ASTROMETRY OF FAINT PLANETARY SATELLITES WITH WFPC2 OF HUBBLE SPACE TELESCOPE

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Abstract. Only the Hubble Space Telescope (HST) can detect about 20 of the faint satellites discovered with the two Voyager spacecraft. We describe here the techniques used in obtaining astrometric positions of the inner satellites of Uranus with the Wide Field Planetary Camera 2 (WFPC2) of HST, and those planned for our scheduled observations of the inner Neptunian satellites.

1. Introduction

Of the 23 satellites discovered with the two Voyager spacecraft, only 3 are detectable from the ground. Any follow-up astrometric observations would have to be made with HST. In fact, HST observations have already been attempted, or are planned, for all of these satellites (Pascu, 1996). But how accurate are these observations, and what techniques are necessary to achieve the highest accuracy? We will try to answer these questions from our experiences with HST observations of the inner Uranian satellites and our plans to observe the inner Neptunian satellites. These faint satellites

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account for the bulk of the Voyager discoveries, and our methods are generally applicable to the remaining few.

Ten inner satellites of Uranus were discovered by Voyager 2 in 1986. They range in brightness from 20th to 24th V mag., and in separation from the planetary limb, from 2 to 5 arcsec. The six inner satellites of Neptune were discovered in 1989 – also by Voyager 2. They range in brightness from 20th to 25th V mag., and in separation from the planetary limb, from 1 to 5 arcsec. None of these satellites had been seen since their discoveries, except for an heroic ground-based detection of Proteus by Colas and Buil (1992).

2. The Observations

In August of 1994 we obtained 33 observational frames of the inner Uranian satellites, taken with PC1 (Planetary Camera) of the WFPC2 (Wide Field Planetary Camera 2) of HST (Zellner *et al.*, 1994; Currie *et al.*, 1994; Pascu *et al.*, 1995). Four different color filters were used (F439wB, F569wV, F675wR, F791wI) and exposure times ranged from 8 to 120 seconds. The upper exposure limits were determined by the two-pixel motions of the inner satellites, while the shorter exposure times were used to prevent saturation in the image of Ariel.

The satellites were recovered by electronically blinking together the two longest exposure F791wI frames in each set and identifying the moving objects. As expected, we recovered eight of the ten inner satellites. Epsilon-ring shepherds, Cordelia and Ophelia, were too faint and moving too rapidly for detection. In addition to the faint satellites, images of Ariel and Miranda were on all the frames. The image of Miranda was unsaturated on all frames, while that of Ariel had some saturation at its center on 15 frames, but no blooming.

3. Astrometric Reductions

Our strategy for the astrometric reductions was to use the highly accurate JPL ephemeris positions of Miranda and Ariel (Jacobson, 1995) to calibrate the scale and orientation of the frames and to use Miranda's image as the coordinate reference origin for the inner satellites.

The images of Miranda, Ariel and the eight inner satellites were measured by fitting them with 2-dimensional Gaussians. The background around the faint satellites near the planet and rings was also modelled. While the point spread function (psf) in PC1 is not typically Gaussian, the satellite images for the most part are not typical psfs for PC1. The faint satellite images are slightly trailed and Ariel's image is just resolved, in addition to being saturated on several frames. A Gaussian appeared to be a better approximation than an archival psf for the distorted images, although centroiding test comparisons with another model showed little difference at the 0.01 pixel level. For the bright satellites – Ariel and Miranda – the measurement precision was expected to be about 0.01 pixel (0.5 mas), and for the faint satellites, 0.1 – 0.5 pixels.

The focal plane of PC1 is affected by geometric distortion due to the magnesium flouride field flatteners located 2 mm above the CCD chip. This distortion is further modified because the optical axis of the HST is at the corner of the PC1 field, not at its center. Three recent studies have produced mathematical models useful for its correction. These are: Holtzman *et al.* (1995), Trauger *et al.* (1995), and Gilmozzi *et al.* (1995). Holtzman and his collaborators modelled the distortion as a general cubic with 10 terms, and fit the model to 30 exposures of Omega Cen. in the F555wV filter. A vector diagram of the nature of the distortion can be seen in their paper. Trauger et al. used the same model but compensated for the bandpass of the observations. While the same general polynomial model was used, each coefficient in each coordinate was computed from 3 empirically derived coefficients of a function involving the refractive index of the MgF2 field flattener. The differences in distortion correction between the F439wB and the F791wI filters varied from zero pixels in the center to 0.35 pixels in the corners.

