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IMPACTOR SPACECRAFT TARGETING FOR THE DEEP IMPACT MISSION TO COMET TEMPEL 1*

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The engineering goal of the Deep Impact mission is to impact comet Tempel 1 on July 4, 2005, with a 370 kg active Impactor spacecraft (s/c). The impact velocity will be just over 10 km/s and is expected to excavate a crater of approximately 20 m deep and 100 m wide. A second spacecraft, the Flyby s/c, is responsible for delivering the Impactor spacecraft and will perform a slowing maneuver, following Impactor release, to observe the impact event, ejecta plume expansion, and crater formation, which will take place over a period of approximately 800 seconds. The science objective is that of exposing the interior material and understanding the properties of the nucleus. Deep Impact will use the autonomous optical navigation (AutoNav) software system to guide the Impactor s/c to Tempel 1 intercept at a location that is illuminated, while the Flyby s/c uses identical software to determine its comet-relative trajectory in order to provide the attitude determination and control system (ADCS) with the relative position information necessary to point the High Resolution Imaging (HRI) and Medium Resolution Imaging (MRI) instruments at the impact site during encounter. There are two key science epochs that drive system performance during the encounter: 1) Time of impact (TOI) when impact event imaging occurs; and 2) Time of final crater imaging (TOFI) where the highest resolution images of the fully developed crater are obtained using the MRI and HRI instruments on the Flyby s/c. These two science epochs require both an impact in an illuminated area and good knowledge of the impact site. This paper describes the Impactor s/c autonomous targeting strategy including image processing and navigation (trajectory estimation and maneuver computation). Impactor s/c system performance is based on Monte Carlo analyses and MATLAB simulation, which allows for study of the targeting sensitivity to different image processing algorithms, nucleus topography, lighting conditions, and attitude determination and control system performance.

INTRODUCTION

Mission Overview

Deep Impact is a dual spacecraft mission planned for launch in January 2005 with the engineering goals of impacting comet Tempel 1 on July 4, 2005, observing the impact event and ejecta plume expansion, and obtaining high resolution images of the fully developed crater using the Medium Resolution Imager (MRI) and the High Resolution Imager (HRI) on the Flyby s/c for the scientific purpose of exposing and understanding the interior composition of a comet nucleus.

After a brief 6 month cruise, the two spacecraft will separate 24 hrs prior to the expected time of impact (TOI). The encounter geometry will result in an illumination phase angle of approximately 65° for the Tempel 1 nucleus, which may induce self-shadowing depending on the shape of the nucleus. The Flyby s/c will perform a slowing maneuver with a ΔV of approximately 102 m/s to provided 800 ± 20 sec of

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post-impact event imaging and control the flyby miss-distance to 500 ± 50 km. During the first 22 hrs following release, the Impactor s/c will acquire and telemeter science and navigation reconstruction images to the ground using the Flyby s/c as a bent-pipe relay. The Flyby s/c will also acquire and telemeter MRI and HRI visible and HRI infrared (IR) images of the nucleus and coma.

Starting 120 min (2 hrs) before TOI, the autonomous phase of the encounter will begin. The type of autonomy may be classified as scripted autonomy.[1] A critical sequence running on-board Impactor s/c will spawn a science and navigation subsequence that issues ITS commands to produce navigation images at a 15 sec interval. The Autonomous Navigation (AutoNav) software[2,3] was originally developed for the Deep Space 1 (DS1) mission and will processes these images to form observations for the purpose of trajectory determination (OD). OD updates will be performed every minute. Four (4) impactor targeting maneuvers (ITM) will be computed by AutoNav and executed by the Attitude Determination and Control System (ADCS): ITM-0 at E-23:25 m (E- designates before impact), ITM-1 at E-100 min, ITM-2 at E-35 min, and ITM-3 at E-9 min. At E-2 min, the Impactor ADCS will point the ITS along the AutoNav estimated comet-relative velocity vector to capture and telemeter high resolution (20 cm) ITS images of the impact site prior to impact. Table 1 lists the key activities for the Impactor s/c during encounter. Meanwhile, the AutoNav software on the Flyby s/c is processing MRI images of the comet every 15 sec and updating the trajectory of the Flyby s/c every minute to continuously point the MRI and HRI instruments at the nucleus. Figure 1 shows a schematic diagram of the encounter activities.

