Data Collection & Processing

Instruments

The Deep Impact scientific instrument suite consisted\(^1\) of three individual instruments – a high resolution instrument (HRI) and medium resolution instrument (MRI) on the flyby spacecraft, and an impactor targeting sensor (ITS) on the impactor. The instruments are described in greater detail by Hampton et al. (2005). Fundamental parameters of the instruments are shown in Table 1.

The HRI consists of a 10.5 m focal length Cassegrain telescope, with a 30 cm aperture, feeding both a filtered CCD camera and a long-slit imaging spectrometer. The two channels are separated by means of a dichroic beamsplitter, reflecting visible light from 0.34 to 1.05 \(\mu\)m wavelength, and transmitting infrared light from 1.05 to >4.8 \(\mu\)m. The visible light passes through one of 9 filters and is collected by a 1024\(^2\)-pixel split-frame-transfer CCD. The CCD is divided into four independent 512\(^2\)-pixel quadrants, each with a separate readout chain, in which the signal is converted to 14-bit digital data. In-flight star measurements showed that the point-spread function of the HRI visible system is approximately 9 pixels, rather than the expected 2.5 pixels, even after a planned bake-out of the graphite structure of the telescope. To gain back a significant fraction of the expected resolution, a deconvolution algorithm (see below) has been applied to many HRI visible images. Images in this paper that have been deconvolved will be indicated as such.

The infrared light is focused onto the slit of a two-prism spectrometer. The wavelength range of the spectrometer is 1.05 to 4.8 \(\mu\)m, with spectral resolving power of greater than 200 over the entire spectrum, and as high as 700 at 1.05 \(\mu\)m. The spectra are collected on one half of a 1024\(^2\)-pixel HgCdTe MWIR detector, for an effective 1024 spectral and 512 spatial pixels. Similar to the CCD, the IR detector is divided into four quadrants, two of which are converted to 14-bit digital data for storage.

To handle the large dynamic range between the warm nucleus and dim gas emission lines, an anti-saturation filter was placed in the center third of the slit. The filter was chosen to attenuate the spectrum at wavelengths longer than 2.7 \(\mu\)m, and thus the thermal spectrum of the nucleus.

The pixel scale for the HRI visible channel is 2 \(\mu\)rad, and 5 \(\mu\)rad per physical pixel for the HRI IR channel. The slit width of the spectrometer is set to span two physical pixels, and most of the encounter data were taken in 2\(\times\)2-pixel binned modes, with an effective pixel scale of 10 \(\mu\)rad.

The MRI and ITS are structurally very similar. Both are based on a 2.1 m focal length Cassegrain telescope, with 12 cm aperture. The MRI has a nine-position filter wheel, while the ITS light is not filtered. Both MRI and ITS have the same four-quadrant frame-

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\(^1\) It now consists of only two.
transfer CCD as the HRI, and are both converted to 14-bit digital data. The pixel scale for both MRI and ITS is 10 µrad/pix. In-flight star measurements show a 1.6-pixel full-width half-max point spread function for both MRI and ITS over 75% of the field.

The two instruments on the flyby spacecraft (HRI and MRI) are body-mounted on the anti-sunward side of the spacecraft (on the opposite side of the solar array) to enable passive radiative cooling of the HRI IR spectrometer. During the encounter the optical bench of the spectrometer maintained a temperature of ~137.5 K, producing a dark signal rate of 750 DN / sec. The IR detector itself was cooled to 84 K with a two-stage radiative cooler. IR images are built up by slewing the spacecraft at a rate that matches the frame readout time (2.88s minimum for a full frame).

CCD data are collected in several modes from full 1024 x 1024 pixel frames to 64 x 64 pixel subframes, with subframe readout times approximately a factor of two shorter for each factor of two in frame size dimension. Image data are compressed by means of a simple look-up table, which converts the 14-bit data to 8-bit values. To accommodate the desired magnitude of images required during the encounter, nearly all of the prime science data shown were stored as compressed images.

<table>
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<th>Table 1. Deep Impact Instrument Suite Summary</th>
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There are no scan platforms on either spacecraft so all pointing is accomplished by rotating the entire spacecraft. This limits slew rates and also makes the pointing susceptible to dust impacts anywhere on the spacecraft.

