PRECISION POINTING RECONSTRUCTION AND GEOMETRIC METADATA GENERATION FOR CASSINI IMAGES.

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Introduction: During the 13 years that Cassini has been in orbit around Saturn, it has taken nearly 400,000 pictures with the Imaging Science Subsystem (ISS) Narrow- and Wide-Angle Cameras (NAC and WAC); these images are freely available through NASA's Planetary Data System (PDS). Before an image can be used for research, two problems must generally be solved:

1) It is necessary to know precisely where the Cassini camera was pointing in space at that time. Approximate pointing information is provided through SPICE C-kernels, but pointing errors can approach 0.04° (~100 NAC pixels), requiring the researcher to embark on a labor-intensive and time-consuming process to determine the correct pointing.
2) The image contents must be analyzed, and various metadata for each pixel must be computed. This metadata might include longitude and latitude for a moon or planet, longitude and radius for a point on the ring plane, or lighting and viewing geometry such as phase, emission, and incidence angles.

The goal of this project is to solve both of these problems and publish the results, through the PDS, to all researchers so that future work can be performed without wasting time repeating these extra steps [1].

Navigation Methodology: We use technology already developed to support Outer Planets Unified Search (OPUS [2]), the PDS Ring-Moon Systems Node search engine, to navigate each image. First, based on available SPICE information, we predict which objects will be present in the image. These objects may include stars, Saturn, moons, or rings. In most cases, we generate a model of how the known objects should appear and perform a 2-D correlation to find the optimal offset that most accurately aligns the model with the image. As necessary, we apply digital filters and other techniques to make the various features easier to detect. When possible, we navigate the images to an accuracy of ~1 pixel, but in all cases we record the probable accuracy actually achieved.

Stars. Image navigation using stars is preferred when available, as star positions are known with extreme accuracy. We use the UCAC4 and Yale Bright Star catalogs [3,4], which together provide a database of almost all stars to magnitude 16. We adjust apparent star position for both stellar aberration and proper motion and also take into account smear caused by spacecraft rotation during long exposures. As a given star pattern will always correlate with an image at some offset, even if the image doesn't contain any stars, we also need to sanity-check the results. We do this by performing aperture photometry on all matched stars, comparing the measured brightness to the brightness predicted by taking the black body spectrum from the star's spectral class and convolving it with instrument and filter response curves. If the photometry does not match within a reasonable error, the star navigation fails and other techniques will be tried (Fig. 1).

Rings. Saturn's rings are a complex dynamical system. Resonances, self-gravity wakes, and the effects of embedded moonlets result in rings that are highly variable both spatially and temporally, and various illumination and viewing geometries make the same ring features appear very different. To create a model of the rings [5], we use all of the circular and near-circular features that are known [6,7,8,9]. As the layout of the rest of the rings is unknown, we must be careful not to include more data than necessary in the model. Since our correlation function is especially good at matching edges, we mark the sharp edges of ringlets or gaps and then shade the model away from each edge so that no false sharp edges are introduced. If the resolution of the image is better than the error bars on the known features, we need to apply a Gaussian blur to both the image and the model to allow the correlation to succeed; this results in navigation accuracy worse than the desired ~1 pixel. This technique is especially important for the outer edges of the A and B rings, which have complex time-varying orbits and many up-close images (Fig. 1).

Icy Satellites and Saturn. Large bodies can be approximated by Lambert-shaded spheres when the images are taken from a sufficient distance. In these cases, correlation is simple and accurately matches the sharp body limbs of the image and model. However, when the body has insufficient curvature showing, is taken at a scale where craters cause a notably irregular limb, or is a close-up where no limb is showing, other techniques must be used.

Our primary technique is "bootstrapping" [5] – the use of images that *can* be navigated using limbs, stars, or other techniques to provide additional information that allows the navigation of otherwise unnavigable images of the same object. In the case of icy satellites, this additional information takes the form of reprojected maps of craters and other surface features. We automatically create our own maps that are geographically precise as they are needed (Fig. 2). Different maps are created for different illumination geometries because the shadowing of craters affects the image navigation.

The accuracy of the map is limited by the accuracy of the navigation of the original seed images. Although the images later navigated using surface features may be much higher resolution, the navigation accuracy of the resulting map can never improve. When a high-resolution image is navigated using a low-resolution map, both the map and the image must be blurred to allow correlation to succeed. Any resulting reduction in navigation accuracy is propagated to later images.

Bootstrapping is a sequential process. The addition of images freshly navigated based on previous maps permits the creation of new, more complete maps that may permit the navigation of even more images. This process continues as long as necessary.

The existing published maps of the icy satellites are not suitable for our use for two reasons: they do not have adequate geometric precision for image navigation, and they are not available for different lighting geometries. Our own bootstrapped solutions are geometrically more precise, although we make no attempt at obtaining photometric accuracy.

Titan. Navigation of images containing only Titan provide a unique challenge because Titan's dense atmosphere makes it "fuzzy" (with no sharp limb), the atmosphere does not behave like a Lambert-shaded sphere, and the visual properties of the atmosphere change dramatically with filter. We have developed a novel navigation technique that takes advantage of the visual symmetry of Titan's atmosphere to provide navigation along one axis, and a library of 1-D atmospheric profiles to provide navigation along the orthogonal axis.

Geometric Metadata: In addition to the reconstructed pointing information, we intend to provide geometric metadata for each pixel of each image in the form of image backplanes. More than 90 backplanes will be available. Some examples are:

• Identification of the frontmost body occupying the pixel

• Latitude and longitude of the frontmost body, or radius and inertial longitude in the ring plane

• Incidence, emission, and phase angles at the surface of the frontmost body or ring plane

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References: [1] French, R. S. et al. (2014) *DPS 46*, 422.01. [2] Gordon, M. et al. (2016) *DPS 48*, 423.02. [3] Zacharias, N. et al. (2013) *AJ*, *145(2)*. [4] Hoffleit, D. et al. (1991) *Yale University Observatory*. [5] French, R. S. et al. (2016) *DPS 48*, 121.14. [6] El Moutamid, M. et al. (2016) *Icarus, 279*, 125–140. [7] Nicholson, P. D. (2014) *Icarus, 227*, 152–175. [8] Nicholson, P. D. (2014) *Icarus, 241*, 373–396. [9] French, R. G. (2016) *Icarus, 274*, 131–162.

Figure 1: N1622036815_1, an image successfully navigated with both stars (boxes) and a model of the rings (shaded area top left).

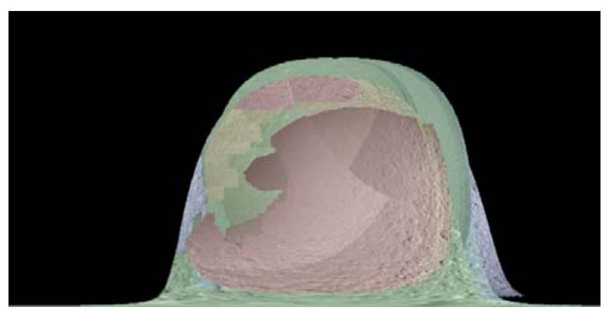

Figure 2: A reprojected map of the surface of Rhea automatically generated by the bootstrapping process. Latitude runs up and down and longitude runs left and right. The map is colored by which seed image was used to provide the surface data.