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DEEP IMPACT SPACECRAFT FLYBY INSTRUMENT POINTING IN THE PRESENCE OF A NON-ACTIVE IMPACTOR SPACECRAFT

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The engineering goal of the Deep Impact mission is to impact comet Tempel 1 on July 4, 2005, with a 350 kg active Impactor spacecraft (s/c), at a relative velocity of just over 10 km/s. The impact is expected to excavate a crater of approximately 20 m deep and 100 m wide. The science objective is that of exposing the interior material and understanding the properties of the nucleus. In order to achieve the engineering goal and science objective, Deep Impact will use the autonomous optical navigation (AutoNav) software system to guide the Impactor s/c to Tempel 1 intercept near the center of brightness (CB), while a second s/c, the Flyby s/c, uses identical software to determine its comet-relative trajectory providing the attitude determination and control system (ADCS) with the relative position information necessary to point the High Resolution Instrument (HRI) and Medium Resolution Instrument (MRI) at the expected impact site during encounter.

If the Impactor s/c is determined to be inoperable prior to release, the issue of predicting the impact location to correctly point the instruments at key science epochs (TOI: Time of Impact; and TOFI: Time of Final Imaging), becomes important and therefore must be studied. This relies, fundamentally, on the ability to determine the trajectory of the Impactor s/c relative to the Flyby s/c by treating the Impactor s/c as an optical beacon, relative to which the Flyby s/c's trajectory is estimated using images of the Impactor s/c. Results show that for a non-active Impactor s/c, the system performance is improved from 519 μrad (1 μrad = 10^{-6} radians) to 28.5 μrad (3σ) at TOI, and from 3.96 mrad (1 mrad = 10^{-3} radians) to 28.8 μrad (3σ) at time of final imaging (TOFI). When compared to the baseline CB targeting/tracking approach, results show the pointing error contribution due to knowledge of the impact location improves from 75 μrad to 28.5 μrad (3σ) at TOI, and from 220 μrad to 28.8 μrad (3σ) at TOFI. This paper deals only with the pointing error contribution due to errors in predicting the impact location and describes the acquisition of optical data of the Impactor and associated errors using the Flyby instruments; the algorithm for autonomously computing a pointing correction; the expected uncertainty in predicting the impact location; the uncertainty in the Flyby pointing correction, and hence the improvement in performance.

INTRODUCTION

The engineering goal of the Deep Impact mission is to impact comet Tempel 1 on July 4, 2005, with a 350 kg active Impactor spacecraft (s/c), at a relative velocity of just over 10 km/s. The impact 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 (deflection 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. Figure 1 shows the flight system configuration with the Impactor s/c stowed in the lower portion of the Flyby structure. Figure 2 shows the encounter geometry for the Deep Impact mission. The science objective is that of exposing the interior material and understanding the properties of the nucleus.

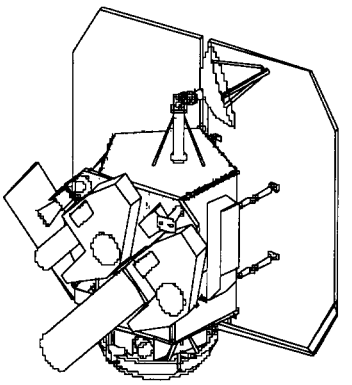

Figure 1 Deep Impact flight system configuration showing the instrument platform, High Gain Antenna, and solar array [1]

