# Post-Print Astrometry of Seven Saturnian Inner Near-Ring Satellites Affected by Scattered Light in Cassini Images

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**Date:** 2023-12-15T00:00:00+00:00

## Abstract

The Cassini spacecraft carried the Imaging Science Subsystem (ISS: Imaging Science Subsystem) and captured images of Saturn’ s inner moons between 2004 and 2017. In some images, the inner moons of Saturn are very close to Saturn’ s rings, and the observed objects are affected by scattered light from the rings, resulting in poor measurement accuracy or even making measurement impossible. Therefore, a background elimination algorithm suitable for such images is proposed, which can measure Saturn’ s inner moons affected by scattered light from Saturn’ s rings. We reduced 70 ISS images of 7 ring-adjacent inner moons (Janus, Epimetheus, Atlas, Prometheus, Pandora, Methone, and Anthe) and compared them with the method without scattered light elimination. The results show that this method can improve the accuracy by at least 43%. Compared with the Jet Propulsion Laboratory’ s Saturnian satellite ephemeris lk SAT415, the mean residuals of the measured right ascension and declination are 0.72 km and 2.26 km, respectively, and the standard deviations are 10.99 km and 11.36 km.

## Full Text

## Preamble

Vol. 64 No. 6
November 2023

**Acta Astronomica Sinica**

**Astrometry of Cassini ISS Images of 7 Near-ring Inner Satellites of Saturn Affected by Scattered Light**

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## Abstract

The Imaging Science Subsystem (ISS) onboard the Cassini spacecraft captured numerous images of Saturn' s inner satellites between 2004 and 2017. In some of these images, the satellites appear extremely close to Saturn' s rings, and the scattered light from the rings degrades measurement precision or even renders measurement impossible. To address this issue, we propose a background elimination algorithm specifically designed for such images, enabling astrometric measurement of Saturn' s inner satellites affected by ring-scattered light. We have reduced 70 ISS images of seven near-ring inner satellites (Janus, Epimetheus, Atlas, Prometheus, Pandora, Methone, and Anthe) and compared our results with those obtained without scattered light removal. The proposed method improves measurement precision by at least 43%. Compared with the Jet Propulsion Laboratory' s Saturn satellite ephemeris SAT415, our measurements yield residual means of 0.72 km and 2.26 km in right ascension and declination, respectively, with standard deviations of 10.99 km and 11.36 km.

**Key words:** astrometry, techniques: image processing, methods: data analysis, planets and satellites: individual: Janus, Epimetheus, Atlas, Prometheus, Pandora, Methone, Anthe

## 1. Introduction

From its arrival at Saturn in 2004 until its final plunge in 2017, the Cassini spacecraft' s Imaging Science Subsystem (ISS) acquired a vast collection of images of Saturn and its satellites, which have been widely utilized in scientific research. In 2008, Cooper et al. [?] used ISS images to discover the new Saturnian satellite Anthe and conducted dynamical studies, followed by joint astrometric reductions of several major Saturnian satellites [?]. Tajeddine et al. [?, ?] performed astrometric reductions of Saturn' s seven major satellites using ISS images. Zhang et al. [?, ?, ?, ?] reduced ISS images of Enceladus, Helen, Anthe, Phoebe, and other Saturnian satellites, while also investigating various ISS image reduction techniques. In 2020, Lainey et al. [?] combined ISS astrometric data to reveal that Titan' s outward migration rate is a hundred times faster than previously thought. These studies collectively demonstrate the significant scientific value of high-precision astrometry of ISS images.