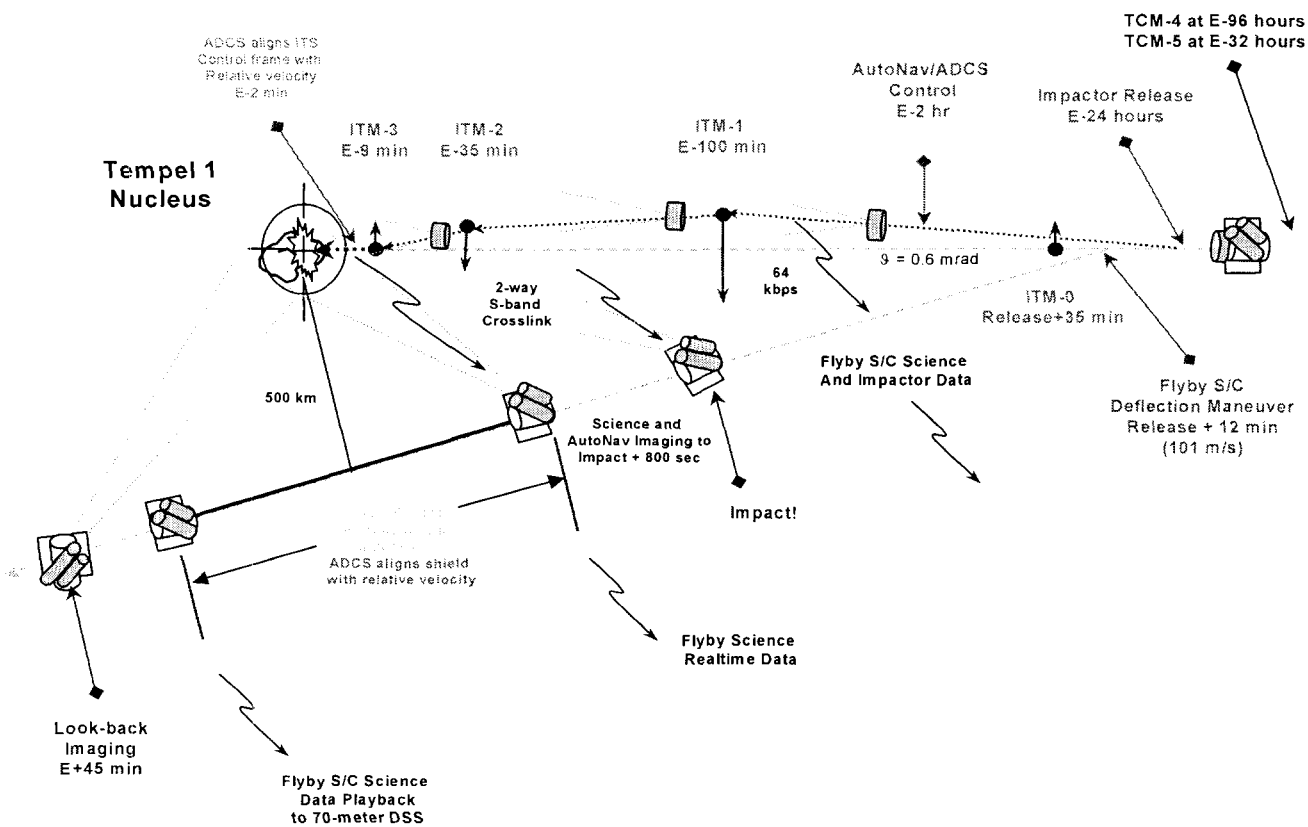

Figure 1 Tempel 1 encounter schematic for the Deep Impact mission

Table 1
Key events for the Impactor s/c during the 24 hr encounter with comet Tempel 1

Event Description		Cmd Issued (HH:MM:SS.S)
Begin Critical Engineering - RELEASE		00:00:00.0
ADCS Rate Capture		00:05:00.0
S-Band Lock-Up		00:07:00.0
ITM-0		00:25:00.0
Spawn ITS Imaging SubSequence A		00:50:00.0
Begin AutoNav/ADCS Terminal Guidance		22:00:00.0
ITM-1		22:20:00.0
Resume AutoNav Commanding		22:25:00.0
ITM-2		23:25:00.0
Resume AutoNav Commanding		23:30:00.0
Command Scene Analysis Images		23:49:00.0
ITM-3		23:51:00.0
Resume AutoNav Commanding		23:54:00.0
Transition to Image Impact Attitude		23:58:00.0

Impactor Spacecraft Flight System

The Impactor spacecraft, shown in Figure 2, was designed and built at Ball Aerospace Technologies Corporation (BATC) and consists of a battery for power after release, a RAD750 computer (SCU) for processing, an Impactor targeting sensor (ITS) composed of a simple inverting telescope and CCD detector, an S-band communications link to the Flyby s/c, a 3-axis stabilized rate control system (RCS), a 4 divert/4 RCS thruster hydrazine propulsion system with a ΔV capability of 25-30 m/s, and an ADCS system that estimates the IERS celestial reference frame (ICRF) attitude based on observations from a single StarTracker, rates and linear acceleration from an Inertial Reference Unit (SSIRU). The mass of the s/c will be approximately 370 kg with an all-copper fore-body cratering mass.

The ITS camera has a 12 cm aperature (73.5 cm^2 collecting area with 35% obscuration), a focal length of 1.2 m and a 10 milliradian (mrad) field-of-view (FOV). The 1024x1024 pixel CCD is a split-frame transfer device with electronics that provides 14-bit digitization (16384 DN full-well). The ITS serves a dual purpose: 1) provide navigation images and 2) provide pre-impact high resolution (20 cm) science images.

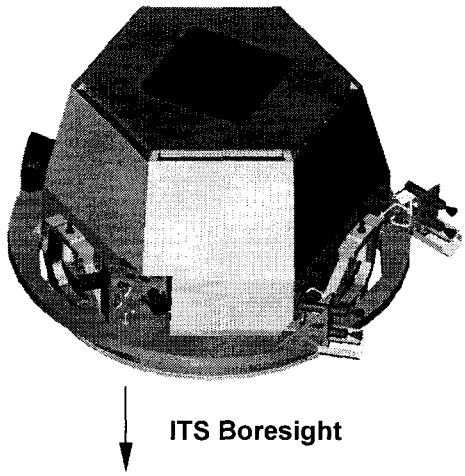

Figure 2 Impactor s/c flight system configuration[4]

Selection of the Impactor Targeting Strategy

Guidance control laws, both general and specific to the particular thrust or control system and measurement system, have been developed for several interceptor designs[5]. There are two basic principles: 1) Tactical homing missiles that use "proportional navigation" or "augmented proportional navigation" techniques, and 2) Strategic interceptors that use either proportional navigation or "predictive guidance" techniques. Ref. 5 discusses the concept of "pulsed guidance", under the section related to predictive guidance.

The proportional navigation strategy is driven by measurement of the closing velocity and line of sight angular rates to control the acceleration via thrust vectoring; on the other hand, predictive guidance makes use of the dynamics (equations of motion) of both the target body and interceptor via state estimation using available measurements that can be related back to the state of the target or interceptor. The former is what can be considered a "non-dynamic" or "reduced-dynamic approach"; the latter is a dynamic approach, which has the advantage of being less susceptible to large, random errors in the observations. Based on the above definitions, the Impactor s/c for Deep Impact can be classified as a strategic interceptor that uses predictive, pulsed guidance (few discrete burns) to achieve impact at the desired location.

Considering the Impactor measurement system (ITS optical observations of the target body center of brightness); the Impactor targeting (maneuver) system characteristics; the well-know target body dynamics; the updating of the interceptor state based on the optical observations; and the use of a few, discrete, lateral burns (ITMs) based on the predicted s/c and target body locations at the time of intercept, the Impactor targeting strategy for Deep Impact is optimal according to Ref. 4.

It should be noted that the best quality optical observations are obtained during non-thrust periods, which suggests a pulsed guidance system, as has been selected, for the Impactor s/c. Though the apriori position of the target body has a fair bit of uncertainty, which is removed using optical navigation techniques, the dynamics are well-known, except that (an important exception) the nucleus rotational

dynamics and solar phase angle induced motion (acceleration) of the center of brightness (CB) with time can cause targeting errors in the impact location on the surface of the nucleus These are mitigated, to some extent, in the batch filtering process by selecting the appropriate arc length over which to perform an orbit solution. This suggests a predictive guidance strategy for Deep Impact and we selected a 20 min orbit determination arc length.

In summary, the Deep Impact Impactor s/c uses a predictive guidance strategy and pulsed guidance system by performing 3 lateral, discrete magnitude burns (ITMs) based on the integrated equations of motion of the Impactor s/c and the evaluated position of the target (apriori comet Tempel 1 ephemeris) at the time of impact to compute the "zero effort" miss distance which is then used to compute the magnitude and direction of each ITM to achieve impact.

AUTONOMOUS NAVIGATION

The autonomous navigation system for terminal guidance of the Impactor s/c relies on both the performance and interaction of the AutoNav and ADCS flight software and subsystems and the ITS camera. As previously mentioned, the AutoNav software was developed for the New Millineum Deep Space 1 (DS1) mission[2,3]. AutoNav consists of three (3) distinct modules: 1) Image processing; 2) Orbit determination; and 3) Maneuver computation. AutoNav was originally developed to operate in two different modes: 1) Star-relative which uses images that contain both the target body (beacon) and two or more stars for determining the orientation of the camera at the time of each image exposure; and 2) Starless which uses the ADCS estimated s/c attitude and camera alignment information to determine the orientation of the camera at the time of each image exposure. For Deep Impact, the Starless AutoNav mode is used based on the expected quality of the ADCS estimated attitudes. The combination of the CT-633 StarTracker and SSIRU rate sensor provides an estimated attitude bias of no more that 150 μrad (3σ), bias stability of 50 μrad/hr (3σ), and estimated attitude noise of 60 μrad (3σ)[6].