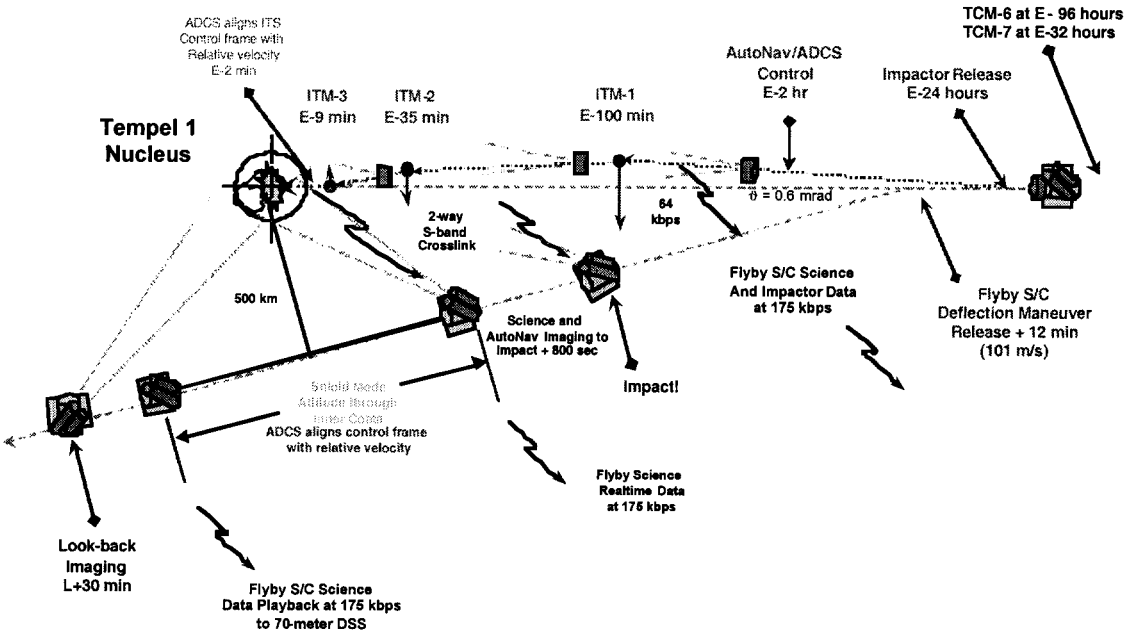

Figure 2 Tempel 1 encounter geometry for the Deep Impact mission

Deep Impact will use the autonomous optical navigation (AutoNav) software system to guide the Impactor s/c to Tempel 1 intercept near the center of brightness (CB), 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 Instrument (HRI) and Medium Resolution Instrument (MRI) at the nucleus CB during encounter. Via this method, the Impactor s/c and the Flyby s/c operate in an independent fashion with the Flyby pointing the instruments at the impact site in an indirect way. Figures 3 and 4 show simulated images of the target body using the Impactor ITS camera and the Flyby MRI /HRI cameras along their respective trajectories.

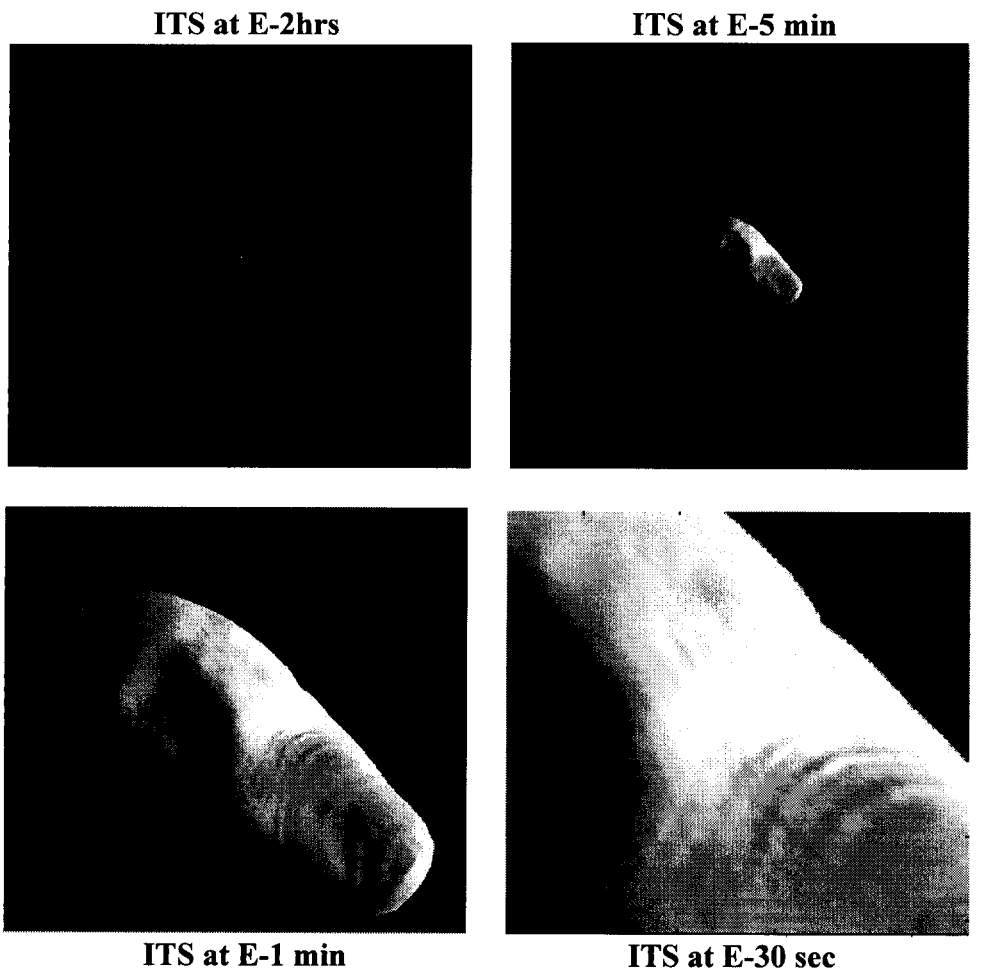

Figure 3 Simulated ITS images of the comet nucleus (based on Halley-Stooke data) during encounter where E- designates time to impact

