmonics has less utility than the other shape models identified above. This model does not lend itself well to supporting calculation of ray intersections or tangent vectors. It is useful primarily from the standpoint of providing a smoothed representation of local surface features for purposes of calculating vectors normal to the surface for defining various illumination angles.

This shape model would evolve in a manner consistent with the triangular plate model, starting at the beginning of the orbit phase of the NEAR mission. The spherical harmonic coefficients and parameters will be provided via the Asteroid Shape File by JPL Navigation in conjunction with various Science Teams. Since this model has not been fully implemented, it will not be discussed any further at this time.

SPACECRAFT EPHEMERIS

Spacecraft Ephemeris information is stored and retrieved in the same manner as asteroid ephemeris information (i.e., as an SP-kernel). Normally, the ephemeris is retrieved in J2000 Asteroid Centered Inertial (ACI) coordinates for use with the asteroid-centered application. This information is converted to an ASCII format by an external utility before being read into STK. Spacecraft ephemeris information is associated directly with the NEAR vehicle and does not require a Programmer's Library function to support it. However, in the future, additional functions may be developed to read spacecraft ephemeris data directly from the SP-kernel. New spacecraft ephemerides will be supplied periodically throughout the NEAR mission to reflect the effects of various propulsive maneuvers.

REPORT GENERATION

The generic reporting and graphing functionality of STK has been extended through the Programmer's Library to provide reports of specific interest to the NEAR mission. Two types of additional data were desired for reporting purposes. The first type of data is geometrical information which may be derived from the position and attitude data for the NEAR spacecraft. The solar panels and the high gain antenna are both oriented along the spacecraft Z axis. The angles between the spacecraft Z axis and the vectors from the spacecraft to the Earth and Sun are of interest for link budget and power considerations, respectively. The angle between the spacecraft X axis and the nadir vector, the nadir angle, may be important in terms of identifying targets of opportunity during periods when the spacecraft high-gain antenna (aligned with Z-direction) must be pointed at the Earth to downlink science and other data. The phase angle, which is defined as the angle between the vectors to the Sun and spacecraft subtended at the asteroid center of mass, is important for evaluating the orientation of the orbit plane in reference to lighting conditions on the surface of the asteroid. These data elements have been grouped into a data providing function associated with vehicles within STK and may be combined with other types of vehicle information in user specified formats. A sample report is shown in Figure 5.

Time (UTCG)	Earth to Z Axis (deg)	Sun to Z Axis (deg)	Phase Angle (deg)
1 Mar 1999 00:00:00.00	5.916	4.485	94.351
1 Mar 1999 00:02:00.00	5.916	4.485	94.350
1 Mar 1999 00:04:00.00	5.917	4.486	94.349
1 Mar 1999 00:06:00.00	5.918	4.487	94.349
1 Mar 1999 00:08:00.00	5.919	4.488	94.348
1 Mar 1999 00:10:00.00	5.921	4.489	94.348
1 Mar 1999 00:12:00.00	5.921	4.488	94.347
1 Mar 1999 00:14:00.00	5.921	4.488	94.345
1 Mar 1999 00:16:00.00	5.921	4.488	94.343
1 Mar 1999 00:18:00.00	5.921	4.488	94.342
1 Mar 1999 00:20:00.00	5.921	4.488	94.341
1 Mar 1999 00:22:00.00	5.921	4.489	94.339
1 Mar 1999 00:24:00.00	5.921	4.489	94.338
1 Mar 1999 00:26:00.00	5.921	4.490	94.338
1 Mar 1999 00:28:00.00	5.922	4.491	94.337
1 Mar 1999 00:30:00.00	5.922	4.492	94.336
1 Mar 1999 00:32:00.00	5.922	4.492	94.335
1 Mar 1999 00:34:00.00	5.922	4.492	94.333
1 Mar 1999 00:36:00.00	5.922	4.493	94.332
1 Mar 1999 00:38:00.00	5.922	4.493	94.331
1 Mar 1999 00:40:00.00	5.922	4.493	94.329

Figure 5. Sample report containing angles of interest for the NEAR mission

The second type of additional data for reporting is useful in the analysis of lighting conditions for data collection opportunities. The incidence angle is defined as the angle between the normal to the surface of the asteroid and the vector to the sun subtended at the location of a target on the surface. The emission angle is defined as the angle between the normal to the surface of the asteroid and the vector to the spacecraft subtended at the location of a target on the surface. These angles are the compliments of the solar elevation angle and the elevation angle of the spacecraft relative to the target which are available in STK. A simple data providing function was added to allow the reporting of these angles in association with accesses determined between the NEAR spacecraft and targets on the surface of the asteroid.

