Deep Impact Project

December 15, 2005

HRI Focus Anomaly Tiger Team Investigation

Final Report

Cover Photo: Ejecta from the comet Tempel 1 impact is imaged by the High Resolution Instrument (HRI). The image has been sharpened by ground data processing.

Executive Summary

The NASA *Deep Impact* spacecraft was launched on Jan 12, 2005 on a mission to intercept comet Tempel 1, to strike the comet with an impactor probe on Jul 4, 2005, and to study the impact ejecta to learn about the comet's composition and structure. During the early cruise phase of the mission, images taken with the High Resolution Instrument (HRI) were notably out of focus. The *Deep Impact* project manager convened a Tiger Team to investigate the anomaly, recommend ways to improve the imaging performance of the instrument en route to the comet, and identify the most likely root cause of the anomaly.

During the course of the investigation the Team determined that the focus was offset by about 6.4mm, and that imaging performance of the HRI could not significantly be improved in flight. The Team recommended that the project pursue ground data processing techniques (deconvolution) to improve image sharpness. The Team further determined the root cause of the focus anomaly to be incorrect spacing between the primary and secondary mirrors of the HRI telescope. The spacing was set incorrectly based on optical tests performed at cold operating temperature using a cryo-flat mirror which, unbeknownst to the team building the instrument, developed optical power at cold temperatures.

Tests of the cryo-flat mirror assembly performed during the course of the investigation conclusively demonstrate that the optical power developed by this mirror at cold temperature accounts for the entire focus anomaly seen in the HRI imaging data.

The investigation by the Tiger Team is now complete. It remains for others to examine the processes and circumstances that resulted in this error not having been prevented or discovered prior to launch.

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Background

Vehicle Configuration

The *Deep Impact* spacecraft comprises two vehicles, a flyby spacecraft and an impactor probe. The flyby spacecraft carries two scientific instruments, the High Resolution Instrument (HRI) and the Medium Resolution Instrument (MRI). The impactor carries the Impactor Targeting Sensor (ITS), essentially a copy of the MRI without a filter wheel. The HRI and MRI are mounted to an instrument platform on the anti-sun side of the spacecraft, and are co-boresighted, as show in Figure 1.

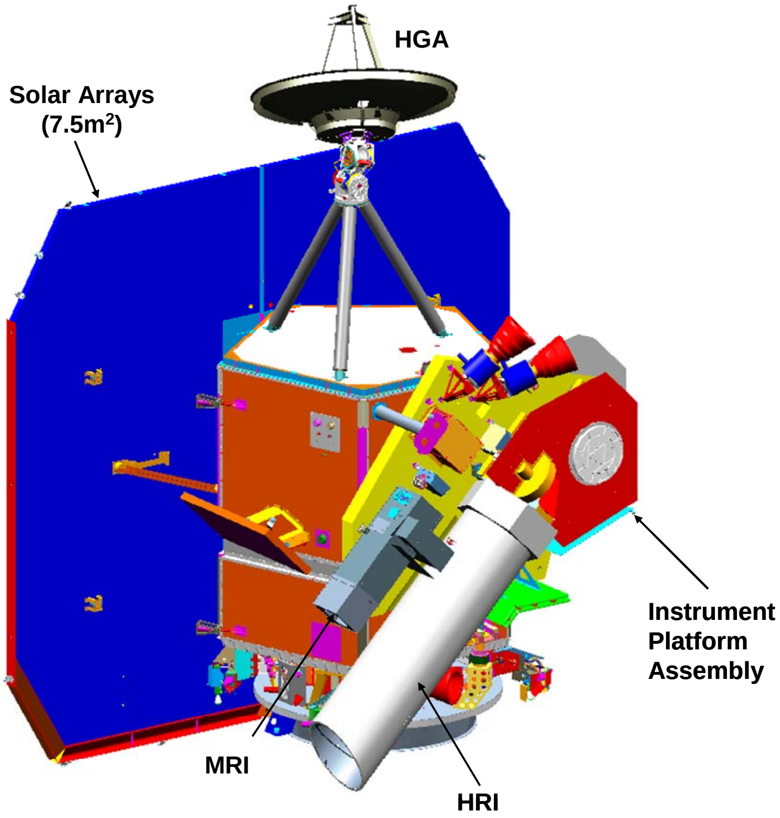

Figure 1. The HRI and MRI are mounted to the instrument platform on the anti-sun side of the vehicle.