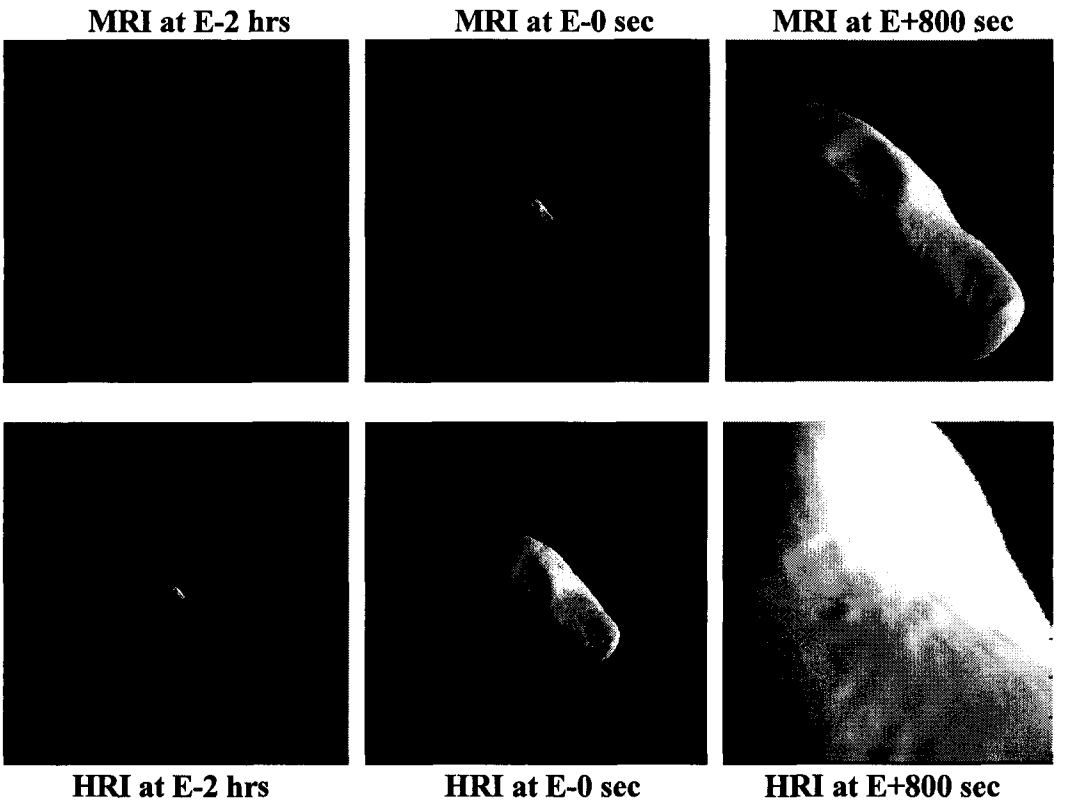

Figure 4 Simulated MRI and HRI images of the comet nucleus (based on Halley-Stooke data) during encounter where E- designates time to impact. Note the apparent rotation of the nucleus, seen in the MRI images, as the Flyby s/c passes underneath

There are two key science epochs that drive system performance during the Tempel 1 encounter: 1) Time of impact (TOI); and 2) Time of final crater imaging (TOFI). In order to obtain the highest possible temporal resolution imaging at the TOI, the HRI will be operated in a high-rate 128x128 pixel sub-frame mode (see figure 5). The HRI instrument has a 1008x1008 active pixel charged-couple device (CCD) detector with a pixel scale of 2 μrad/pixel (1 μrad = 10^{-6} radians), giving it a 2 mrad (1 mrad = 10^{-3} radians) field-of-view (FOV). Therefore, overall pointing error must not exceed 128 μrad at TOI in order to capture the impact event in the HRI 128x128 pixel sub-frame. At the time of final imaging, the Flyby s/c will be at a range of 700 – 1000 km from the surface of the nucleus. At this range, the HRI FOV covers only a small portion of the nucleus (mean nucleus radius is estimated to be 2.6 km with an approximate axial ratio of no more than 2:1). Pointing at both of these science epochs requires good knowledge of the impact site. Analysis shows that for an active Impactor maneuvering to intercept the center of brightness (CB), pointing at TOI is achievable and less than 100 μrad (3σ) of which 75

μrad (3σ) are due to uncertainties in knowledge of the actual impact site location. The probability of capturing a high-resolution image of the fully developed crater is 97% for the expected HRI instrument performance (will depend on actual HRI instrument performance). If we consider only the contribution of impact site knowledge uncertainties, the baseline targeting and tracking approach provides TOI and TOFI pointing performance as shown in table 1. In addition, table 1 shows that for a non-active Impactor s/c our ability to point the Flyby s/c instruments is substantially degraded due to uncertainties in knowledge of where the impact will occur relative to the nucleus center of brightness as observed from the Flyby s/c during AutoNav operations.

Owing to the short lifetime requirement of the non-redundant Impactor s/c, 7 days total lifetime, the non-active Impactor failure scenario has warranted attention. There are a number of considerations that must be addressed under this contingency, broadly divided into two aspects: 1) achieving an impact in an illuminated area with a non-active Impactor s/c; and 2) predicting the impact location of the non-active Impactor s/c, computing and applying a pointing correction relative to the CB in an effort to minimize Flyby pointing performance degradation at the key science epochs. The first problem is addressed by fine-tuning the trajectory of the flight-system to intercept the nucleus of Tempel 1 prior to the release of the Impactor s/c. Here we discuss the method for solving the second problem.

Table 1

Expected Flyby s/c pointing performance results at Time of Impact and Time of Final Imaging for the baseline targeting/tracking approach and for the current non-active Impactor s/c scenario

Approach	**TOI Pointing Error 3σ** (μrad)	**TOFI Pointing Error 3σ** (μrad)
Baseline (Maneuvering Impactor)	75	220
Non-active Impactor	519	3960