Among Saturn' s satellites, several small inner satellites orbit very close to the rings or even within ring gaps, making them extremely difficult to observe from ground-based telescopes and requiring large ground-based or space telescopes for detection. In 2001, Poulet et al. [?] published 145 astrometric positions of four inner satellites (Janus, Epimetheus, Prometheus, and Pandora) derived from observations made with the ESO 3.6 m telescope in August 1995 and the Hubble Space Telescope in November 1995, using these data to compute orbital parameters. Porco et al. [?] discovered new small inner satellites including Methone, Pallene, and Polydeuces from Cassini ISS images in 2005, while also studying the orbits of both new and known satellites. Spitale et al. [?] determined orbital data for ten Saturnian inner satellites using various datasets, employing Gaussian fitting to determine satellite centers in Cassini images and resorting to manual selection of peak intensity pixels for difficult-to-measure objects. However, as demonstrated by Zhang et al. [?], Gaussian methods perform poorly for ISS images, and manual peak selection yields even worse precision. Zhang et al. [?] also published a set of measured positions for Anthe, expanding upon and improving the precision of earlier data published by Cooper et al. [?] in 2008. Jacobson et al. [?] updated orbital data for Saturn' s inner satellites using subsequent ISS images, building upon the work of Spitale et al. [?]. Cooper et al. [?] further refined orbital and mass measurements using Cassini observations of several inner satellites from 2004–2013. In 2018, Cooper et al. [?] released Caviar, a dedicated astrometric software package for Cassini ISS images, along with astrometric positions for several near-ring inner satellites. Lainey et al. [?] measured ISS images in 2019 to update physical parameters including mean densities for multiple Saturnian inner satellites.

These studies establish that Cassini images provide crucial data and occupy an important position in the astrometry of Saturn' s near-ring inner satellites. However, previous ISS image reductions did not explicitly address whether images affected by scattered light were used. The standard astrometric software Caviar encounters problems when processing such images—some cannot be measured at all, while others yield low precision, primarily because it does not handle scattered light backgrounds. High-precision measurements of these images can provide additional data for dynamical studies of the Saturn system and are highly beneficial for detailed investigations of tidal effects and libration models [?].

Various methods have been developed for complex background processing. Shen et al. [?] proposed a target detection method based on background elimination that sets pixel values below a threshold to zero and generates a mask image through stacking of consecutive frames and morphological dilation to block stars. This approach requires multiple consecutive images with relatively simple backgrounds and fixed stars as references, conditions that ISS images do not satisfy. Xie et al. [?] developed an algorithm to eliminate Uranus' s symmetric halo before background fitting, achieving high-precision astrometric positions, but ISS images lack such symmetric halos. Li et al. [?] applied mathematical morphology operations to estimate star image backgrounds and used grayscale morphological Top-Hat transforms to eliminate backgrounds, effectively suppressing non-uniform stray light backgrounds. Popowicz et al. [?] proposed estimating strongly varying astronomical backgrounds by interpolating missing pixels after removing small foreground targets such as stars, cosmic rays, or impulse noise. These methods are clearly applicable only to specific situations and are not suitable for handling scattered light backgrounds in ISS images.

This paper investigates astrometric techniques for point-source imaging of observation targets affected by scattered light from Saturn' s rings in ISS images. We propose a simple scattered light background elimination method and apply it to measure 70 relevant images, yielding a set of high-precision astrometric positions for near-ring inner satellites. Section 2 presents the centroiding algorithm for targets affected by scattered light, Section 3 outlines the main steps of ISS image astrometry, Section 4 presents astrometric results for several small near-ring inner satellites, Section 5 compares and analyzes the measurement results and proposed method, and Section 6 summarizes our work.

## 2. Centroiding of Near-ring Inner Satellites Affected by Scattered Light

In ISS images of near-ring inner satellites, the point-source imaging of satellites is affected to varying degrees by scattered light from Saturn' s rings. While some targets are sufficiently distant from the rings for the effect to be negligible, others are so close that scattered light severely interferes with center measurement, making conventional methods ineffective and requiring manual selection of peak pixels as the center. [Figure 1: see original paper] illustrates such a case where a satellite is positioned very close to the rings and affected by scattered light. The inner satellite Methone is highlighted with a yellow box near Saturn' s rings, with a magnified local view shown in the upper right corner. This magnified view clearly shows that Methone' s image is significantly affected by ring-scattered light. Failure to address this scattered light background in centroiding calculations reduces precision and, in severe cases, prevents standard centroiding algorithms from obtaining reliable results.