The steps involved in the Impactor autonomous guidance process are as follows:

1. Acquire ITS images of the comet nucleus, every 15 sec, starting 2 hrs before the expected time of impact
2. Process ITS images to compute pixel/line location of the nucleus center of brightness (CB)
3. Use observed CB pixel/line locations to compute measurement residuals for comet-relative trajectory estimation
4. Perform trajectory determination updates (OD), every 1 min, starting 1 hr 59 min before the expected time of impact
5. Perform three (3) Impactor targeting maneuvers (ITMs) at 100 min (ITM-1), 35 min (ITM-2), and 9 min (ITM-3) during the terminal guidance phase
6. Acquire ITS images for computing an Scene Analysis-based offset, relative to observed CB, just prior to ITM-3 maneuver computation and use the offset in the maneuver computation for ITM-3
7. Perform the final targeting maneuver (ITM-3) 9 min before predicted time of impact
8. Align the ITS boresight with AutoNav estimated comet-relative velocity vector starting 2 min prior to predicted time of impact to capture and transmit high-resolution images (20 cm resolution) of the nucleus surface

Processing ITS Images

Image processing for the AutoNav system serves the purpose of providing observations of the s/c comet-relative trajectory over time. When images are received by AutoNav, they can be processed in one of three ways: 1) Brightness centroiding of all pixels above a brightness threshold and within a predetermined pixel subregion (Centroid Box); 2) Image blobbing to detect one or more contiguous regions of pixel brightness above a brightness threshold and compute the pixel/line location of each blob based on a simple moment algorithm (Blobber); or 3) Scene analysis to compute the pixel/line offset, relative to the CB location as determined from either 1) or 2) above, of the region most suitable for an illuminated impact.

Brightness centroiding is the process of determined the center of brightness using a moment algorithm. The ITS images consist of an array of 1008x1008 pixels (when they arrive at AutoNav) with various brightness expressed as a data number (DN). Based on the best estimate of the s/c trajectory relative to the nucleus, a predicted pixel/line location is computed. All pixels in an NxN pixel region surrounding this predicted location are used and the center of brightness determined by summing brightness values in the pixel and line direction.

$$p_{sum} = \sum_i \sum_j (j) pic[i][j] \qquad l_{sum} = \sum_i \sum_j (i) pic[i][j] \ , \qquad sum = \sum_i \sum_j pic[i][j]$$

$$p_{center} = \frac{p_{sum}}{sum} \qquad l_{center} = \frac{l_{sum}}{sum}$$

Here, i denotes the pixel direction (column of the image array advancing left to right) and j denotes the line direction (row of the image array advancing from top to bottom). N is specified in an on-board parameters file. The brightness threshold can be a fixed value specified in the parameters file or based on a percentage of the peak pixel brightness. For Deep Impact we will use N=500 to cover uncertainties in the ADCS estimated attitude and take 35% of the peak pixel brightness as the brightness cutoff. The brightness cutoff removes both instrument noise that is not gain dependent as well as the signal from the dust or coma surrounding the nucleus.

The Blobber algorithm is well-known and makes use of brightness centroiding, but is different in that it first seeks and detects regions of contiguously lit pixels, then computes and returns the CB pixel/line location for each "blob" that is detected above the brightness threshold thus removing any dependence on AutoNav's ability to predict where the nucleus will be located in the image array. As will be discussed later, this approach has many advantages over the Centroid Box approach, but also has its own set of difficulties.

Scene Analysis was first developed by George Null and enhanced by Nickolaos Mastrodemos at the Jet Propulsion Laboratory specifically for the Deep Impact mission. *Mastrodemos* discovered that Scene Analysis, while improving the number of illuminated impacts, could drive the impact site to a region that is obscured from view as the Flyby passes beneath the nucleus depending on the orientation, size and shape of the nucleus, which led several enhancements. *Mastrodemos'* version provides AutoNav with the ability to target a specific illuminated location on the nucleus in a biased fashion. The biasing drives the site selection to a location that is biased toward the Flyby s/c's point of closest approach, thus

enhancing the ability of the Flyby s/c to imaging the fully developed crater at the time of highest resolution. Here, images are first processed using either the Centroid Box approach or the Blobber algorithm to provide a reference CB location. Scene analysis is applied and the pixel/line location of the selected site is returned. The difference between the CB reference location and the selected site is computed and converted to an inertial correction vector that is stored and used by the AutoNav maneuver computation software. If no suitable site is found, then no correction vector is returned which results in a default to targeting the CB.

Trajectory Determination

For the Impactor s/c, the trajectory is estimated and updated every minute during the last 2 hrs of encounter. The trajectory determination software supports both ADCS attitude control and AutoNav maneuver computations.

After images are processed, the important information needed to relate the observations back to the state of the spacecraft are stored in an optical navigation (OpNav) file. This information consists of the time the image was exposed, the camera inertial orientation (right ascension, declination, and twist), the pixel and line location of the observed CB, the data weight associated with a given observation and whether or not the observation was declared useful. When AutoNav receives the command to perform orbit determination, the best estimate of the s/c position and velocity is read from the orbit determination file. The trajectory is integrated, making use of on-board accelerometer data that is stored in a non-gravitational history file, to the time of each observation and the predicted pixel and line location of the nucleus center of mass is computed. The difference between the computed pixel/line location and the observed pixel/line location corresponding to the observations contained in the OpNav file represents the residual, which is minimized in a least-square sense using AutoNav's batch-sequential processing algorithm. The orbit determination (OD) arc length was selected to be 20 min for Deep Impact and with image processing every 15 sec, each OD arc contains 80 observations.

Following completion of each OD, the trajectory is updated and a representation of the estimated trajectory is generated in the form of Chebyshev polynomial coefficients (Chebys). These Cheby coefficients represent a time series prediction of the Impactor position relative to the nucleus and are passed to the ADCS flight software for evaluation and pointing control. ADCS evaluates the Chebys, computes the relative position vector and aligns the ITS camera boresight with the comet-relative position vector to center the nucleus in the instrument FOV.