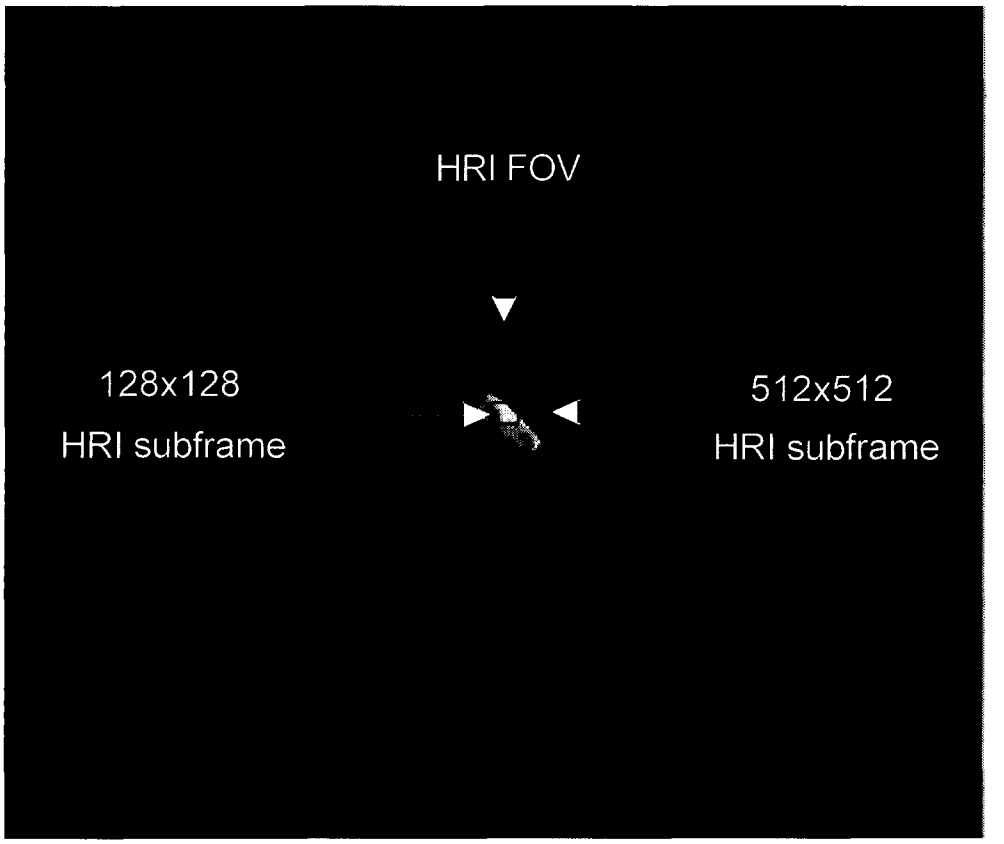

Figure 5 MRI image at TOI showing the HRI FOV (blue), the 512x512 pixel HRI subframe (green) and the 128x128 pixel HRI subframe (red) within which the impact site must reside at TOI

IMPACT SITE PREDICTION FOR A NON-ACTIVE IMPACTOR

The basic problem with a non-active Impactor s/c is that it cannot maneuver itself to impact at a location that is expected, independently, by Flyby s/c. Although the Impactor s/c has a high likelihood of impacting somewhere on the surface (80% probability **ref**), pointing the narrow FOV HRI instrument with the Flyby s/c is degraded: the Flyby s/c can point at the CB which may be as much as 4.5 km (3σ) from the actual impact site; an approach that will place a lower limit on the spatial resolution (7 m, 3σ) of the crater images that may only be captured in with the wider FOV MRI instrument instead of the desired spatial resolution obtained with the HRI instrument.

The basic idea of impact site prediction and crater-tracking relies on the fact that following release, the Impactor's trajectory will remain unperturbed until impact. Approximately 12 minutes after release, the Flyby s/c will initiate a deflection maneuver designed to control the Flyby miss distance to 500 ± 50 km and slow the Flyby spacecraft to provide 800 ± 20 seconds of science imaging from the time of impact to the

time of shield mode entry prior to passage through the inner coma dust environment (shield mode occurs approximately 50 sec before the Flyby s/c reaches it's closest approach point). The maneuver will nominally take place at E-23: 48 hrs, where E- designates time of impact, and will be ~ 102 m/s in magnitude. The magnitude of the maneuver results in execution errors that map to a 32 km B-plane position error (3σ) at encounter and an 8 sec (3σ) time-of-flight (TOF) error. If, following the deflection maneuver, the trajectory of the Flyby s/c can be estimated relative to that of the Impactor, then the Flyby's trajectory can be mapped to encounter relative to the actual impact site. The key is to treat the Impactor as an optical beacon, relative to which the Flyby s/c's trajectory may be estimated using optical images of the Impactor. The expectation is that these images will provide very accurate determination of the Flyby's trajectory perpendicular to the line-of-sight relative to the Impactor. Alongtrack information will come primarily from radiometric tracking of the Flyby, i.e., range and Doppler. This post-deflection radio tracking is part of the baseline approach and serves to establish the need for a contingent deflection trim maneuver, at E-12 hrs, as well as to estimate the TOF error introduced by the deflection burn. A summary of the post-deflection Flyby navigation plan is as follows:

1. Continue radio tracking of the Flyby s/c for 6 hrs after end of deflection burn
2. Image the Impactor from the Flyby, beginning 35 minutes after the end of the deflection burn
3. Estimate the Flyby's heliocentric trajectory with a radio-only solution
4. Estimate the Flyby's Impactor-relative trajectory with an optical solution using initial conditions obtained from the radio-only solution

OBSERVING THE IMPACTOR SPACECRAFT

Following Impactor separation and the deflection burn, the Impactor remains on a trajectory, which is essentially the incoming asymptote relative to comet Tempel 1, and the Flyby s/c slows down by ~ 101 m/s with an ~ 5.7 m/s velocity component perpendicular to the incoming asymptote, giving a constant inertial view angle of the Impactor from the Flyby s/c of ~ 3° with respect to the Impactor's comet-relative trajectory. This angle does not change until impact. Images of the Impactor and background stars will be acquired, beginning 35 minutes after completion of the deflection burn, and processed on the ground. The accuracy of the orbit determination based on these optical data depends, among other things, on the Signal-to-Noise Ratio (SNR) of background stars and the observability of the Impactor s/c using the Flyby instruments.