THE ROLE OF STK IN THE NEAR MISSION

STK will be available to perform several tasks in support of the NEAR mission. STK will serve as a backup/verification tool for opportunity analysis. The goal of this process is to develop a prioritized list of opportunities which can be compared against observation requirements laid down by Navigation and various Science Teams to facilitate sequence planning for the science instruments, including the Multispectral Imager (MSI), NEAR Infrared Spectrometer (NIS), X-Ray and Gamma-Ray Spectrometers (XGRS) and, to a lesser degree, the NEAR Laser Rangefinder (NLR) and Magnetometer (MAG). Access computations to points on the surface of the asteroid will be able to take into account the observation masks defined by the shape of the central body as well as lighting conditions and many other possible geometrical constraints. The access calculations allow baseline timing constraints to be established on the basis of a known or assumed spacecraft orbit.

STK/VO, STK with the 3-D Visualization Option, will also be available for use as a visualization/demonstration tool to allow mission operators and analysts to achieve better understanding of the geometrical constraints and relationships associated with the NEAR mission.

STK will be made available to the APL Mission Operations and Design Teams and Cornell MSI/NIS Science Team. In addition to use during the rendezvous and orbit about 433 Eros, STK will be useful for the analysis of the flyby of the asteroid 253 Mathilde. This flyby is scheduled to occur on June 27, 1997[5].

RESULTS

Importing the data describing the dynamics of the Eros asteroid and the NEAR spacecraft has presented no significant problems. The triaxial ellipsoid model for the shape of the asteroid has proven, as expected, to give very good performance during animation of the mission. The performance during animation of the triangular plate model is much less desirable. The drop in computational performance is due to the need to determine the plate of interest as part of the local radius, ray intersection and tangent algorithms. The efficiency of access computations is affected by the presence of elevation mask data when the triangular plate model is used. The software for describing the shape of the asteroid was designed to allow for a hybrid approach. This means that the triangular plate model of the shape of the asteroid can be used for visualization of the asteroid shape and access computations while the triaxial ellipsoid model is used to support animation graphics such as the depiction of sensor fields of view on the surface of the asteroid.

The modeling of a central body whose shape is so far from being spherical also served to bring to light any spherical body assumptions that were made within STK. Without exception, these assumptions of a nearly spherical central body were made in the graphics and visualization software. All but two of these problems have been corrected up to the time of this paper. The two remaining issues are the projection of a sensor field-of-view which leaves the surface of the central body in multiple, but not all, locations and the projection of the umbra and penumbra boundaries to an altitude above the surface of the central body. Examples of the visualization of the NEAR mission are given in Figures 6-9.