Impactor Targeting Maneuvers

Impactor targeting maneuvers (ITM) are initiated via sequence command to AutoNav. These commands are issued from the critical sequence that will be running during encounter. When AutoNav receives the command, an impulsive maneuver (magnitude and direction) relative to the ICRF frame is computed for the time contained in the command packet and passed it to ADCS in the form of a command issued by AutoNav. ADCS receives the maneuver ΔV information in the command packet, computes the finite duration burn start time, and populates the necessary flight software current value table (CVT). When the CVT is populated, ADCS issues a command to spawn a trajectory correction maneuver (TCM)

transition sequence consisting of the following commands:

1. Disable AutoNav image processing
2. Command ADCS to transition (turn) to burn attitude
3. Reset accelerometer accumulated ΔV
4. Command ADCS to delta-V mode in preparation for ITM execution

The ADCS flight software continually monitors the accumulated ΔV information based on incremental ΔV values measured by the SSIRU accelerometers and continuously adjusts the pointing and thruster duty cycle until the accumulated ΔV matches the desired maneuver ΔV, which results in burn termination. When the burn is complete, ADCS returns to instrument point mode and issues another command to spawn a second TCM transition sequence to re-enable AutoNav image processing. The need for TCM transition sequences and for disabling AutoNav image processing arises from the non-deterministic burn duration of each ITM. This allows instrument commands for AutoNav images to be issued every 15 sec without regard to when a particular maneuver will occur or how long the burn will last. When image processing is disabled, AutoNav simply ignores the navigation images since the quality of images acquired during the burn may be degraded.

ITM-0

Just prior to separation of the Impactor s/c, the both the Flyby and Impactor ADCS actuators will be disabled for the release event. Following separation, the Impactor ADCS actuators are re-enabled to allow for RCS rate capture. The rate capture has the possibility of imparting as much as 10 cm/s crosstrack (lateral) ΔV since the rate capture is an unbalanced maneuver. Left uncorrected, this could result in a B-plane intercept error of more than 8 km. Figure 4 describes the B-plane and shows the miss parameter $\overline{B}$. Since this has the tendency to corrupt the Flyby pre-release delivery targeting and could take the Impactor off-course exposing the mission to failure should subsequent ITMs fail to be accomplished, ITM-0 will be performed. Figure 3 shows an ITS 25x25 pixel subregion surrounding the nucleus at the time of ITM-0. At this time, the nucleus is not spatially resolve (< 1 pixel), but the optical signal is spread over an area of 9 pixels due to the ITS optical properties (point spread function of 1.5 pixels). At this range, the performance of the ITS instrument is not sufficient to provide accurate optical observations for the purpose of trajectory determination to support ITM-0 and therefore we rely on the pre-release optical and radio data as well as the accelerometer measurements for trajectory integration and ITM-0 computation

The accuracy of each ITM is expected to be 2-3 mm/s (3σ) for a burn of 10 cm/s in magnitude[7]. For ITM-0 this maps to a B-plane intercept error of 252 m. ITM-0 will make use of the best pre-release estimate of the Impactor's post-release trajectory and its associated uncertainty from ground-based optical navigation. AutoNav will compute a targeting maneuver 25 min after release for execution at 35 min after release. AutoNav integrates the initial state to B-plane intercept using the on-board accelerometer data to account for the spring release event and rate capture. The associated covariance is mapped to the time of intercept and the B-plane miss distance is compared to the covariance. If the miss distance is greater than the error ellipse, then a maneuver is computed and returned to ADCS for execution, otherwise, AutoNav "waives" the maneuver by never returning a result to ADCS. If the lateral accelerations adversely affect the trajectory, then ITM-0 will be performed.

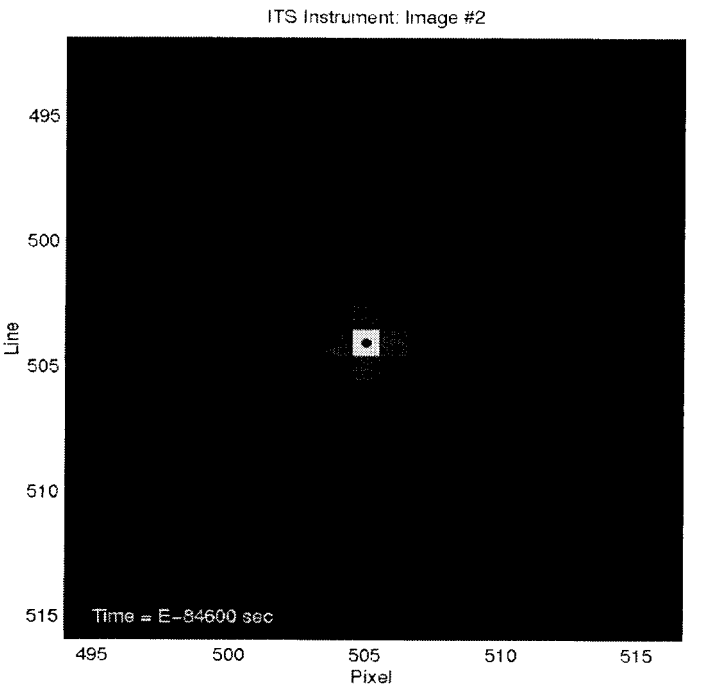

Figure 3 Simulated image of the comet nucleus at the time of ITM-0 (E-23 hrs 30 min)

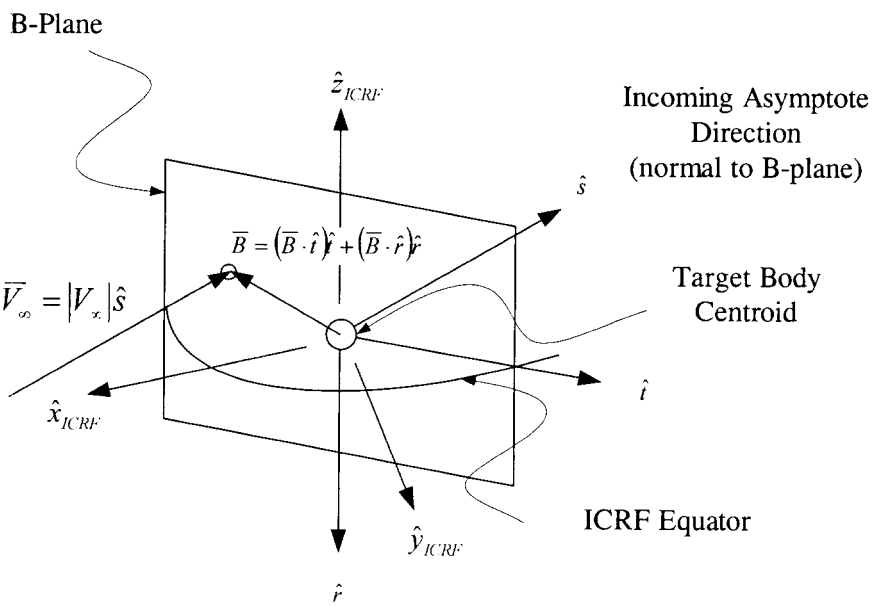

Figure 4 Definition and orientation of the B-plane relative to the International Celestial Reference Frame (ICRF)

ITM-1 (E-100 min)

The terminal guidance phase of the mission begins 120 min before impact. ITM-1 is the first targeting maneuver based on ITS observations and an updated trajectory. The primary purpose of ITM-1 is to remove the Flyby pre-release delivery errors while minimizing ΔV. ITS observations have to be good enough to provide improvement over the pre-release orbit determination, but waiting too long for ITM-1 increases the amount of ΔV required to remove the delivery errors that are expected to be 6 km (3σ) due to the quality of the Flyby approach phase optical navigation solutions. ITM-1 targets the nucleus CB (blue dot). Figure 5 shows a simulated image of the nucleus at a range of approximately 60,000 km. The optical signal from the nucleus spans approximately 10 pixels at the time of ITM-1.