Impactor s/c Surface Properties

The Impactor has an irregular shape, and a mix of materials with varying reflective properties, e.g., metal, paint, thermal blanket etc. The ITS anti-boresight side of the Impactor s/c bus, the one that for most of the time will be facing the Flyby s/c, has a hexagonal shape (figure 6). The ITS boresight direction has a dome shape made up of copper plates, with six panels connecting the two sides. An accurate determination of the optical signal obtained from the Impactor at a given orientation would require knowledge of the reflective properties, exact shape modeling and attitude history. The Impactor, during the time it is imaged from the Flyby, may be turning off-nucleus to obtain calibration images, or in case that it is non-active it will be tumbling at an unknown rate and direction. The overall phase darkening of the Impactor at different attitudes will vary in a complicated way, requiring a modeling process beyond the scope of a contingency treatment. The approach is not to compute the exact signal from the Impactor, but rather to establish whether reasonable, as well as conservative assumptions, result in a sufficient SNR.

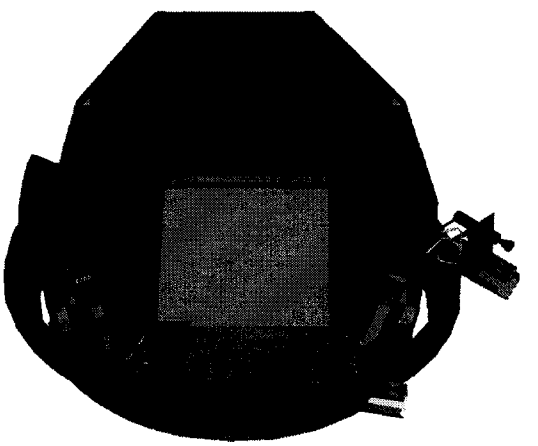

Figure 6 Impactor s/c flight system configuration [2]

Our simplified assumption is an irregular shape with an average diameter of 0.9 m and albedo of ~ 0.35 based on drawings and data from Ball Aerospace Technologies Corporation (BATC). Assuming that we view mostly a flat Impactor surface and that the single particles on the surface scatter isotropically, we may adopt a Lommel-Seeliger reflection law with an average incidence angle, i, equal to the phase angle ≈ 65°; an average emission angle, e, equal to the view angle from the Flyby s/c of 3°. The integrated intensity at that phase angle co-mapped to 0° is: cos i/(cosi + cose) = 0.29 corresponding to a phase darkening of ≈ 1.3 magnitudes or a phase coefficient of 0.02 mag/degree. By parameterizing the phase darkening of the Impactor with a phase coefficient, we can consider a variety of more conservative phase functions: 0.04 mag/degree, a value typical for comets and asteroids[3], or 0.06 mag/degree corresponding to some of the most phase-darkened objects, such as comet Encke[3].

In figures 7 and 8 we show the expected SNR in the peak pixel for a 1 second exposure, as a function of time for 3 different phase functions for the HRI and MRI, respectively. The SNR is computed with the current data for each instrument and with the rather conservative assumption of 4 DN ($\approx$ 120 e-) of read noise. As shown in figure 7, HRI imaging guarantees a high SNR for many hours after separation even for very steep phase functions. For the MRI, however, the SNR is significantly lower. To maintain a value of SNR $\geq$ 7, which will typically guarantee a center-finding accuracy of ~ 0.1 pixels (1σ), we may need to consider longer exposures. Figure 8 shows that a 3 second exposure can provide a SNR $\geq$ 7 for ~ 3 hours of imaging, even for the steepest phase function. In general, the choice of instrument depends on many factors, which include:

1. Sufficient signal from the background stars. The FOV of the MRI, 10 mrad (1008x1008 pixel CCD with 10 μrad pixel), is 5 times larger than that of the HRI 2 mrad FOV (1008x1008 pixel CCD with 2 μrad pixel), but the HRI can detect stars fainter by at least 4 magnitudes compared to the MRI. Depending on the approach trajectory, i.e. launch date, background star availability may favor one instrument over the other.

2. Ability to acquire the Impactor in a narrow HRI FOV. Because of errors in the deflection maneuver, which map to errors in the Flyby s/c position at time of Impactor acquisition, the Impactor will not necessarily be at the predicted location during imaging. The 3σ position error is approximately 2 times larger than the FOV of the HRI. Since immediate detection of the Impactor with the HRI is not guaranteed, depending on the time and other resources available, it will be preferable to use the MRI throughout.

These considerations will be examined in detail after the approach asymptote of the flight system becomes known. Another issue, which is common to both instruments, is that of obtaining star-relative Impactor images in the presence of an extended diffuse coma, which is foreground to the stars and background to the Impactor. Based on the Deep Impact Science Team predictions for the coma brightness, a worst-case scenario, whereby all of the observed outgassing is the result of a narrow jet, we estimate the peak pixel brightness due to coma of up to 80,000 e-/s in the pixels adjacent to the nucleus. For a late release at E-12 hrs, imaging of the Impactor could extend to as late as E-9 hrs. At that time the Impactor will be projected, relative to the Flyby instruments, in a direction where the background coma is ~ 15,000 km from the nucleus. At that distance the coma is quite faint; assuming the observed linear brightness decrease with distance from the nucleus, the coma background will be ~ 3 - 3.5 DN, i.e. comparable to the CCD system noise for an exposure in the 1 - 3 sec range. This will result in a small decrease of the Impactor's optical signal relative to the background, and therefore, has no affect on center-finding accuracy. Figure 9 shows a simulated image of the Impactor s/c as seen in the HRI

instrument at a range of approximately 60 km and with an exposure duration sufficient to bring the signal up near full-well (16,384 DN).