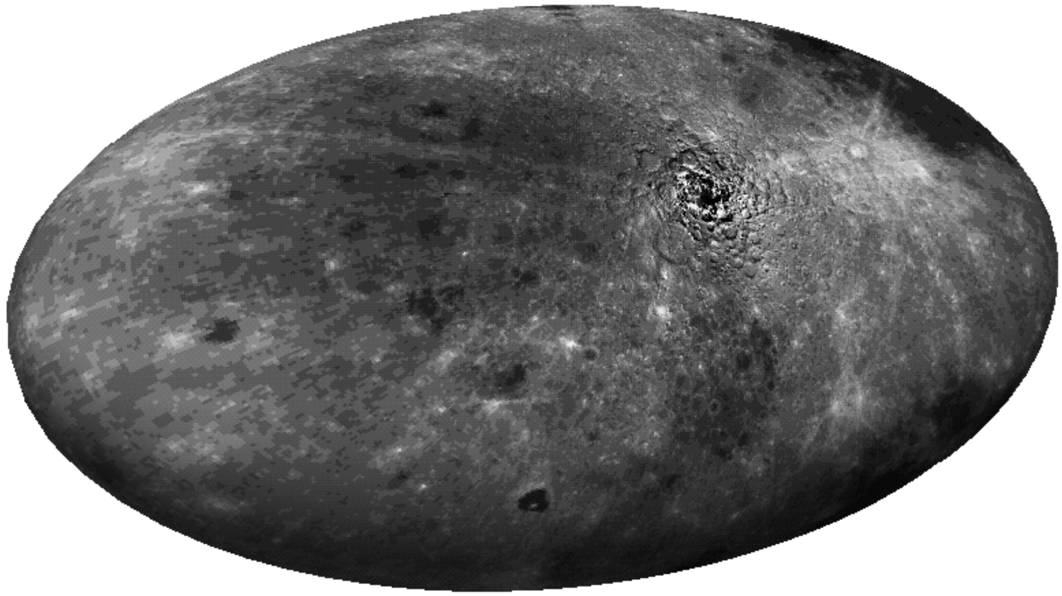

Figure 6. Eros using triaxial ellipsoid model with lunar texture

Figure 7. Eros using flat plate model with lunar texture

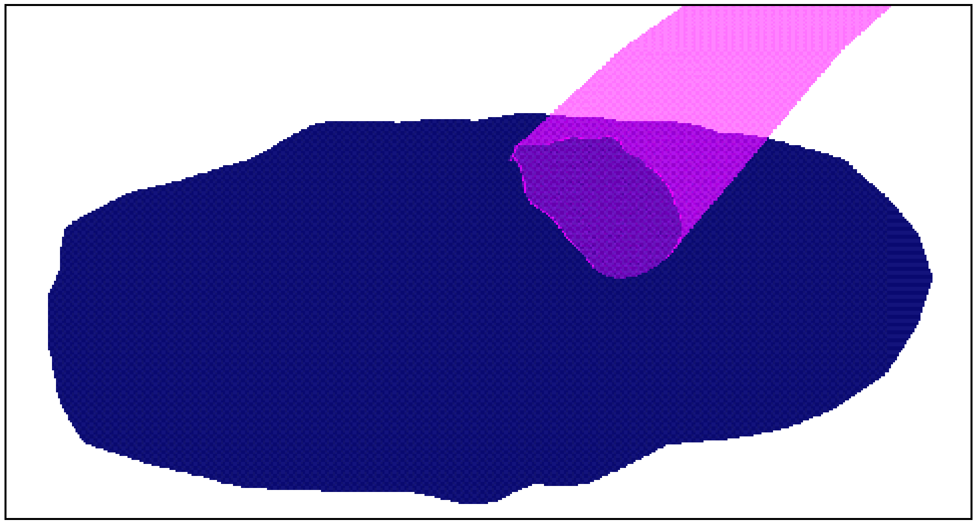

Figure 8. Intersecting sensor projection using the flat plate model

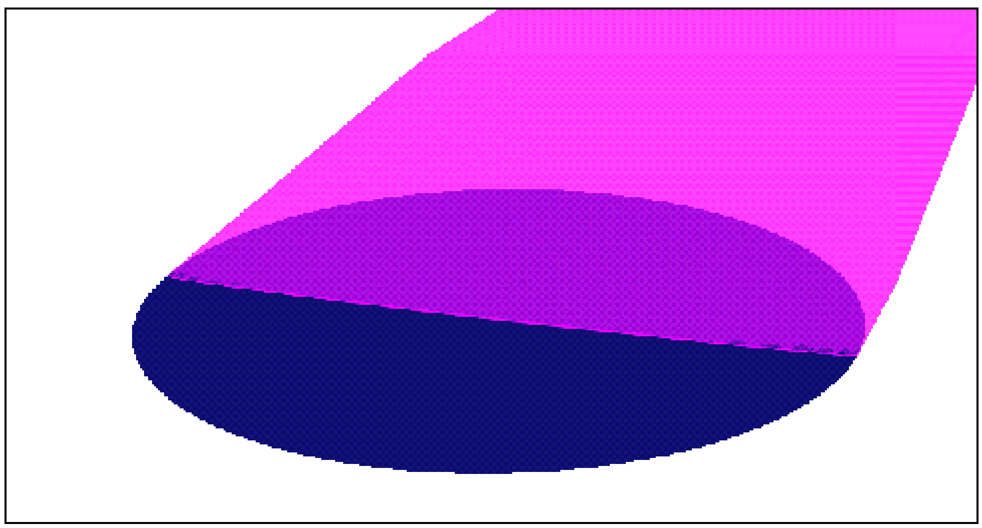

Figure 9. Tangent sensor projection using triaxial ellipsoid model

CONCLUSIONS AND FUTURE CONSIDERATIONS

STK, though the use of the Programmer's Library, has been proven to be useful tool for the visualization and analysis of missions where the spacecraft is designed to orbit about a central body other than the Earth. The off-the-shelf characteristic of STK allows for a low cost solution to many of the analysis needs for planetary missions with short development timelines.

The computational efficiency of the triangular plate model may be able to be improved through the application of a more efficient search algorithm. It is felt that since the system of dynamic objects is small (one spacecraft and a small number of sensors) that a moderate improvement in the efficiency of this model will make it a viable candidate for use during animation as well as being the preferred model for opportunity analysis.

There are some additional sources of information from at APL and other components of the NEAR mission which may be utilized in the future. For instance, there is the possibility of updated texture maps from Science Data Center (SDC) Catalog, derived from MSI images and associated NEAR Infrared Spectrometer (NIS) data. Such texture maps could be overlaid on the surface of Eros, as viewed within STK/VO.

Modifications are planned to add the capability to read SPICE kernels directly from STK. This would remove some intermediary processing that is currently necessary and allow for the importing of other data such as instrument fields of view. Spacecraft attitude information could be utilized to support more detailed sequence planning. Spacecraft attitude data is accessible in the form of SPICE C-kernels and real-time telemetry which may be piped directly from the NEAR Ground System to STK via a UNIX socket.

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