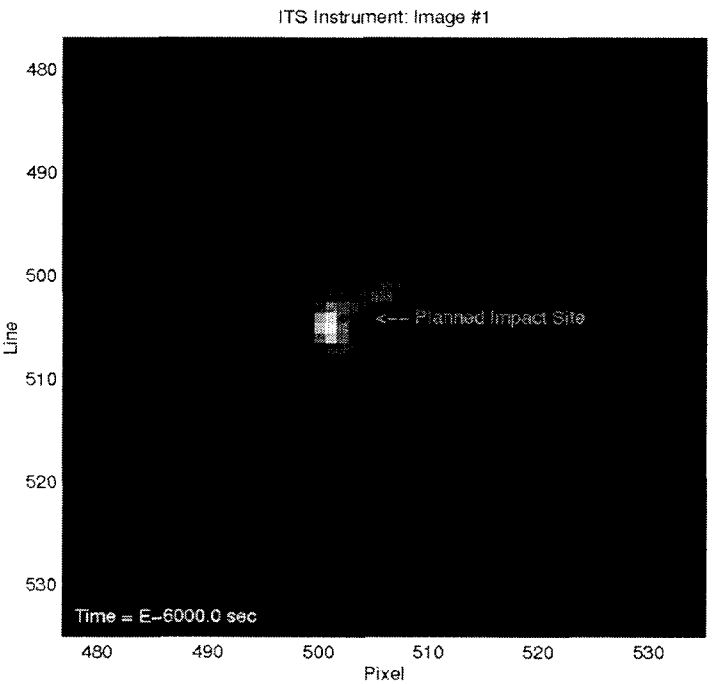

Figure 5 Simulated image of the comet nucleus a 65° illumination phase angle at the time of ITM-1 (E-100 min)

ITM-2 (E-35 min)

The second Impactor targeting maneuver, ITM-2, was placed at E-35 min to provide redundancy in the form of improved targeting over ITM-1 in the event ITM-3 fails. The trajectory solution is based on ever improving ITS observations of the nucleus. As seen in Figure 6, the nucleus spans more than 25 pixels. ITM-2 also targets the nucleus CB (blue dot).

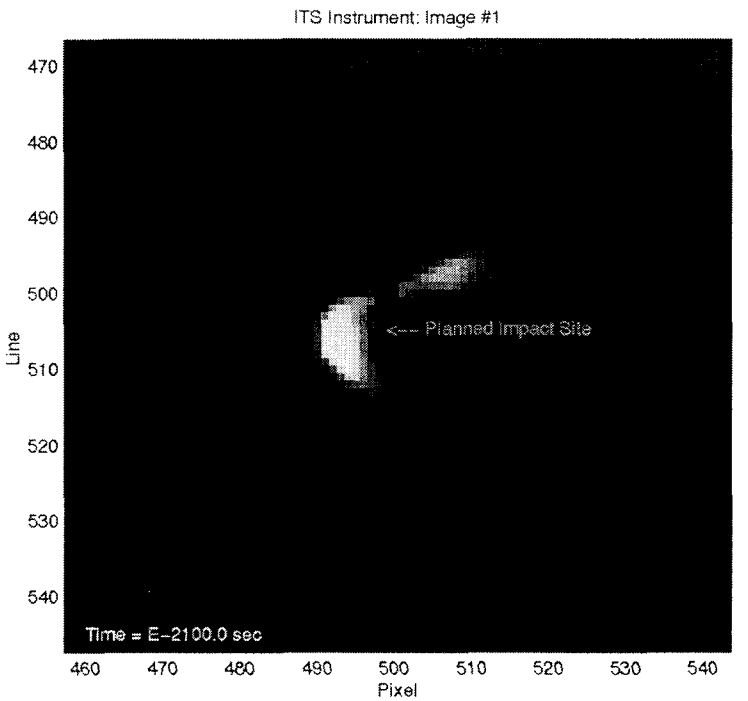

Figure 6 Simulated image of the comet nucleus with a 65° illumination phase angle at the time of ITM-0 (E-35 min)

ITM-3 (E-9 min)

The third and final Impactor targeting maneuver, ITM-3, is the most important and provides the fine targeting for an illuminated impact. The trajectory determination for ITM-3 is based on CB observations of the nucleus. However, at E-11 min a Scene Analysis image is sequenced to provide a targeting offset from the CB. This offset, as previously mentioned, provides an increased probability of an illuminated impact and increases the probability that the crater will be seen from the Flyby s/c at the time of highest resolution imaging. Figure 7 shows that the nucleus spans nearly 100 pixels at E-11 min. The blue dot represents the computed CB. The red "+" symbol and surrounding circle represent the Scene Analysis based selected impact site. It is important to note that for this nucleus orientation (particularly challenging), the CB lies in a shadowed region on the nucleus surface and would likely result in a dark impact. ITM-3 will nominally be centered at 9 min before impact. Placing ITM-3 as late as possible is ideal for minimizing maneuver computation errors and maneuver execution errors, however, the Impactor s/c is constrained by the amount of propellant (25 m/s ΔV capability) available for ITMs and the worst-case coma environment could result in ADCS control upsets due to particle impacts. To ensure a high-probability of successful maneuver completion it was determined that ITM-3 be completed prior to E-6 min or at a range of approximately 3600 km from the nucleus.