A comparison of the Holtzman *et al.* and the Trauger *et al.* models at F555wV is shown in Figure 1. Not only is the disagreement asymmetric with respect to the center, but more important, it amounts to as much as 1 pixel (= 46 mas) in the corners. Even in the inner 400×400 pixel matrix, the discrepancy is as large as 0.2 pixel (= 10 mas).

The model of Gilmozzi *et al.*, although wavelength independent, is considerably more complex. It involves the sums of products of Legendre polynomials, in x and y, of order 0 to 3. The correction to each coordinate requires the sum of 16 such products. The 16 coefficients of these products in each coordinate were determined from fits to stars in the globular NGC1850. While the vector diagram of this model is similar to those for the Trauger *et al.* and the Holtzman *et al.* models, a comparison with the Trauger *et al.* model (Figure 2) shows sizeable discrepancies – larger than those shown in Figure 1. In the corners they're as large as one pixel, and 0.3 pixel in the central 400×400 matrix.

For our reductions, we used the Trauger *et al.* model because our observations were made in four different filters. The distortion-corrected measurements of Ariel and Miranda were compared with their relative ephemeris positions supplied by Jacobson (1995) of Jet Propulsion Laboratory (JPL). The ephemerides of these two moons was based on the GUST86 Uranian satellite theory (Laskar and Jacobson, 1987). Measured separations were compared with ephemeris predictions to determine scale values for each

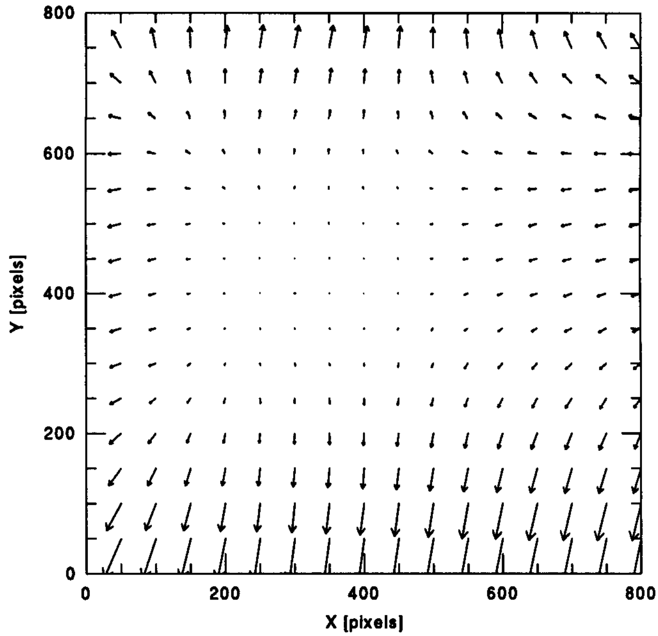

Figure 1. A vector diagram comparing the distortion model of Holtzman *et al.* (1995) with that of Trauger *et al.* (1995) at 555nm. The sense is Holtzman *et al.* minus Trauger *et al.* corrections (times 100). In the corners the disagreement is as large as 1 pixel (= 46 mas), and in the central 400 × 400 matrix, the discrepancy is as large as 0.2 pixel.

TABLE 1. Scale of PC1 (arcsec/pixel)

Filter	set 1	set 2	set 3	Mean(me)
F439wB	0.045572	0.045559	0.045550	0.045560(4)
F569wV	0.045579	0.045567	0.045551	0.045566(4)
F675wR	0.045580	0.045563	0.045547	0.045564(5)
F791wI	0.045585	0.045568	0.045558	0.045570(4)
Mean(me)	0.045580(6)	0.045565(6)	0.045552(5)	0.045566(2)

exposure. The ephemeris position angles of Ariel with respect to Miranda were used to determine orientation corrections, for each frame, to the equator and equinox of the GUST86 ephemeris. Mean scale values are given for each filter and data set in Table 1.