High Resolution Instrument (HRI)

The HRI is the primary science instrument on the flyby spacecraft and consists of a 30cm aperture telescope, a multispectral CCD imager, and an infrared spectrometer. The Cassegrain telescope has a focal length of 10.5m and secondary mirror axial magnification of 61x. The primary and secondary mirrors of the telescope are made of Zerodur, with mounting hardware made of Invar and support flexures made of titanium. The structural elements, in particular the metering structure, are made from graphite-cyanate composite with laminate composition and orientation designed to render the telescope alignment insensitive to temperature. The instrument is intended to operate at a temperature of about -135C and has no focus adjustment capability. The telescope is shown in section view in Figure 2.

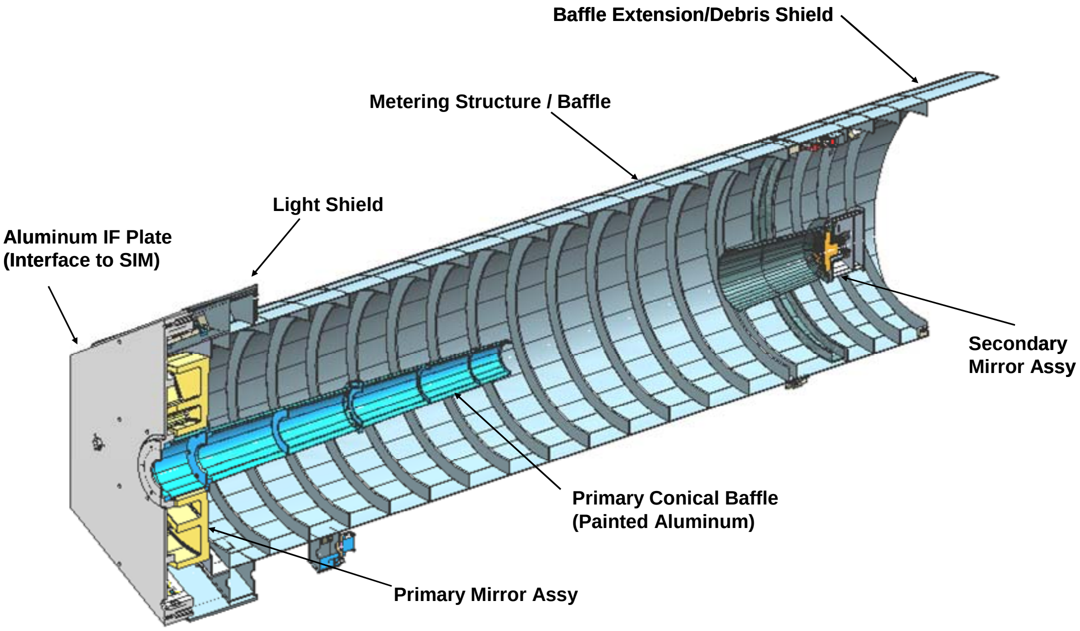

Figure 2. The HRI telescope is composed of Zerodur optical elements and a graphite-cyanate composite metering structure. The focal length is 10.5m and secondary magnification is 61x. The HRI has no focus adjustment capability in flight.

Setting the Focus of the HRI Instrument

Although the instrument alignment is athermal by design, some change with temperature and moisture absorption is inevitable. For this reason the telescope's focus position and image quality were measured at cold operating temperature in a thermal-vacuum chamber following an elevated temperature vacuum bakeout. The position of the secondary mirror was subsequently adjusted (shimmed) in the laboratory in such a way that the focus of the instrument would be in the correct position at the flight operating temperature of about -135C.

To measure the focus of the telescope an external beam of light was projected through a window in the thermal-vacuum chamber. The presence of the chamber window distorts the optical wavefront of the light (mainly affecting focus); the beam must therefore be adjusted to compensate. Ball Aerospace and Technologies Corp. (BATC), the developer of the instrument, devised a means to accomplish this which involved placing a flat mirror on a translation stage inside the thermal-vacuum chamber. By reflecting the optical beam off this mirror and back through the chamber window, the focus of the beam could be adjusted such that the portion of beam inside the chamber was collimated, i.e., it simulated light from a star at infinity. Once the beam was properly adjusted, the flat mirror (hereafter called the cryo-flat) was translated out of the way, allowing the collimated beam to enter the telescope. Figure 3 shows the HRI and MRI telescopes in the thermal vacuum chamber in preparation for the focus test. Figure 4 shows the cryo-flat mirror, an assembly that was developed for the SIRTF (Space Infrared Telescope Facility) project, and used in the characterization of the SIRTF full aperture autocollimation flat.

After the telescope focus had been adjusted, the fully integrated instrument was again optically tested at cold temperature to verify that the instrument remained in focus. The same approach was used to collimate the optical test beam, and the results repeated within the precision of the tests.