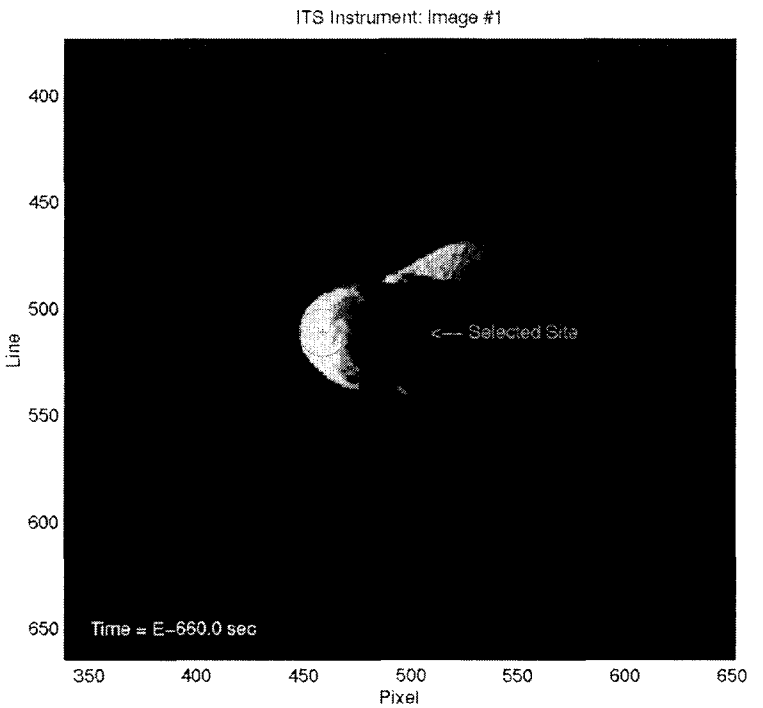

Figure 7 Simulated image of the comet nucleus with a 65° illumination phase angle at the time of Scene Analysis for ITM-3 (E-11 min)

IMPACTOR TARGETING ANALYSIS

A MATLAB simulator has been developed to test the performance of the Impactor targeting strategy and performance of the actual AutoNav flight code. The simulator creates images of the nucleus based on the true position of the s/c relative to the comet, the true attitude of the imaging instrument based on specified camera properties. The nucleus model for this analysis was developed by Robert Gaskell at the Jet Propulsion laboratory and is based on data acquired during the DS1 encounter with comet Borrelly in September 2001. The Borrelly nucleus model was accepted by the Science Team as the baseline model for Tempel 1 navigation analysis, which consists of Impactor targeting performance and Flyby instrument pointing performance. *Mastrodemos* performed an in-depth Monte Carlo analysis (not discussed here) and computed the targeting statistics for various nucleus orientations and rotation pole directions. The impact statistics were determined to be 99.98% (2 misses in 9000 simulation runs) based on CB observations and biased Scene Analysis targeting for ITM-3. Results from the MATLAB simulations discussed in this paper show good agreement with the results obtained by *Mastrodemos* for the two nucleus orientations that led to a miss or dark impact. The first of these orientations has the long axis of the nucleus in the ecliptic plane with the rotation axis normal to the ecliptic plane as seen in Figure 8. The second has the long axis of the nucleus normal to the ecliptic plane and rotation axis also normal to the ecliptic plane. The remaining discussion deals with the first nucleus orientation.

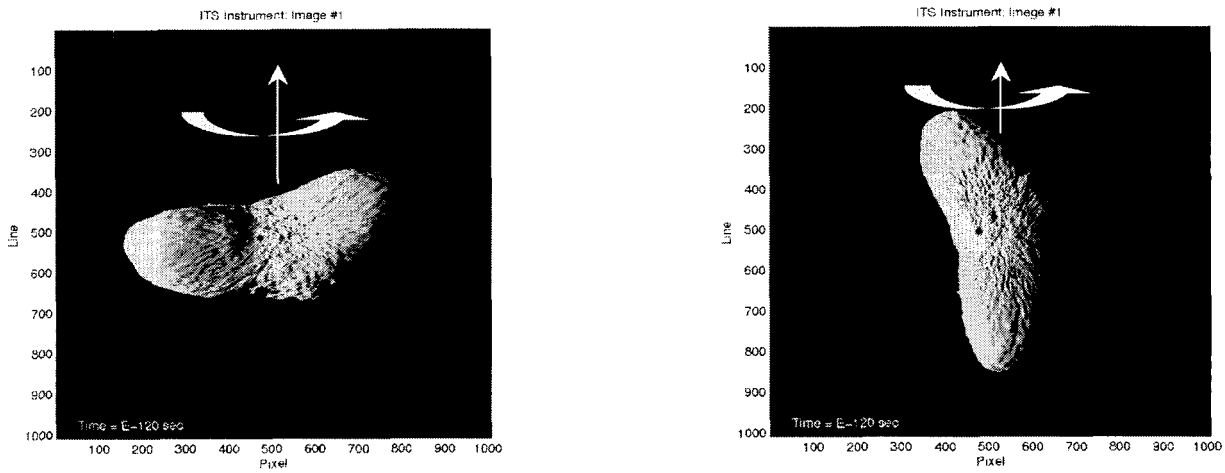

Figure 8 Two Borrelly model nucleus orientations that are particularly problematic for AutoNav. The first orientation has the long axis in the ecliptic plane (left); the second orientation has the long axis in normal to the ecliptic plane (right). Both rotate about the axis shown

AutoNav Performance Dependencies

The performance of the Impactor targeting is assessed via simulation "scorekeeping" images. The scorekeeping images are generated at E-30 sec and are based on ITS pointing along the truth comet-relative velocity vector. The center of the image is taken to be the true impact location from which a miss, dark, or illuminated impact is assessed. Here, by definition, an illuminated pixel is one where the DN value is greater than 0.01 x (peak pixel DN brightness value). If more than 80% of the pixels in a circle with a diameter of 90 m surrounding the impact site are illuminated, then the impact is considered to be a lit impact. The results taken from the scorekeeping images indicate a successful or unsuccessful targeting run and are influenced by several parameters:

1. Nucleus characteristics: size, shape, orientation, pole direction, rotational period
2. ADCS noise, bias, and bias drift performance
3. AutoNav trajectory determination performance
4. AutoNav maneuver computation performance
5. ADCS maneuver execution performance

The characteristics of the nucleus are essentially unknown, with the exception that the average radius, axial ratio, and rotational period have been studied for Tempel 1. The Deep Impact Science Team has estimated an average radius for Tempel 1 of approximately 3.0 km with a 2:1 axial ratio from ground-based observations. The Tempel 1 light curves suggest a rotational period of 42 hrs. The rotational period is of particular interest to the AutoNav systems engineers: when combined with the 65° phase angle and certain nucleus orientation, the rotation induces a shift in the CB over time due the change in shadowing conditions. This shift appears as a lateral velocity in the AutoNav observation time series and results in ITM computation errors by overestimating the Impactor's cross-track comet-relative velocity.

Similarly, ADCS bias drifts are not accounted for and instead of being modeled on the measurement side

of the estimation process, they find their way into the dynamics thru the estimated velocity and they result in ITM computation errors that can be unacceptably large. It turns out that the expected ADCS bias drift stability of 50 μrad/hr (3σ) results in lateral velocity errors that are dominated by the estimated lateral velocity errors due to nucleus rotation. Figure 9 shows the ITM-3 maneuver computation error and equivalent targeting error as a function of ADCS bias drift. For ADCS bias drift values less than 100 μrad/hr (3σ) the nucleus rotational dynamics dominates; beyond 100 μrad/hr (3σ), the ADCS bias drift is the dominant targeting error source as determined from Monte Carlo analysis (*Mastrodemos*).