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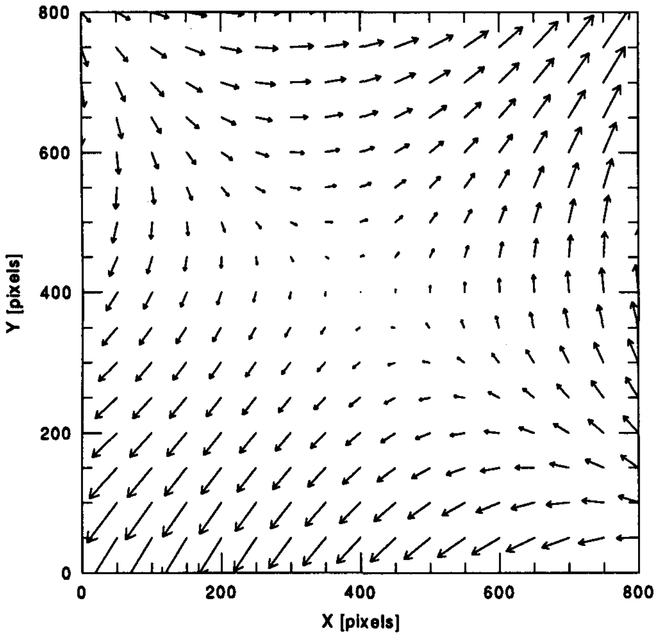

Figure 2. A vector diagram comparing the distortion model of Gilmozzi *et al.* (1995) with that of Trauger *et al.* (1995) at 555nm. The sense is Gilmozzi *et al.* minus Trauger *et al.* corrections (times 100). The differences are larger than those of Figure 1; the inner 400 × 400 pixel matrix has differences as great as 0.3 pixel.

4. Discussion; Assessment of Precision

The measured coordinates of the faint satellites were referred to those of Miranda and the individual frame scale and orientation calibrations applied. Since the calibrations were made in separation and position angle, that coordinate system was used for the faint satellite orbital corrections. These observed positions were compared to computed positions based on the orbital elements of Owen and Synnott (1987) and least squares corrections derived for the mean motions only. The remaining residuals following the orbital correction are the errors of observation. These are plotted for each of the faint satellites against their V magnitudes (from Thomas *et al.*, 1989) in Figure 3. Since the solutions in separation and position angle were compatible, we concluded that the calibrations were also compatible and made a final solution, combining the equations of condition for each satellite.

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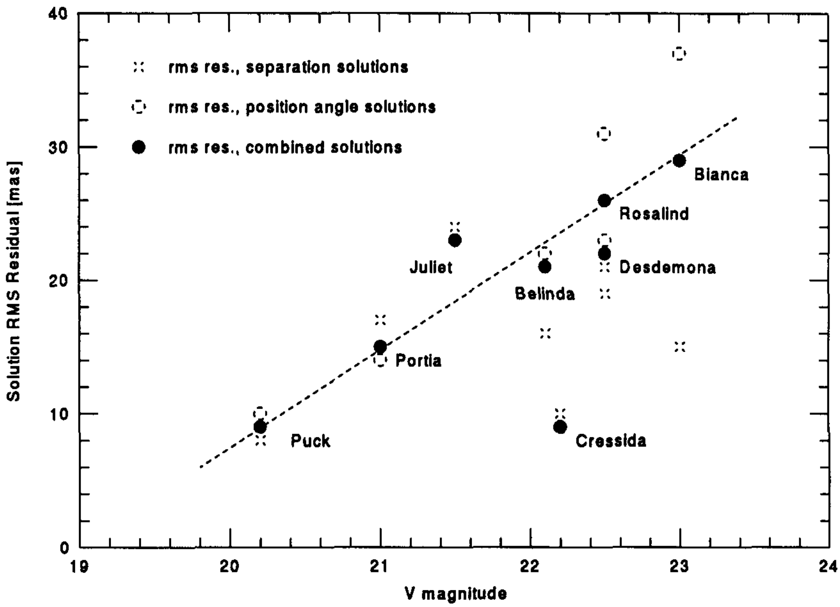

Figure 3. The correlation of the rms residuals after solution with the magnitude of the satellite. This correlation demonstrates that the residuals are related to the signal-to-noise in the faint satellite images, indicating a measuring error limitation.