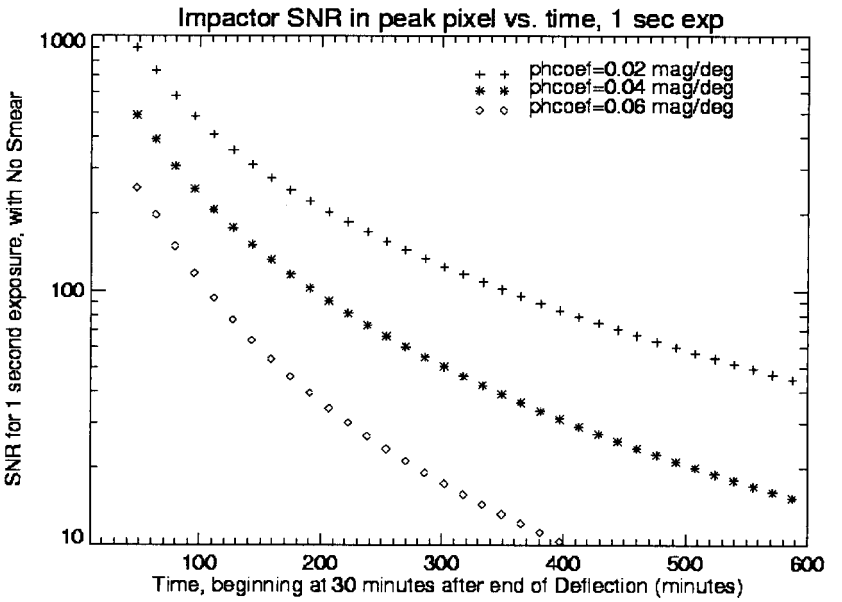

Figure 7 SNR of the Impactor s/c as observed with the HRI

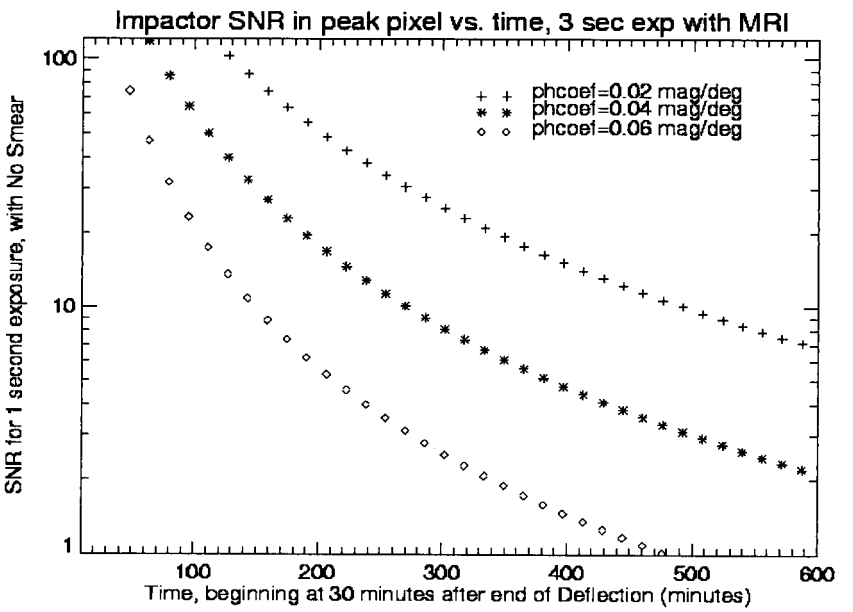

Figure 8 SNR of the Impactor s/c as observed with the MRI

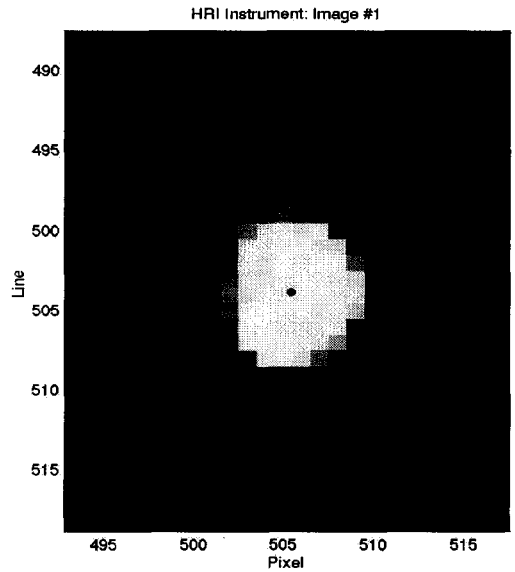

Figure 9 Simulated subframe image of the Impactor s/c in the HRI at a range of ~ 60 km and phase of ~ 65°

SIMULATIONS AND MONTE CARLO BASED PERFORMANCE ANALYSIS

Given that there is sufficient optical signal from the Impactor s/c, as shown in the previous section, a suite of MATLAB algorithms have been developed to:

1. Drive the AutoNav flight code (image processing and orbit determination)
2. Simulate images of the Impactor s/c using either the MRI or HRI instrument
3. Integrate the Impactor and Flyby s/c truth trajectories
4. Evaluate the Flyby position error (true – estimated) at the Key Science epochs (TOI and TOFI)
5. Compute the pointing error at TOI and TOFI
6. Perform a Monte Carlo analysis to assess the pointing performance at the Key Science epochs