One interesting point to note is that it seems intuitive that the larger the nucleus, the better from a targeting perspective. However, the combination of self-shadowing due to the 65° phase angle, uncertain nucleus shape model and nucleus rotation, can result in a higher rate of CB shift and a larger error in the estimated cross-track relative velocity for a larger nucleus target. This maps into a larger ITM-3 ΔV computation error.

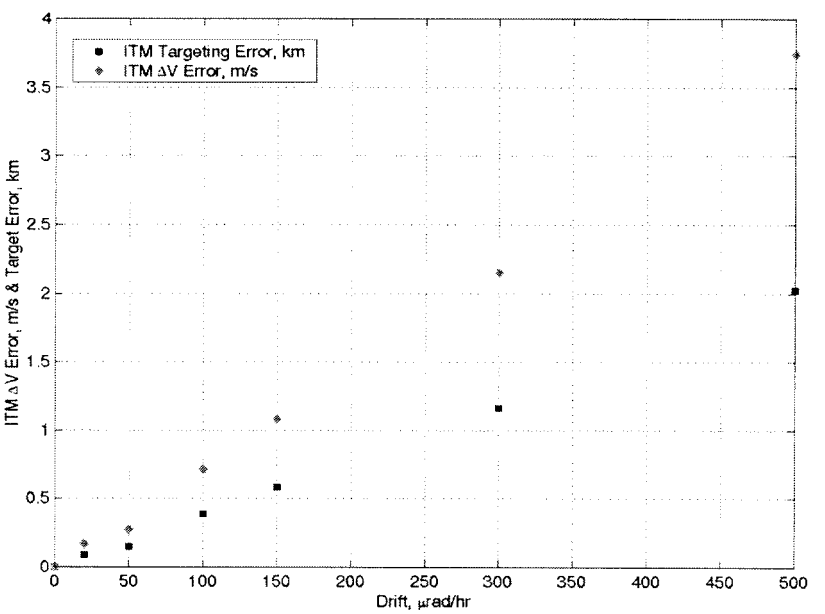

Figure 9 ITM-3 ΔV Error and resulting B-plane targeting error vs ADCS bias drift

Blobber vs Centroid Box

As previously described, the Blobber algorithm has the advantage of not being dependent upon apriori trajectory information, but simulations show a dependence on the lighting conditions (phase angle) that can lead to large targeting errors for certain nucleus orientations. The Centroid Box algorithm has it's own limitations in that it requires apriori knowledge of where the target will be located in the image, but performs satisfactorily when the box is sized to handle expected attitude and relative position uncertainties. Figure 10 shows the image that was used to compute the SA offset using the AutoNav Centroid Box algorithm on the left and the AutoNav Blobber algorithm on the right for a particular simulation run. Figure 11 shows the "scorekeeping" image that is used to assess whether or not the impact was illuminated, dark, or a miss altogether. Finally, Figure 12 shows the RMS of fit per OD

update during the 2 hr simulation run. The increase in the RMS of fit during the last 13 min of encounter, shown in Figure 13, indicates that this particular nucleus orientation is problematic when using the Blobber algorithm to compute the nucleus CB.

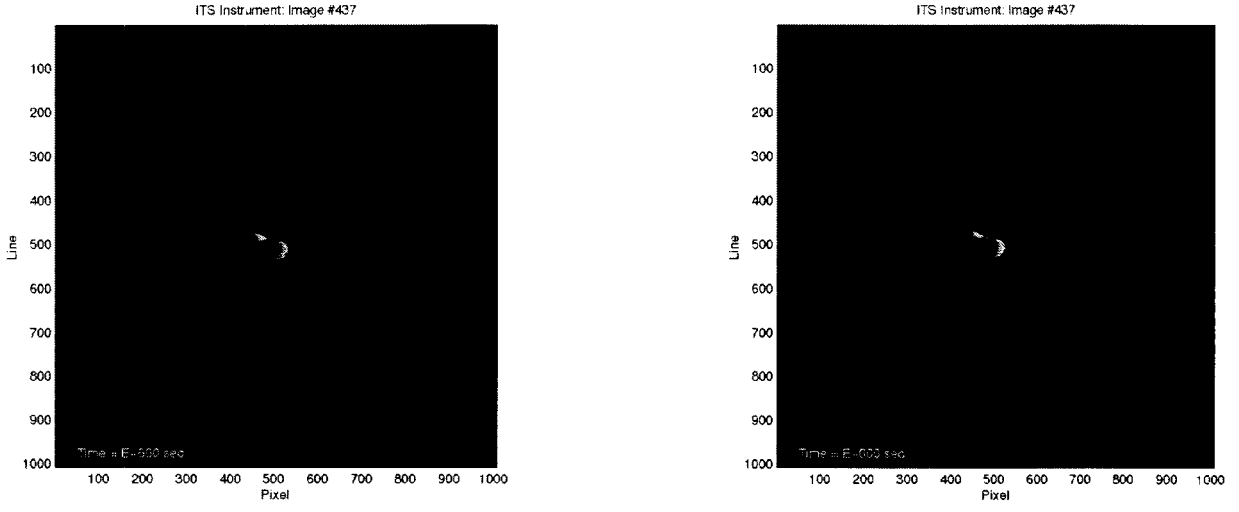

Figure 10 Scene Analysis image, showing the selected impact site, for simulation run using the centroid box algorithm (left) and the blobber algorithm (right) for computation of the CB location; same site is selected

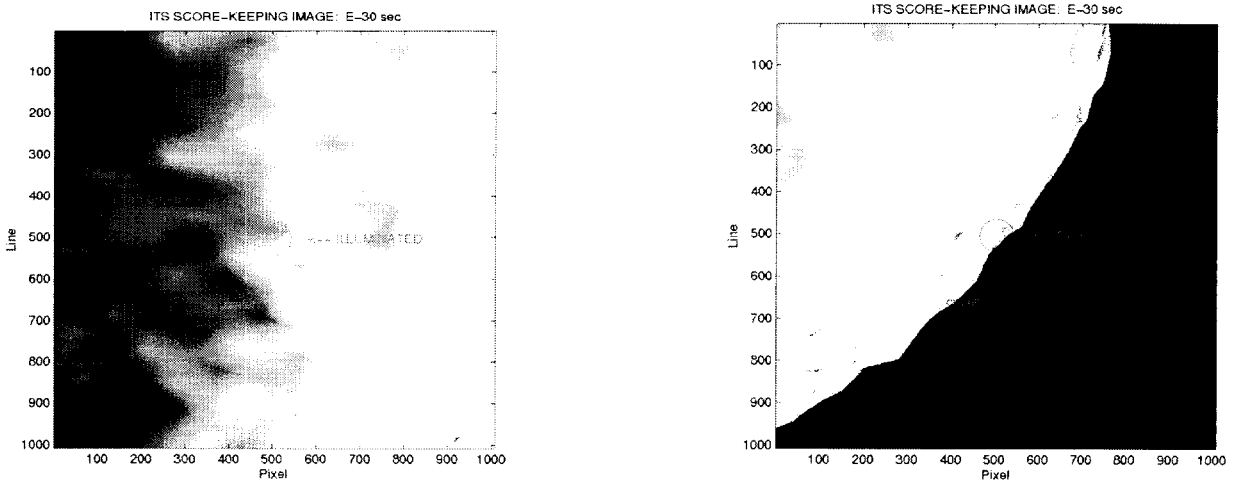

Figure 11 Simulated ITS scorekeeping image for the simulation run using the Centroid Box algorithm (left) and the Blobber algorithm (right) for computation of the CB location