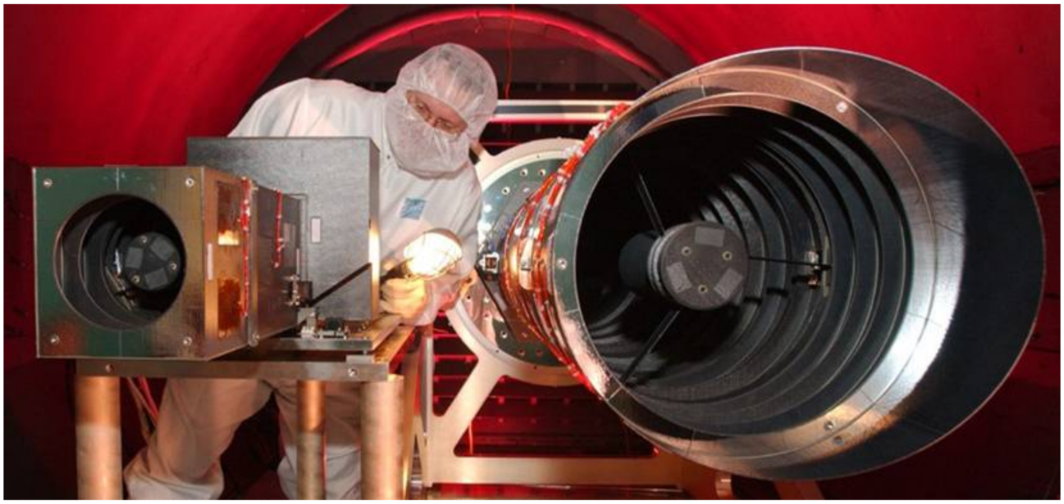

Figure 3. The MRI (left) and HRI (right) telescopes are prepared for low temperature testing. These tests were used to determine the adjustments needed to set the focus of the instruments at the cold operating temperature.

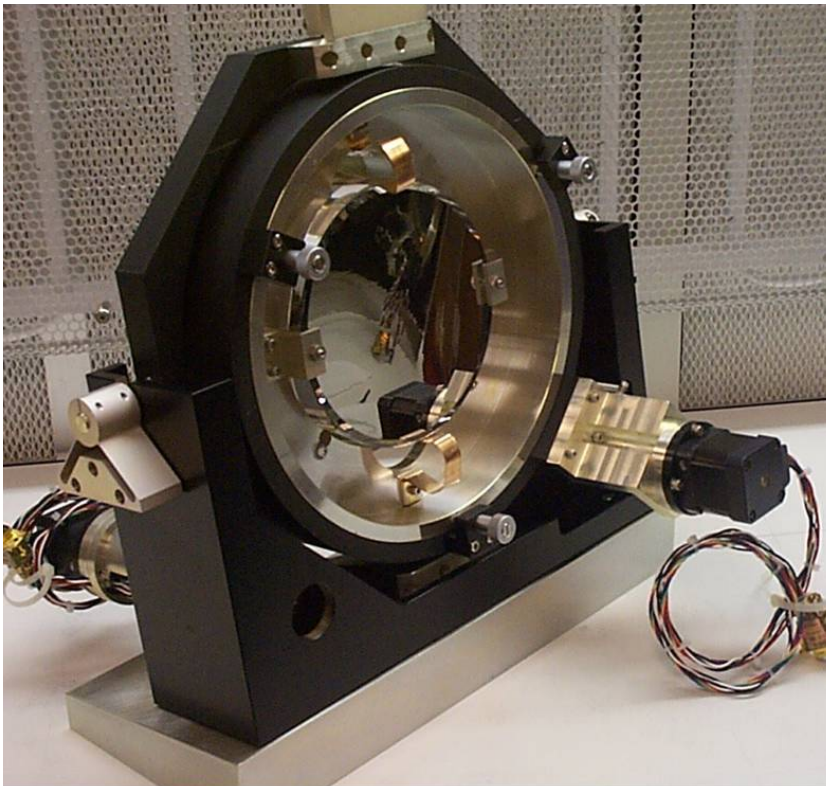

Figure 4. The cryo-flat mirror assembly used to collimate the optical beam inside the thermal-vacuum chamber. This assembly was originally developed for the SIRTF project.