We have investigated centroiding for such inner satellites affected by ring-scattered light and propose a simple method. The method comprises three steps: determining background and foreground regions, background fitting, and target centroiding.

**Step 1: Determining Background and Foreground Regions.** In the region near the target, we first locate the peak pixel and designate its position as the initial target center. The target' s full region includes both background and foreground components. We assume both the full and foreground regions are square areas, as illustrated schematically in [Figure 2: see original paper]. In the diagram, the black dot represents the target center, the white area represents the foreground region, and the shaded area represents the background region. L1 is the foreground region side length, and L2 is the full region side length. L1 and L2 can be set according to specific circumstances. In practice, the minimum value of L1 is generally 3 pixels, and the minimum value of L2 is 7 pixels. If the star image peak intensity is large, these values are expanded, ensuring that L2 $>$ 2L1 + 1.

**Step 2: Background Fitting.** After determining the foreground and background regions, we model the stray light background based on the background region. A typical stray light background is shown in [Figure 3: see original paper], which presents a 3D view of a 15$×$15 pixel neighborhood around Methone from [Figure 1: see original paper], where height represents pixel intensity. The background intensity distribution approximates a 2D plane, so we fit the background region' s intensity distribution with a 2D plane using least squares, as expressed by:

where (x, y) are the coordinates of pixels in the background region (coordinate system reference [Figure 2: see original paper]), z is the pixel intensity, and a, b, c are fitting coefficients.

It should be noted that the initially defined background region is empirical or visually determined and does not represent a completely accurate background area. To achieve a more accurate background fit, we must reduce noise or the influence of non-background pixels within the region. Therefore, the background fitting process requires iterative refinement, as detailed below.

First, assume S1 is the set of all pixels in the background region, with each pixel at coordinates (i, j) having intensity fij. Compute the mean m and standard deviation $\sigma$ of all fij values, then reject pixels with intensities not satisfying m - $2\sigma \leq$ fij $\leq$ m + $2\sigma$ (i.e., $2\sigma$ outlier rejection) to obtain a new background pixel set S2.

Next, perform plane fitting using least squares on set S2 and corresponding fij values to obtain plane equation p1. Calculate the background intensity value bij for each pixel in S2 using p1, then compute the intensity difference $\Delta$ij = fij - bij for each pixel. Perform another $2\sigma$ outlier rejection on S2 based on $\Delta$ij to obtain a new background pixel set S3.

Finally, perform least squares plane fitting again on set S3 and its pixel intensities fij. Typically, after two refinement iterations, a satisfactory background plane fitting result is achieved.

**Step 3: Target Centroiding.** After fitting the background plane, the background intensity value for each pixel in the target' s full region can be calculated. Subtracting the background intensity from the original intensity effectively eliminates scattered light from the background. For the star image with updated intensities, we compute the target' s center position using the modified moment centroiding algorithm proposed by Zhang et al. [**?**].

## 3. Astrometric Procedure

We use Caviar, a dedicated software package for ISS image astrometry, to measure near-ring small inner satellites. While Caviar provides a complete astrometric pipeline for ISS images, it performs poorly on images with targets affected by scattered light. By embedding the aforementioned scattered light elimination centroiding algorithm into Caviar, we achieve accurate astrometry for such images.