Although we did not produce observations of Miranda and Ariel independent of the scale and orientation calibrations, we can comment on the expected accuracy of such observations. For full-well images the measurement precision is below the 1 mas level. The limitation on astrometric accuracy would, thus, be due to the accuracy of the distortion corrections and the scale and orientation calibrations.

The scale and orientaion calibrations are only as good as the Ariel – Miranda ephemerides. A comparison of the GUST86 ephemeris with a Voyager integration ephemeris showed agreement at about 5 mas. However, the GUST86 ephemeris was expected to be the better of the two at this epoch because of run-off in the integration. This means that the calibrations were accurate to at least one part in 4000. In fact, it should be possible to do much better. Since the mass of Uranus and the mean motions of the satellites are known to a high degree of accuracy, the scales of the orbits are also known to the same accuracy. If the satellites are observed near their elongations where the scale errors are maximum and the longitude errors are minimum, the scale calibration would only be limited by the measuring precision. All this is contingent on the accuracy of the geometric distortion correction. Figures 1 and 2 show us that at least two of the distortion models are not as accurate as the claimed 0.1 pixel. Even within the central 400×400 matrix of the PC1 chip, the Trauger *et al.* model differs from the Gilmozzi *et al.* model by as much as 0.3 pixel in each coordinate.

In addition, while Table 1 shows only a marginal excess color dependence of the scale, the position angle dependence is significant, amounting to 0.3 pixel. This suggests that the Trauger *et al.* model may be incomplete, although the ephemeris errors may account for a third of this error. In any case, for full-well images such as Ariel and Miranda, the astrometric precision, about 5 mas, is limited by the accuracy of the distortion model and the distance from center, not by centroiding precision. Once an improved model for the distortion is available, it will be possible to provide very accurate calibrations, resulting in positional accuracies of 1 mas for the brighter satellites.

The situation is clearly different for the faint satellites. The smaller separations and the central CCD position makes the distortion correction errors and calibrational errors much less important to their precise astrometry. In particular, if Puck were used as the coordinate origin rather than Miranda, the distortion correction errors and the calibrational errors would amount to 0.1 pixel or less (about 4 mas). Figure 3 suggests that it is low signal-to-noise (S/N) in the images of the faint satellites which limits the accuracy of the observations, and implies measuring errors ranging from 0.2 to 0.6 pixel. Since the S/N is maximum in the red filters (e.g. F791wI), such filters should also be calibrated for astrometry.

5. Neptunian Satellites

We are expecting HST observations of the inner Neptunian system at the 1997 opposition. Astrometry on Neptune's inner system is considerably more difficult than for the Uranian system. There is, for example, only one bright satellite to use for calibration and coordinate origin. Since the orbit of the satellite is known accurately, we plan to centroid the planet on unsaturated images using special software being developed by J.L. Hershey (1996). A problem arising from the small scale of the system is crowding. The orbits of several of these satellites are less than 1 arcsecond apart, and just as close to the ring arcs. Double-image centroiding software has also been developed to deal with this (Hershey, 1996). A more serious problem is the large delta m between Triton and the faint satellites, which in the best case is 6.8 mag. It may be necessary to first correct the orbit of Proteus relative to Triton from the shorter exposures, and then correct the orbits of the fainter satellites relative to Proteus from the longer exposures. In fact, the first step may not be necessary. The orbits of Proteus and the fainter satellites can be corrected simultaneously, provided that correlations between the corrections to the mean motions are small.

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