Characterizing the Anomaly and Exploring Options to Improve In-Flight Performance

Early In-flight Images

The Tiger Team was formally convened on Feb 3, 2005 by the *Deep Impact* Project Manager after early in-flight images indicated a significant focus offset in the HRI instrument. Given the relatively short cruise duration, and the fact that flight operations might need to adapt to a degraded HRI instrument, it was important to determine as quickly as possible whether or not the focus of the instrument could be improved. Early efforts of the Tiger Team were therefore directed at characterizing the optical state of the instrument and determining whether it might be possible to improve the performance en route to comet Tempel 1.

Images taken on Jan 14 (L+2) and later, following a 50hr water desorption bakeout, on Jan 30 showed a point spread function (PSF) that was donut-like in appearance, together with a noticeable amount of trefoil[1], as shown in Figure 5. The focus offset was estimated at the time to be approximately 9.5mm, although the direction of the offset (in front of or behind the detector) was not known. Focus appeared to be the main component of the anomaly.

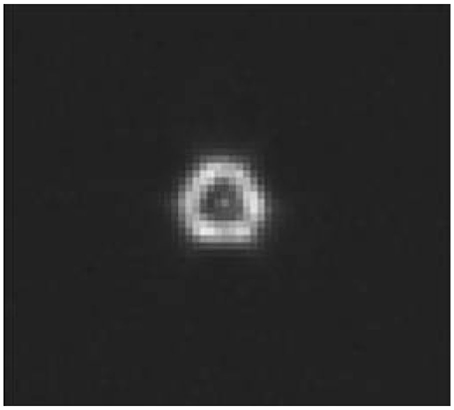

Figure 5. HRI star image taken on Jan 14, 2005 (L+2) showing the point spread function of the instrument optical system. Significant focus offset can be seen together with a noticeable amount of trefoil distortion.

Since there is no focus adjustment mechanism in the instrument, the only two methods potentially available for shifting the focus were: 1) driving out moisture absorbed into the graphite composite (a nonreversible process), and 2) adjusting the temperature or temperature gradients in the instrument, specifically the telescope metering structure. The 50hr bakeout that had been performed between Jan 14 and Jan 30 appeared to have minimal affect on the focus position, but BATC engineers developed a theory that because the instrument had gone cold after launch prior to being baked out, remnant moisture might have somehow frozen in the composite, causing a bulk dimensional change (and hence the focus offset), and that the limited bakeout would not have been sufficient to sublime away the ice. This theory argued for an extended bakeout to ensure that all moisture was removed from the structure. Before considering such a bakeout, however, the Team felt that the direction of the focus offset must first be determined, so that confidence could be gained that additional moisture desorption would not make the situation worse.

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[1] The trefoil distortion was later found to be consistent with ground test results, and of acceptable magnitude.

Determining the Direction of the Focus Offset

Two in-flight tests were performed to determine the direction of the focus offset. The first was a quasi “knife-edge” test, where the filter wheel was stepped incrementally through the converging beam behind the telescope (see Figure 6). By observing the direction from which the filter wheel occulted the image the focal surface was determined to lie in front of the detector.

The second test involved overexposing a star to reveal the ghost images resulting from reflection off the CCD and the filter. These tests, combined with optical modeling, determined that the focal surface was located about 7mm in front of the detector. The ghost images produced an image of the pupil with interference effects. From these data, again in conjunction with computer modeling, it was determined that the trefoil distortion was due to the difference in coefficient of thermal expansion between the Invar mounting pads on the primary mirror and the Zerodur mirror substrate (see Figure 7).