The entire centroiding and measurement process includes the following steps:

1. **Camera pointing correction.** First, read the relevant Cassini trajectory and instrument files (downloaded from: https://naif.jpl.nasa.gov/pub/naif/pds/data/co-s_{j_e}v-spice-6-v1.0/cosp_{1000}/data/) to extract the camera's initial pointing. Then use DAOphot' s Find algorithm [?] to detect point sources in the image. Based on the initial camera pointing, load stars from the Gaia EDR3 catalog [?, ?] and apply classical aberration formulas to correct for stellar aberration and compute their image coordinates. Match image stars with catalog stars using a combination of automatic [?] and manual inspection methods, then correct the camera pointing using least squares.
2. **Target center measurement.** Apply the scattered light elimination centroiding algorithm described above to compute the target' s center position in image coordinates. Perform geometric distortion correction on the target using Owen' s Model 1 [?], then apply phase correction based on the geometric relationship among Cassini, the Sun, and the observation target during observation [?] to obtain the final image coordinates.
3. **Compute target right ascension and declination.** Using the camera pointing and target image position, compute the target' s right ascension and declination via inverse heliocentric projection, yielding the final astrometric position in Cassini-centered ICRS (International Celestial Reference System) coordinates.

Following these three steps, we obtain astrometric positions of near-ring inner satellites in each ISS image.

## 4. Astrometry of Seven Near-ring Inner Satellites

We collected 70 ISS images of near-ring inner satellites that show obvious scattered light effects (downloaded from the PDS website: http://pds-imaging.jpl.nasa.gov) and performed astrometric reductions. [Figure 4: see original paper] shows examples of ISS images of near-ring inner satellites. In these images, the measurement targets are located near Saturn' s rings, appear as point sources, and are all affected by ring-scattered light. The near-ring satellites are faint and are marked with yellow boxes and yellow text. Since the inner satellites in the left and middle images are particularly dim, magnified local views are also provided. All images are 1024 × 1024 pixels in size.

These images were taken between 2004 and 2014, with observation targets not necessarily being inner satellites—many were intended for ring observations. This measurement campaign involved seven small inner satellites: Janus, Epimetheus, Atlas, Prometheus, Pandora, Methone, and Anthe. lists these satellites and their observation counts.

A total of 71 measurements were obtained. presents all results. Column 1 lists the Cassini image ID, Column 2 gives the mid-exposure time in UTC, Column 3 identifies the measured satellite, and Columns 4-5 provide the measured right ascension $\alpha$ and declination $\delta$ in Cassini-centered ICRS coordinates. For user convenience, the table also includes camera pointing and target image positions in Columns 6-10. Columns 6-8 contain Cassini camera pointing data, including right ascension $\alpha$c, declination $\delta$c, and twist angle, all in the same coordinate system (see [**?**] for pointing details). Columns 9-10 give the target's pixel coordinates in the image, where the origin is at the upper left corner, with x increasing to the right and y increasing downward. Recognizing that users may have better phase correction methods, Columns 11-14 provide right ascension, declination, and pixel coordinates before phase correction. Since image N1462095966 contains both Epimetheus and Pandora, the total dataset includes 71 astrometric measurements.

## 5. Analysis and Comparison

To evaluate our measurements, we compared them with calculations from the Jet Propulsion Laboratory' s Saturn system ephemeris SAT415. Specifically, we converted SAT415 target positions to Cassini-centered ICRS coordinates accounting for light aberration and light-time, then computed residuals between our measurements and these calculated positions. Using the image pixel scale, these residuals can also be expressed as distances. Additionally, measurement residuals in the image coordinate system' s x and y directions can be obtained. Three scales of residuals were ultimately derived, as shown in [Figure 5: see original paper]-[7]. [Figure 5: see original paper] shows residual distributions in x and y directions, [Figure 6: see original paper] displays residuals in $\alpha$ cos $\delta$ and $\delta$ directions (in arcseconds), and [Figure 7: see original paper] shows distance residuals in $\alpha$ cos $\delta$ and $\delta$ directions (in kilometers). provides statistical results for measurement residuals, including means and standard deviations for all three scales both before and after phase correction.