The Monte Carlo simulations consist of sampling Flyby trajectory deflection maneuver errors and Flyby s/c attitude errors, which are representative of the expected center-finding errors described previously (0.1 – 0.2 pixels; 1 – 2 μrad for the MRI). The epoch time is taken to be Release plus 5 minutes (start of the deflection burn). The deflection burn is modeled as an impulsive maneuver occurring at release plus 5 minutes, with

maneuver execution errors randomly sampled in the alongtrack direction (0.50 m/s, 1σ), relative to comet Tempel 1, and crosstrack direction (0.12 m/s, 1σ). These errors represent the expected flight system deflection maneuver execution capability and are used to integrate the Flyby s/c truth trajectory. The beginning of Impactor image acquisition occurs at Release plus 35 minutes and ends at Release plus 4 hours and 35 minutes to give a batch orbit determination (OD) arc length of 4 hours. Images are sampled at a 15 minute interval providing 17 observations that are used in the estimation process. At the beginning of image acquisition, differences between the Flyby s/c's true position and the Flyby s/c's expected position result in pointing errors on the order of 4 mrad (3σ). Figure 10 shows the location of the Impactor in the MRI FOV at initial acquisition for 500 simulation runs. The HRI FOV is superimposed (red) and shows that the associated Flyby s/c maneuver execution errors require use of the MRI instrument for Impactor tracking to give a reasonable assurance of capturing the Impactor observations. In 7 out of 500 simulation runs, the Impactor s/c is outside the MRI FOV at initial image acquisition and therefore and Impactor-relative orbit solution for the Flyby s/c cannot be determined without a search to first located the Impactor. The maximum dispersion from the MRI boresight was found to be 1301.1 pixels or approximate 13 mrads.

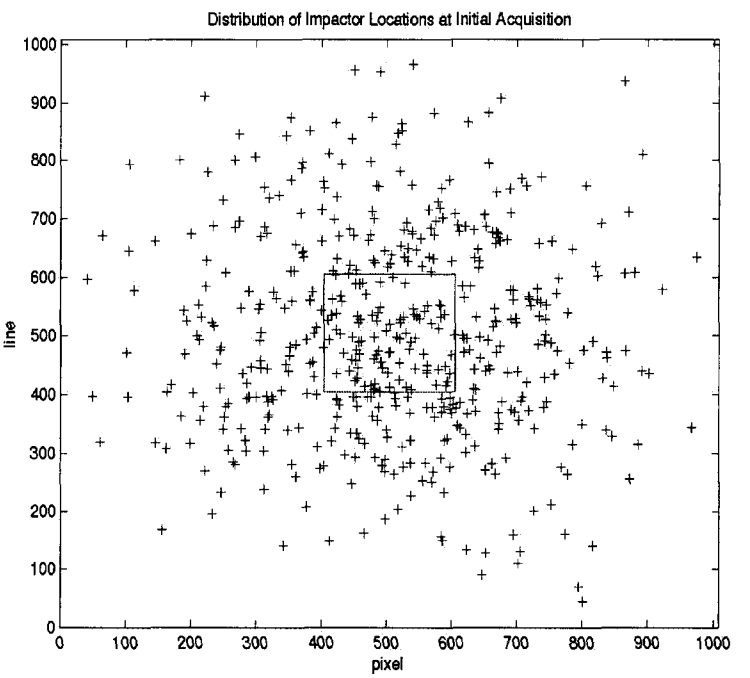

Figure 10 Dispersion of Impactor locations in the MRI FOV at initial image acquisition (Release + 35 min) for 500 simulation runs; the HRI FOV is superimposed in red

After computing the orbit solution, the estimated Flyby position is evaluated at TOI (Release + 24 hrs) and TOFI (TOI + 750 sec). The difference between the true Flyby s/c

position and estimated Flyby position over the true range to the Impactor gives the pointing error. Table 2 shows the statistical performance at TOI and TOFI and represents our ability to predict the Impact location. The following section will describe the autonomous algorithm that is necessary to point the MRI and HRI instruments at the Key Science epochs using the estimated Flyby s/c's trajectory.

Table 2

Monte Carlo Flyby s/c pointing performance results at Time of Impact and Time of Final Imaging based on 500 simulation runs

Key Science Epoch	**Min** (μrad)	**Max** (μrad)	**RMS Error** (μrad)
TOI Pointing	11.2	44.4	28.5
TOFI Pointing (TCA-100 sec)	11.5	44.8	28.8

THE AUTONOMOUS POINTING CORRECTION ALGORITHM

Once the Flyby s/c's inertial, heliocentric trajectory has been determined based on optical observations of the Impactor s/c, the Chebyshev coefficients that represent the Flyby s/c and Impactor s/c position and velocity as a function of time throughout the entire encounter period, are uploaded to the AutoNav flight software on the Flyby s/c. As shown in figure 2, AutoNav acquires and processes images of comet Tempel 1 starting 2 hrs prior to the expected TOI. Every minute, AutoNav updates its position and velocity relative to the CB of Tempel 1 and generates an ephemeris in the form of Chebyshev coefficients. These coefficients are passed to the ADCS software, which evaluates, at 10 Hz, the inertial position of the Flyby s/c and inertial position of Tempel 1 (from Chebyshev coefficients representing the Tempel 1 ephemeris) and computes the desired inertial pointing to center the target body CB in the HRI FOV. With every AutoNav OD update, the difference between the Flyby s/c's ground-based inertial position, based on optical observations of the Impactor s/c, and AutoNav's updated estimate of the Flyby s/c's inertial position, based on optical observations of Tempel 1, may be computed and applied directly to correct the Impactor's heliocentric position as shown in figure 11.