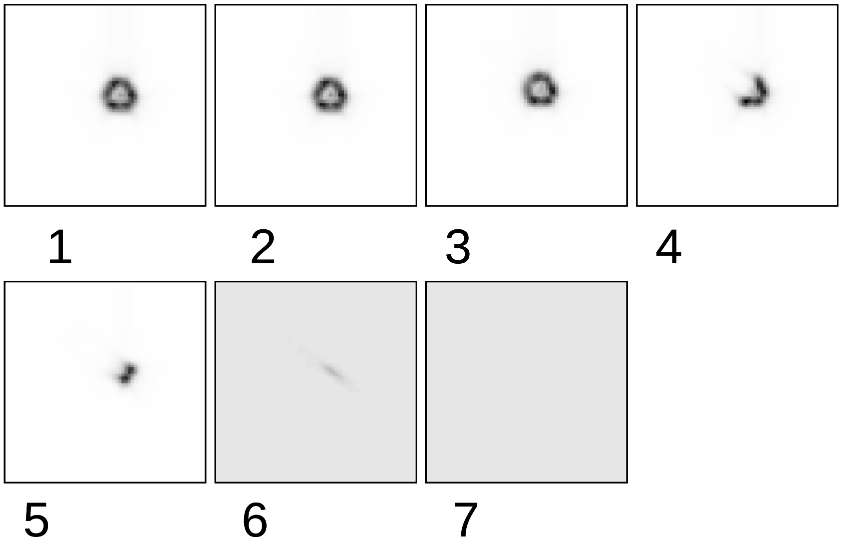


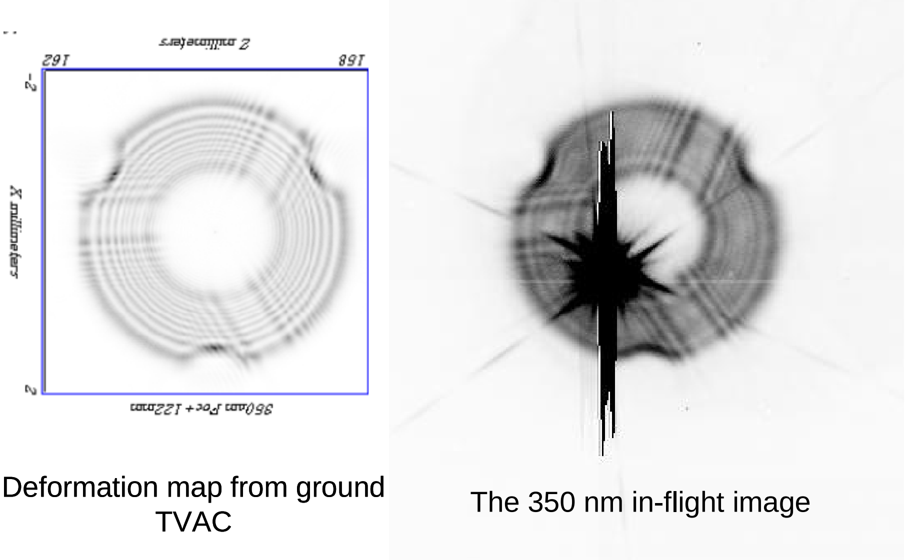
Figure 6. PSF images taken during the quasi “knife-edge” test. The direction of the occultation revealed that the focus was in front of the detector.

Moisture Desorption Bakeout

Although the material expert on the Team was doubtful that water absorption in low moisture graphite cyanate could form ice (as had been hypothesized) it was determined that water desorption would tend to improve the focus position (i.e., lengthen the focus) and was very unlikely to make the situation worse. Therefore, it was recommended to proceed with a vigorous bakeout to assure that all moisture was removed from the graphite structure. A bakeout was performed between Feb 19 and Mar 15, 2005 using all available heaters on the instrument, with care taken to assure that no portion of the instrument was subjected to temperatures exceeding those experienced during ground testing.

Post bakeout in-flight images confirmed that the bakeout had minimal effect on the focus position, improving the offset by perhaps 1mm. This amount of focus shift, combined with the possible small shift seen after the earlier 50hr bakeout, is consistent with ground test results that showed at most a 2mm shift in focus due to moisture desorption.

350 nm ASAP image at 117 mm defocus.



Deformation map from ground TVAC

The 350 nm in-flight image

Figure 7. Ghost image (right) of over exposed star compared to computer prediction (left) confirmed that the focal surface was located about 7mm in front of the detector. Computer analysis also determined that trefoil distortion seen in the ghost image (and the PSF) is due to the difference in coefficient of thermal expansion between the Invar mounts and the Zerodur mirror.

Adjusting Focus by Means of Temperature Control

While the moisture desorption bakeout was in progress, analysis was undertaken to determine whether or not temperature adjustments of the HRI instrument could be used to improve the focus. This analysis determined that a bulk reduction in the temperature of the instrument would improve focus somewhat, but the instrument was already about as cold as it could get, given that it was on the anti-sun side of the spacecraft and not actively heated. During the cruise to the comet the distance from the sun would gradually increase, causing slightly lower temperatures before encounter, but this was estimated to improve focus by only about 0.5mm.

A study was also undertaken of whether temperature gradients could be induced in the instrument which would improve focus. The result of this analysis determined that the highly conductive nature of the graphite composite metering structure, together with the athermal design of the instrument, made it virtually impossible to induce a helpful gradient. It was possible to produce a transient gradient for a short period of time that would improve focus somewhat, but this would quickly give way to a steady state condition that was worse than doing nothing at all.

The Project was advised on Apr 4, 2005 that it would not be possible to substantially improve the focus of the HRI, and that ground data processing (deconvolution) to improve image sharpness was the only remaining option.