The results show clear improvement in both accuracy and precision after phase correction. After phase correction, the pixel-level measurement precision reaches 0.10 pixel in x and 0.14 pixel in y, while distance precision achieves 10.99 km in right ascension and 11.36 km in declination. According to [**?**], this distance precision is at least an order of magnitude better than ground-based telescope observations, primarily due to the advantages of close-range space observations.

To specifically assess the impact of scattered light removal, we compared results from our method with those obtained without scattered light elimination. Among the 70 images, 10 could not be measured at all without scattered light removal. For the remaining 60 images, we measured target positions without background elimination and compared these with JPL ephemeris SAT415 to compute residuals. Statistical comparison of residuals from both methods is presented in , which shows that the scattered light removal method improves both mean residuals and standard deviations. Standard deviations improve from 0.20 pixel to 0.09 pixel in x and from 0.20 pixel to 0.14 pixel in y.

As mentioned, scattered light removal renders the previously unmeasurable 10 images measurable, and comparison of the 60 images measurable by both methods demonstrates significant improvement from our approach.

### Comparison with Previous Work

Some of our measurements overlap with previous studies: 41 images overlap with [?], 28 with [?], and after accounting for overlaps between these two studies, we found 48 images with repeated measurements. We compiled these 48 images' measurement data from the literature, retaining only the best result (i.e., the measurement closest to the ephemeris-calculated value) for cases with multiple measurements. Using these data, we computed residuals for both previous and our measurements relative to ephemeris SAT415. The residual statistics are shown in .

Our measurements achieve standard deviations of 0.11 pixel in x and 0.16 pixel in y, compared to 0.18 pixel and 0.56 pixel from previous measurements—representing precision improvements of 64% and 250%, respectively. This substantial improvement stems primarily from the lack of background elimination and the use of Gaussian centroiding in [?, ?]. These results demonstrate that the combination of modified moment method and background elimination yields dramatic precision improvements for point-source images affected by scattered light. For reference, presents results for the 48 repeatedly measured images, including both previous measurements and our corresponding results, along with ephemeris-calculated positions. Note that [?] used a slightly different coordinate system; the data from [?] in [TABLE:6} have been transformed to match our system for consistent comparison.

## 6. Conclusion

When performing astrometry on ISS images where point-source targets are affected by scattered light from Saturn' s rings, direct application of modified moment or Gaussian centroiding algorithms reduces measurement precision or makes measurement impossible. To address this issue, we propose a background elimination centroiding algorithm that uses plane fitting to model scattered light backgrounds, followed by modified moment centroiding on the background-subtracted image. This method successfully measures images that cannot be measured using Gaussian or modified moment methods alone and further improves precision for images that could be measured conventionally.

Using our proposed method, we measured 70 ISS images and obtained 71 astrometric positions for seven small inner satellites: Janus, Epimetheus, Atlas, Prometheus, Pandora, Methone, and Anthe. Compared with JPL ephemeris

SAT415, our measurements yield residual means of 0.04 and -0.02 pixels in image coordinates x and y, with standard deviations of 0.10 and 0.14 pixels, respectively. In Cassini-centered ICRS coordinates, the standard deviations of residuals are 10.99 km in right ascension and 11.36 km in declination. This represents a precision improvement of over 43% compared with algorithms that do not eliminate scattered light backgrounds, and an even more significant improvement compared with previous measurements.

These measurements demonstrate that our method is effective for astrometry of ISS images of inner satellites affected by scattered light and provide high-precision data supplements for dynamical studies of these targets. The method can also be applied to other targets in ISS images. We note that the proposed method has limitations: when a satellite' s position is extremely close to Saturn' s rings, the background is affected by scattered light too strongly to identify appropriate background regions, and the background intensity distribution no longer follows a planar pattern. In such cases, our method cannot achieve measurement. Future research will continue to investigate these challenging cases to obtain more valuable high-precision astrometric data for Saturn' s satellites.

## Acknowledgments

We thank the anonymous referee whose comments significantly improved the quality of this paper.

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*Note: Figure translations are in progress. See original paper for figures.*