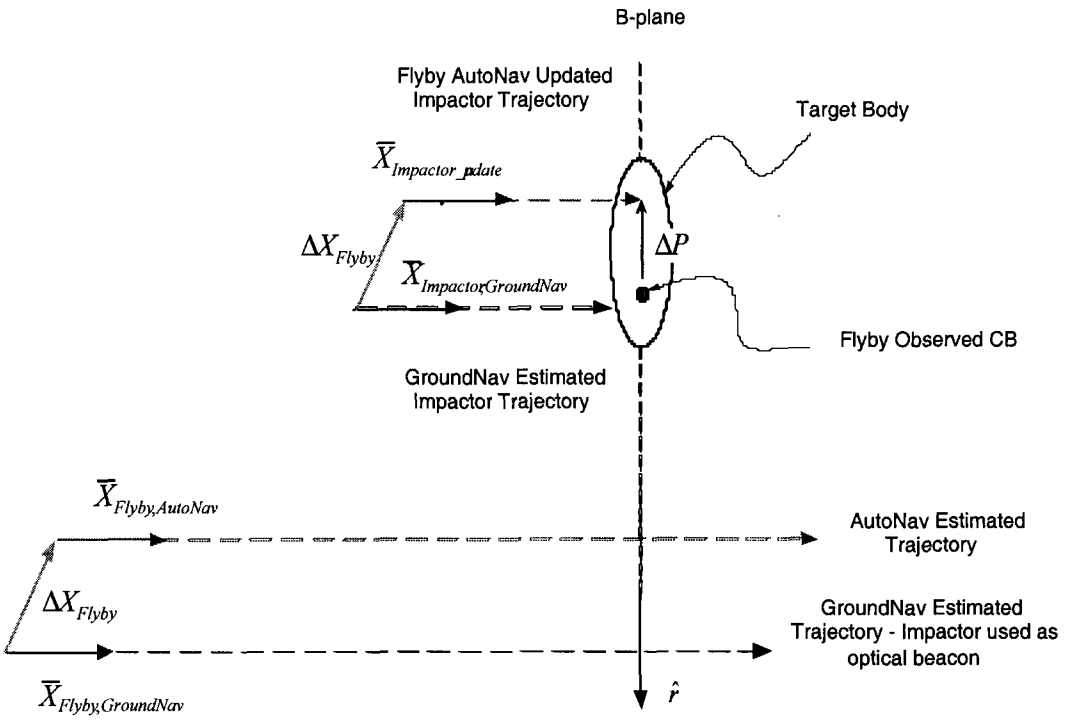

Figure 11 Graphical depiction of the inertial pointing correction, ΔP, which is computed by AutoNav. All state vectors correspond to the same AutoNav OD update epoch time (i.e. 5 min prior to estimated TOI); B-plane is normal to view

The difference between the Flyby s/c AutoNav solution and the Flyby s/c GroundNav solution is computed to be

$$\Delta \overline{X}(t_{OD})_{Flyby} = \overline{X}(t_{OD})_{Flyby,AutoNav} - \overline{X}(t_{OD})_{Flyby,GroundNav}$$

This correction is applied directly to the Impactor s/c's inertial state obtained by evaluating the on-board Chebyshev coefficients for the Impactor s/c at t_{OD}

$$\overline{X}(t_{OD})_{Impactor_update} = \overline{X}(t_{OD})_{Impactor,GroundNav} + \Delta \overline{X}(t_{OD})_{Flyby}$$

The updated Impactor s/c state is then mapped into B-plane coordinates, where $B \cdot r, B \cdot t$ give the 2-D pointing correction, relative to the observed CB, in the B-plane. Since the orientation of the B-plane is known relative to the Inertial Celestial Reference Frame (ICRF), the 2-D vector is transformed into an inertial 3-D pointing correction, ΔP , and passed to ADCS for application.

$$\bar{X}_{Impactor_update} = \begin{pmatrix} B \cdot r \\ B \cdot t \\ TOF \end{pmatrix} \Rightarrow \Delta P = \begin{pmatrix} \Delta P_x \\ \Delta P_y \\ \Delta P_z \end{pmatrix}_{ICRF}$$

The process of computing the pointing correction should occur with every OD update until TOI after which time the applied correction must remain constant.

SUMMARY

Predicting the impact site to point the Flyby s/c instruments in the presence of a non-active Impactor s/c can be achieved by treating the Impactor s/c as an optical beacon, estimating the Flyby s/c's inertial trajectory using images of the Impactor, uploading the estimated trajectory to the Flyby s/c's AutoNav software and autonomously computing a pointing correction for ADCS. Uncertainties in the Flyby's position relative to the Impactor at the time of initial image acquisition require use of the MRI instrument for Impactor optical navigation purposes. Results show that for a non-active Impactor s/c, the system performance is improved even when compared to the baseline approach of a maneuvering Impactor s/c that will target the nucleus center of brightness. For the case of a non-active Impactor, results show that treating the Impactor as an optical beacon improve pointing performance from 519 μrad to 28.5 μrad (3σ) at TOI, and from 3.96 mrad to 28.8 μrad (3σ) at TOFI; meaning the difference between a mission with seriously degraded science return and a mission with flight system performance that exceeds the current baseline approach, provided of course that the non-active Impactor impacts in an illuminated area viewable from the Flyby s/c; both of which have substantially improved probabilities when the Impactor is active and maneuvering to intercept the nucleus center of brightness.

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