Deconvolution to Sharpen Image Data

The *Deep Impact* PI organized a working group to explore the possibilities of image processing to improve the sharpness of the images. Deconvolution approaches were developed extensively in response to the *Hubble Space Telescope* spherical aberration problem, and these methods are now well understood. A deconvolution workshop was held at the University of Maryland on Apr 14, which concluded that deconvolution techniques would be effective on the high signal-to-noise ratio data expected from the encounter. Deconvolution works best with a well characterized PSF, and so emphasis was placed on ways to characterize the PSF shortly before encounter. In the event, deconvolution was successfully used to sharpen the HRI images and recover science performance.

The In-Flight Optical State at Encounter

Analysis of images supported by computer modeling determined that the optical anomaly was principally focus offset with a small amount of trefoil distortion. The best estimate of the focus offset at encounter is that it lay in front of the detector (i.e., the focus was short) by approximately 6.4mm. For comparison, the specification for the instrument calls for the focal surface to be placed at the detector within +/- 2mm.

Identifying the Root Cause of the Anomaly

Fault Tree

The Tiger Team developed a fault tree to assist in identifying the most likely root cause of the anomaly, and this tree was updated as new information and understanding was developed. The final version of the fault tree is shown in Figure 8.

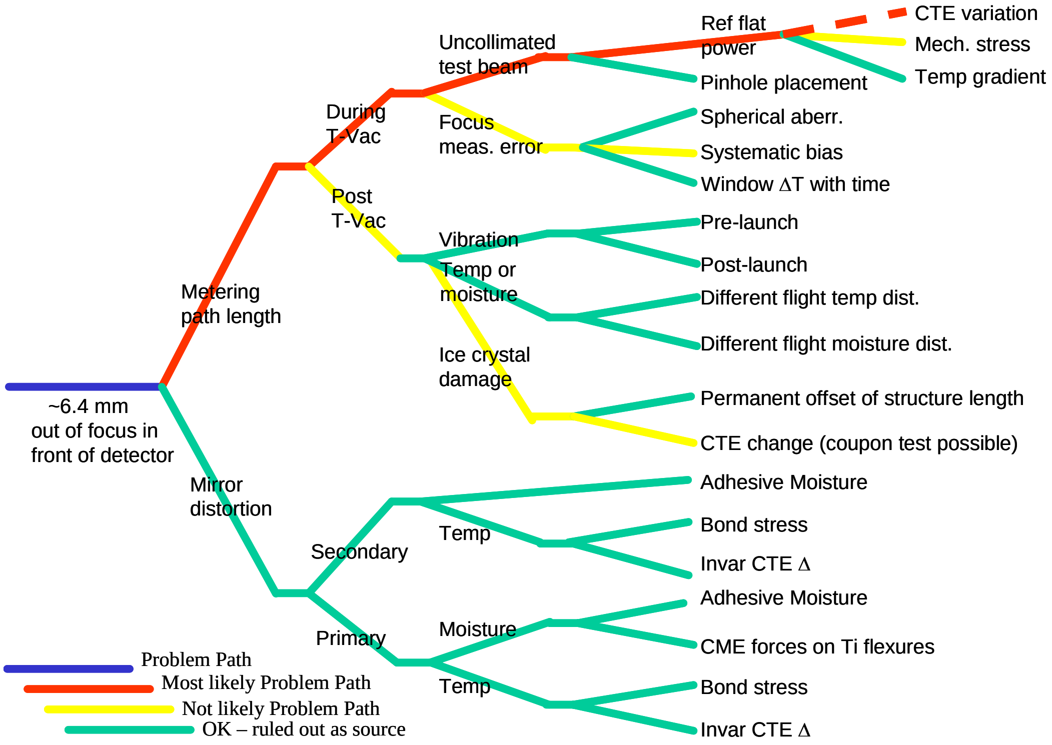


Figure 8. Final fault tree developed by the Tiger Team to assist in root cause determination.

The two main branches of the fault tree identify mirror distortion and metering path length as possible sources of the focus offset. Mirror distortion was ultimately ruled out by examination of the fabrication data for the primary and secondary mirrors, and detailed thermo-mechanical analysis of the mirror mounts. Mirror distortion was determined to be the cause of the trefoil seen in the PSF and ghost images, and was predictable based on known mechanical and thermal properties of the design.

The metering path length branch subdivides into effects which may have occurred during ground testing and alignment (“During T-Vac”) and those which may have occurred after the last optical test was performed on the ground (“Post T-Vac”). The Post T-Vac branch identifies vibration, temperature or moisture, and ice-crystal damage as possible causes. Vibration, temperature and moisture were ruled out based on examination of the in-flight images, the in-flight desorption bakeout, and computer modeling. The ice crystal theory was deemed implausible.

