abstract

Among the many Cassini ISS (Imaging Science Subsystem) images of Enceladus are a few severely undersampled, motion-blurred images that were acquired on ‘flossing/dragging’ events on the closest flyby. During scene-tosign images, ISS is statically aimed at a point that intercepts the predicted path of Enceladus across the sky. The ISS Narrow angle (NAC) and Wide Angle (WAC) cameras are repeatedly triggered together in hope of serendipitously capturing a close-up ‘BOTSIM’ image pair of the body as it passes. Because the events are so fast, the surface footprints and lighting geometry cannot be predicted in advance – a cascade of images are just quickly shuttered at the minimum 5 ms exposure. On each of four ‘flossing/drag’ scenes, surface images were captured. However, the two most recent ‘flossing/drag’ scenes captured on November 2010 and April 2012, respectively, were poorly illuminated – three of four images in one satellite were altogether black. Despite their poor signal quality, they are raw images of Enceladus surface obtained with substantially higher signal/noise ratios than a few meters/pixel. Careful use of Fourier filtering and spatial reconstruction techniques was needed to eliminate image noise and residual electronic banding that was not removed during routine radiometric calibration of the images. Fourier motion deblurring techniques were then applied to correct for significant motion smear.

Periodic Noise Removal: The most prominent periodic electronic noise in ISS NAC and WAC images is a 4 Hz coherent noise pattern (Porco et al. 2004) that appears as horizontal banding in the images (see Fig. 2a). Routine radiometric calibration of the images by the ISS CССС (Computer program for Science Calibration) reduces a significant component of this noise, leaving only very low-amplitude residual banding artifacts (see Fig. 2b). However, as seen in Fig. 2c, residual periodic noise is still present in ISS images, often in linear spectral components of orthogonal banding. The most prominent (by far) periodic noise in the WAC image is horizontal banding that is split into a spatial frequency content along the vertical axis of the images (see Figs. 2d and 2e). Application of a notch filter (see text) to the FFT of filtered image (Fig. 2f) is used to mask spatial frequencies that dominate the horizontal banding. The notch filter is designed to remove the spatial spectral components of orthogonal banding. The notch filter has been separately contrast-stretched to show shadowed area (6 m/pixel) on the left side of the image. Results in context

Figure 1: Example of motion blur in WAC C11-C12 filter image W173106045. Left: A 512×512-pixel section of the spatially uncorrected (i.e. blurred) image that was obtained during a 512×512 section of the WAC band that was produced by the shortest retinoic ray. Right: Image after correction for motion blur. Because no pre-filtering of noise was done prior to deblurring, an iterative approach was used to minimize noise artifacts (Xu and Jia 2010).

Spatial Filtering and Noise Reduction

When an image is obtained under conditions for which the spacecraft cannot accurately track the target, motion blur can significantly degrade the image quality and may severely reduce feature definition. In addition, in a severely undersampled, low-signal image, electronic noise, such as coherent horizontal banding and vertical banding and random noise from radiation and other causes can obscure real features in the image scene. To recover details in our highest-resolution images, we apply two-dimensional Fast Fourier Transform (FFT) signal filtering, which has long been the most successful, widely used approach for removing periodic or other Fourier spectral components from digital images (e.g. Jensen 1968). We divide the approach into correction for blurring due to camera motion (see text) and periodic or other electronic noise, filtering of random noise and other non-systematic artifacts, and removal of high-resolution details from Cassini ISS NAC images by the CISSCAL computer program (Knowles 2012) removes a significant portion of this spatial noise, leaving only very low-amplitude residual banding artifacts (see Figs. 2d and 2e). However, as seen in Fig. 2c, residual periodic noise is still present in ISS images, often in linear spectral components of orthogonal banding. The most prominent (by far) periodic noise in the WAC image is horizontal banding that is split into a spatial frequency content along the vertical axis of the images (see Figs. 2d and 2e). Application of a notch filter (see text) to the FFT of filtered image (Fig. 2f) is used to mask spatial frequencies that dominate the horizontal banding. The notch filter is designed to remove the spatial spectral components of orthogonal banding. The notch filter has been separately contrast-stretched to show shadowed area (6 m/pixel) on the left side of the image. Results in context

Figure 2: Spatial filtering of random noise in NAC BOTSM image N096034053. (a) Raw, unprocessed image except for contrast-stretching to show image content. Raster noise is seen as relatively uniform horizontal banding superposed over the scene. The short (5 m) exposure resulted in poor signal-to-noise characteristics, evident from the red quantum noise level at 0.5 pixels and the poor radiometric calibration. (b) Spatial domain image showing the noise that is removed by the notch filter (Fig. 2f). But the surface noise and contrast stretching artifacts were not strongly elevated above the DN level of random background noise. Fig. 3 shows the unfiltered Fourier transform amplitude image of the noisy image (note: the zero spatial frequency is at the center of the image). The FFT error is shown by the red area of the residual periodic noise in the spatial frequency content along the horizontal axis. A secondary but much weaker error pattern along the vertical axis is due to the non-linear radiometric calibration of the ISS NAC image. Noise is also present in the calibrated images although it is less uniform so that a relatively broad deblurring filter can be used. Random noise and spatially uncorrected pixels are produced by the notch filter. (c) Image showing the noise that is produced by the this notch filter. (d) Image after filtering and spatial noise reduction. Notice that some small impact craters are evident, especially in the top half of the frame. Due to the poor signal strength in the original image and some motion blur, the predicted spatial resolution limit of 720 cm/pixel was probably not realized. However, where details are present, they likely present spatial resolution that is a factor of two or better than the resolution of the BOTSM image alone.

Figure 6: BOTSIM observation ISS_143EN_GRAVITY001_BSS. Left: Frames of ISS image ISS_164EN_ENCEL18001_INMS at 66.9°–29.5° latitude with the area cropped to show the Potemkin crest of the south polar region. The image was obtained on 12 May 2012 with a black and white telescope and a 0.6 m/pixel resolution. The image has been contrast stretched and the black areas in the upper right corner are due to a cloud passing over the region.