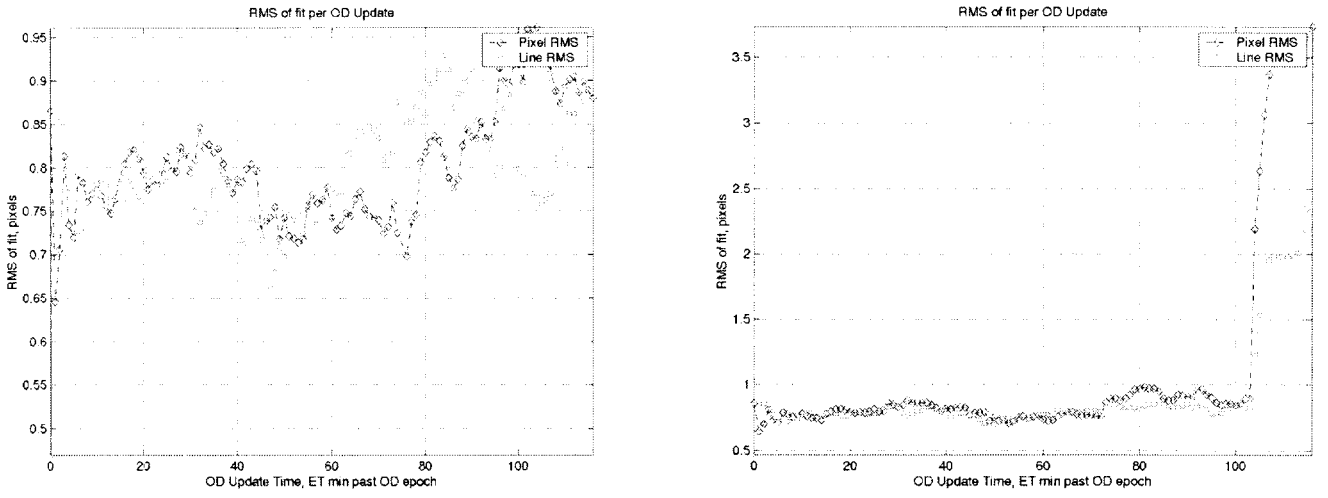

Figure 12 RMS of fit per OD update for the simulation run using the Centroid Box algorithm (left) and the Blobber algorithm (right) for computation of the CB location

Inspection of the RMS of fits reveals a sudden increase at approximately E-16 min. Figure 13 highlights the tenuous connection between two regions of contiguously lit pixels. This suggests that a hybrid approach may increase the robustness of AutoNav. Blobber should be used initially for the first 20 min of encounter to ensure AutoNav target lock followed by a transition to Centroid Box for ITM-2 and ITM-3 to ensure there are no sudden shifts in the observed CB due to the change in shadowing from nucleus rotation that results in either the formation of a bridge between two large areas or destruction of a small bridge connecting the two large areas of contiguously lit pixels. The ability to switch between Blobber and Centroid Box image processing was built into the instrument command packet information that tells AutoNav how a particular image is to be processed. This allows the sequence designer to control how and when the navigation images are processed.

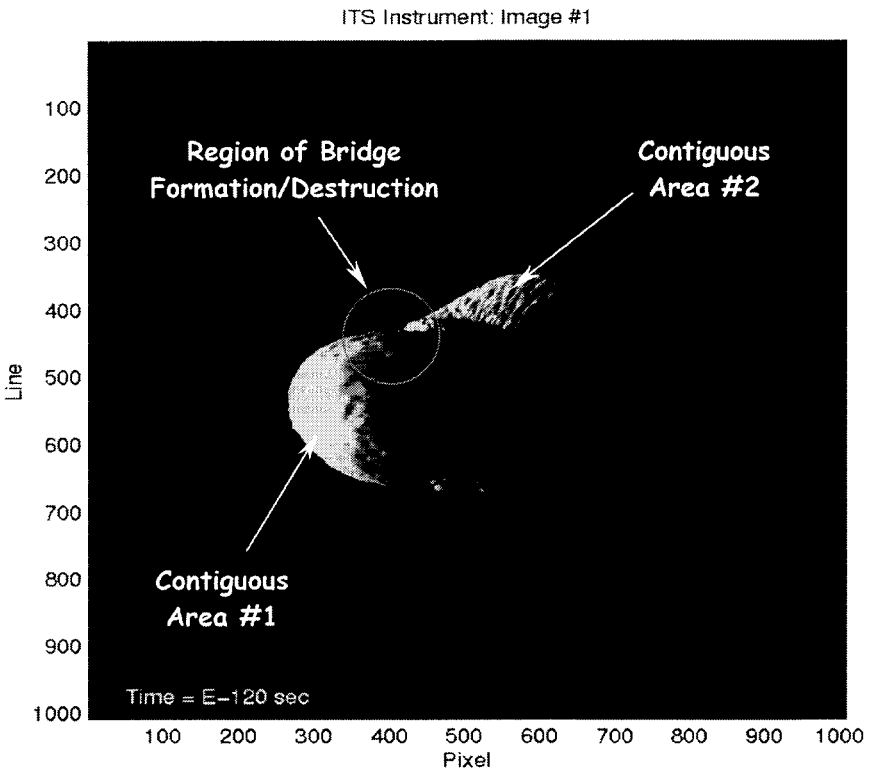

Figure 13 Nucleus orientation showing region where subtle changes in orientation can result in a sudden CB shift when using Blobber due to bridge formation or destruction between two areas of contiguously lit pixels

SUMMARY

This paper deals with just one of the many possible orientations for a single nucleus model and the results highlight many of the considerations that went into selecting the Impactor targeting strategy for Deep Impact. The strategy must be compatible with the design of the Impactor s/c and must allow for several considerations that influence the performance of the AutoNav system: Pre-release delivery errors, ADCS noise, bias, and bias drift characteristics, ITS response and noise characteristics, nucleus size, shape and rotational dynamics. MATLAB simulations provide the flexibility necessary to study the performance of the actual flight code for various sources of error and assess whether or not a particular simulation run resulted in an illuminate impact, dark impact, or miss. Analysis will continue right up to the days prior to Impactor release and the final configuration of the AutoNav system will depend on the in-flight characterization of s/c performance during the 6 months leading up to encounter. Future investigations will study the feasibility of estimating ADCS attitude bias drifts, which can and should be accounted for in the measurement model.

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