The uppermost branch identifies either an uncollimated optical test beam or a focus measurement error as possible causes. The optical test procedure and test setup were reviewed by the Tiger Team and found to be sound; therefore, the most likely root cause was identified as a systematic error in the optical test beam, which caused it to be uncollimated at the cold operating temperature of the test. Evidence for a systematic error in the test was reinforced by in-flight images from the MRI instrument, which showed a degree of focus offset consistent with a common source of error in the ground test setup. Since the cryo-flat mirror was used to collimate the optical test beam at cold temperature, this mirror assembly immediately became suspect.

The Cryo-Flat Mirror Assembly

The cryo-flat mirror is approximately 5.5in in diameter, is made of fused silica, and is kinematically mounted on a tip/tilt stage. As mentioned earlier, the cryo-flat assembly was originally developed by BATC for the SIRTF project, and was used to characterize the flatness of the full aperture autocollimation mirror used to test the SIRTF Cryo Telescope Assembly.

The SIRTF test was performed cold, and involved injecting an optical test beam through the window of a thermal-vacuum chamber, reflecting the beam off the SIRTF autocollimation flat and the cryo-flat. The test approach included a separate characterization of the combined temperature dependent distortion of the cryo-flat mirror and the vacuum chamber window, which was subsequently subtracted from the autocollimation test data. Any temperature dependent distortion of the cryo-flat mirror was therefore calibrated out of the SIRTF test results. The HRI focus measurement test approach, on the other hand, depended upon the cryo-flat mirror remaining flat between room temperature and -135C. If the cryo-flat developed optical power at cold temperature the test beam would not be collimated and the HRI would have a focus offset built into the instrument. This is in fact what happened.

Characterizing the Cryo-Flat

As part of the investigation, a carefully designed thermal-vacuum test was conducted by BATC to determine the temperature dependent behavior of the cryo-flat mirror. The test involved comparing the wavefront returned from the cryo-flat with that returned by a Zerodur flat located in the same chamber but maintained at room temperature (a temperature at which the flatness of the Zerodur mirror was known). The results of this test indicate that the cryo-flat develops optical power as it cools below room temperature (see Figure 9). The mirror develops concave curvature with a radius of curvature of approximately 18km at the operating temperature of HRI. This corresponds to about 6.1mm of focus offset in the HRI test setup, and has the correct sign to account for the focus being short (i.e., in front of the detector). Within the precision of the measurement this accounts for all of the measured focus offset in the HRI and is compelling evidence that the temperature dependent curvature of the cryo-flat is the root cause of the HRI focus anomaly.

BATC analysis suggests that through-the-thickness variation of the coefficient of thermal expansion of the fused silica used to manufacture the mirror could cause such a distortion, and that plausible values for this effect are consistent with the degree of distortion measured.

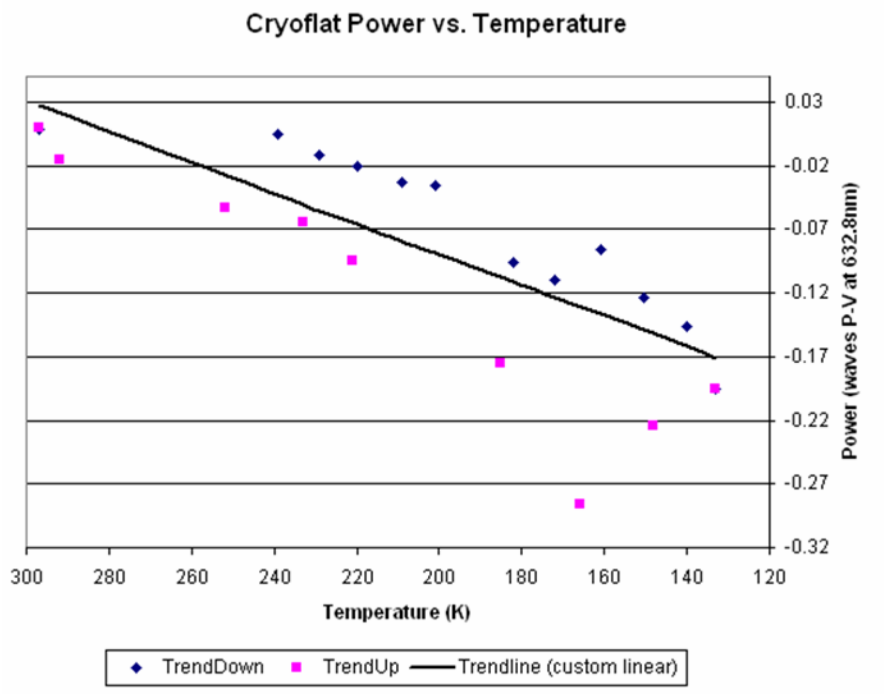


Figure 8. Results of the cryo-flat mirror characterization test showing temperature dependent optical power in the mirror.