**Data Sequences**

During approach, data were regularly transmitted to Earth from the flyby. After separation of the two spacecraft, data from both spacecraft were transmitted to Earth via the High Gain Antenna on the flyby spacecraft. Memory on the flyby spacecraft was last cleared roughly 5 hours before encounter. From that point on, data were taken much
faster than could be downlinked in real time. The auto-navigation system controlled the timing of the sub-sequences of data-taking on both spacecraft to optimize the sequences as knowledge of the distance to closest approach improved. The last image from the impactor that was relayed through the flyby spacecraft was taken 4 seconds before impact. Images and spectra were taken by the flyby until 500 km before closest approach, thus at a range of approximately 700 km. This left the spacecraft in the correct attitude for shielding against dust.

During approach the phase angle (cometocentric) was gradually increasing from 56.9° at E-10 days and during the last day varied only from 62.3° to 63.0°. The lookback images, beginning approximately 45 minutes after impact, were taken at a cometocentric phase angle of 117°.

During the encounter (starting at roughly E-27 hours through the end of look-back imaging), we successfully acquired 218 images from the ITS, 927 MRI images, 575 HRI images, and 1797 long-slit spectral images. An additional 5% or so were obtained with partial corruption in the downlink.

**Pipeline**

The details of conversion to scientific units have been described by Klaasen et al. (2005) and we mention only the uncommon aspects here. Due to limitations of memory on the spacecraft, the 14-bit data for many of our images and spectra are compressed to 8 bits. This leads to quantization noise in some of our data when the compression was set for a planned signal level different from that actually obtained. There are numerous subtleties in reducing the spectrometer data associated with the use of a state-of-the-art detector. These anomalies in the IR detector include non-linearity of response and significant variation of the dark background as a function of readout cycle, including a dependence on the time since the last readout. For this paper we have not used the exact pipeline described by Klaasen et al. (2005) to process the IR data. Instead, the offset level of the IR spectrometer has been applied manually, using changes in the spectra within a sequence to determine a representative dark level, and scaling a master dark frame to that level. Finally, the presence of the anti-saturation filter on the central 1/3 of the infrared detector introduces further complications in the reduction. For the VIS cameras, the only uncommon step is the need to correct for frame-transfer smear when the frame transfer time is not negligible compared to the exposure time.

Both raw data and calibrated data will be delivered to NASA’s Planetary Data System (PDS) via its Small Bodies Node (SBN) by the end of CY2005. They will be reviewed by PDS and made public shortly thereafter.

**Deconvolution**

The HRI is not properly focused because of an error in the ground optical test system. This results in a noticeable loss of resolution (i.e. the images are blurred). Most of the resolution can be recovered using image deconvolution algorithms such as the Richardson-Lucy method (Richardson 1972; Lucy 1994). The largest obstacles to successful deconvolution of the HRI images are image artifacts (e.g. detector blemishes and cosmic ray hits) and the noise properties of the calibrated images. Artifacts will
expand to much larger regions in a restored image. Improvements both to the removal of artifacts and to the deconvolution itself are still underway, but it is clear already that the ultimate science will not be significantly degraded when the deconvolution is complete, as shown in Figure 1.

![Image](image1.jpg)

**Figure 1.** HRI Image 9000985. Left: Original calibrated image. Right: Image after 40 iterations of the Richardson-Lucy algorithm.

**Pre-Impact Activity**

Photometric coverage of the unresolved comet nucleus in various color filters began 63.4 days before impact (I; taken as JD2453555.73932), with samples taken, when possible, approximately every 4 hr using both the MRI and the HRI. Data were obtained at phase angles that rise from an initial value of 25.5° to a maximum of 62.8° 0.3 days before impact. At I - 19 days (phase angle 51.3°) a new sequence of images, more densely sampled, was begun for navigational purposes and continued through I - 0.6 days (referred to as NAV data below). These two independent databases provide excellent coverage for studies of coma activity, the spin state and the dependence of nucleus brightness on solar phase angle. In the preliminary studies reported here we have primarily made use of versions of MRI data taken through the clear filters and based on 5x5 and 15x15 pixel arrays centered on the nucleus.

In order to extract the signature of the spinning nucleus the 5x5 data were adjusted to a common range and heliocentric distance using an inverse square dependence and then an approximate correction for phase angle was applied under the assumption that the nucleus behaves similarly to 19P/Borrelly (Buratti et al 2004). With this renormalization the nucleus signal should, except for the periodic rotational variations, be constant and any non-periodic residual variation with range should be due to coma. In this way it is possible to separate the signal due to the nucleus from the total signal in the 5x5 array. At
the beginning of the data sequence the nucleus represents 13% of the total signal, while at the end of the sequence it represents 94%. The mean nucleus signal was equal to the coma component at about 1 - 21 days.