The Root Cause of the Anomaly

The root cause of the HRI focus anomaly is temperature dependent distortion of the cryo-flat mirror assembly used to collimate the optical test beam during thermal-vacuum tests of the instrument. Curvature of the cryo-flat at cold operating temperature resulted in the spacing between the primary and secondary mirrors of the HRI telescope being adjusted to the wrong value, building in approximately 6mm of focus offset.

Discussion

This investigation focused on identifying the root cause of the anomaly and ways to improve the in-flight performance of the HRI instrument en route to comet Tempel 1. The Team did not explore the question of why this mistake occurred, and why it was not caught prior to launch. To draw the appropriate lessons learned for the future, these questions should also be investigated.

Observations

NASA flies many imaging instruments that do not have provision for in-flight alignment adjustment. For imaging systems that do not carry alignment mechanisms it is imperative to assure that the alignment is correctly set prior to launch. For systems that do carry alignment mechanisms it is important to assure that any in-flight misalignment falls within the correctable range of the adjustment mechanism. Measuring the focus of an instrument is an optical test, and such tests often rely on test equipment and setups that can be subtle and complex. Accurate measurement of the instrument depends on detailed understanding of the test equipment and setup, and proper certification that the equipment and setup are performing as expected. The most celebrated example of a failure to properly certify optical test equipment is the spherical aberration of the *Hubble Space Telescope*, which was caused by an incorrectly assembled null corrector that resulted in the primary mirror being precisely polished to an incorrect shape.

In the case of *Deep Impact*, the instrument alignment approach depended critically on a piece of optical test equipment—the cryo-flat mirror—remaining flat from room temperature to -135C. Such a critical dependency requires verification. The SIRTF project had carefully calibrated the cold temperature optical distortion of the cryo-flat and chamber window combination for the test setup they had used, and subtracted this combined effect from their final test results. The SIRTF test could not distinguish between distortion of the cryo-flat and the chamber window, but in their test report the SIRTF team speculated that the distortion was probably due mainly to the chamber window, and provided a rationale for why this might be the case. The *Deep Impact* team appears to have been falsely reassured by this language. Instead of conducting a test to verify that the cryo-flat remained flat at cold temperature, the team proceeded under an assumption that it did.

There were indications of a problem in the test data that were obtained during thermal-vacuum tests of the telescope. Computer models predicted only one third as much change in focus from room temperature to operating temperature as was measured in the optical test. While some disagreement between experiment and model prediction is expected, a factor of three is a large discrepancy for coefficient of thermal expansion effects using modern modeling techniques. Instead of pausing to understand this discrepancy, the team attributed the difference to modeling error and chose to believe the test results. We now know that the models accurately predicted the actual amount of focus shift that occurred in flight.

Finally, *Deep Impact* was fortunate in that the imaging of comet Tempel 1 produced high signal-to-noise ratio data, making deconvolution a viable option to restore science performance. Deconvolution in essence trades signal-to-noise for image sharpness. Had this focus anomaly occurred on an astrophysics mission, where signal-to-noise is typically much lower, the ramifications might have been much more serious.

Closing Comment

During the course of this investigation, although there was intense pressure to understand the anomaly quickly and find a way to achieve the mission objectives, the members of the Tiger Team and support staff from BATC, JPL, and the University of Maryland (U of M) worked together in a most professional fashion. Our collective focus was on understanding the facts as they existed and learning the appropriate lessons for the future. We are all gratified that the *Deep Impact* mission has been a spectacular success at comet Tempel 1, and look forward to a new and deeper understanding of these mysterious objects.

Applicable Documents

- BATC Systems Engineering Report No. 2232193, Rev. A, Cryoflat Thermal Vacuum Results

- BATC Drawing No. 2230502, Rev. A, Test Procedure, Cryoflat Thermal Vacuum (as run copy)

- BATC Systems Engineering Report No. 2232794, Deep Impact Cryoflat Test Thermal Analysis

- BATC Systems Engineering Report No. S20447-OPT-055, Results of OSCAR Cryogenic Characterization.

The Tiger Team

The Tiger Team was composed of the following members, with their affiliation and area of expertise identified:

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Bill Smythe	JPL	Instruments
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The following individuals provided material assistance to the Tiger Team:

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End.