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# Astrometric CCD observations of the inner Jovian satellites in 1999–2000

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**Abstract.** This paper presents the results of observations of the inner Jovian satellites Thebe, Amalthea, Adrastea and Metis made in October–November 1999 and in November 2000. We provide $\Delta\alpha$ and $\Delta\delta$ of Thebe and Amalthea with respect to the Galilean satellites, while the positions of Adrastea and Metis are referred to either the Galilean moons or to Thebe or to Amalthea. All observed positions are compared with theoretical ones. Residual statistics show an inner accuracy of our observations in the range from about 0.1 to 0.9 arcsec. The dependence of the differences of the observed and calculated positions on the orbital longitude is presented for our observations of Adrastea and Metis.

**Key words.** planets and satellites: individual: Jovian inner satellites – astrometry

## 1. Introduction

The inner Jovian satellites Thebe, Amalthea, Adrastea and Metis move around the planet on orbits with semi-major axes of about 3.11 $R_j$, 2.54 $R_j$, 1.81 $R_j$ and 1.79 $R_j$. The mean radii of these satellites are 49.3, 83.5, 8.2, 21.5 km (Thomas et al. 1998), the orbital inclinations are 0.8°, 0.4°, 0°, 0° as provided by JPL (Giorgini et al. 1996) and the visual magnitudes are 15.7, 14.1, 18.7, 17.5 respectively (Veverka et al. 1981; Pascu et al 1992; Nicholson & Matthews 1991). The information obtained by Galileo suggests that the inner moons supply the dust grains of the Jovian ring, and the orbital characteristics of the satellites determine the morphological ring features (Ockert-Bell et al. 1999). Although the inner satellites are difficult for ground based observations because of their proximity to the bright planet and their faintness, some astrometric observations have been acquired from the Earth. The ground based observations together with the spacecraft ones are used for determination of orbital constants for these inner satellites (Breiter 1996; Veiga & Martins 1995; Jacobson 1994; Colas & Vu 1992; Jewitt et al. 1981; Mulholland et al. 1979). Amalthea, Thebe, Adarastea and Metis have been observed with the 2-m Zeiss RCC telescope of Terskol Observatory (Terskol peak, Northern Caucasus, $\lambda = 42.50083°, \phi = 43.27427°$, $H = 3100$ m) since 1998. This observational program was continued during the Jovian oppositions in 1999 and 2000. The first results of our observations of Amalthea and Thebe and the astrometric calibration of the device were published in the previous paper (Ledovskaya et al. 1999[1]). Now we present the results of the observations of Amalthea, Thebe, Adrastea and Metis made during 12 nights around the 1999 and 2000 oppositions.

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## 2. Observations

The Two-Channel Focal Reducer of the Max-Planck Institute for Aeronomy (MPAe, Germany) was used for acquisition of the images. The optical arrangement of this device and the main parameters of the optical systems are published in Jockers et al. (2000). There are two channels in the device. The beam from the Cassegrain focal plane is recollimated and divided by a color divider that transmits the long-wave part of the light into the "red" channel and reflects the short-wave part into the "blue" channel. Each cannel contains a camera lens with a focal length of 140 mm that reimages the beam. A mask containing black occulting areas is put in the focal plane of the telescope in order to block the light from Jupiter and the Galilean moons. The width of the mask covering Jupiter is

[1] Data are also available in electronic form at the CDS via anonymous ftp `ftp://cdsarc.u-strasbg.fr/pub/cats//J/other/KFNT/15.483`.

**Table 1.** Number of observations of inner Jovian moons.

| Satellite | Year | Number of nights | Number of frames |
|---|---|---|---|
| Thebe | 1999 | 3 | 28 |
| Amalthea | 1999 | 3 | 25 |
| Amalthea | 2000 | 1 | 10 |
| Metis | 1999 | 1 | 11 |
| Metis | 2000 | 8 | 76 |
| Adrastea | 2000 | 3 | 35 |

about 77 arcsec. We placed Jupiter image near the western or eastern edge of the glass to observe Metis and Adrastea at the corresponding elongations. We were able to observe the innermost satellites Metis and Adreastea at distances of about 10–12 arcsec from the Jovian limb. Both channels allow interference filters. A Lyot stop suppresses Jupiter's diffraction pattern. The images are recorded by two CCDs. The red channel CCD array has 576 × 385 pixel, the image scale is approximately 0.83" per pixel for an overall field of view of $7.8' \times 5.2'$. The blue channel CCD array has $512 \times 512$ pixel, the image scale is about $1.01''$per pixel for an overall field of $7.8' \times 7.8'$. The observations were made in the methane absorption band at 890 nm ($\lambda = 887$ nm, $FWHM = 28.5$ nm) where the disk of Jupiter is comparatively dark. We used the red channel with the image scale $0.83''$per pixel to obtain the images in 1999. In 2000 the CCD of the blue channel (image scale $1.01''$) was placed into the red channel during all observations. Twilight sky was used for flatfield frames. The integration time was from 180 to 300 s for the frames with the satellite images. The observational data are summarised in Table 1.

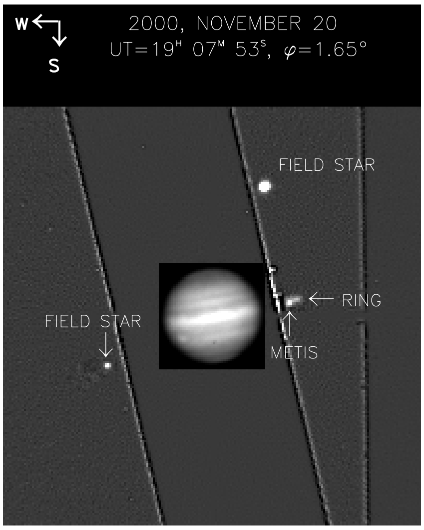


**Fig. 1.** Images of Metis and Jupiter's ring after background processing. $\varphi$-solar phase angle.

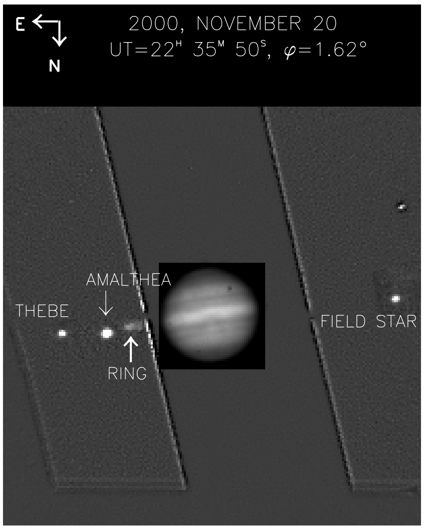


**Fig. 2.** Images of Thebe, Amalthea and Jupiter's ring after background processing. The densest point is shown near the ring edge inside of the inner satellite orbits that may shift the centers of Metis' and Adrastea's images towards Jupiter.

## 3. Data reduction

The flat-fielding procedure was applied to each individual frame to correct pixel-to-pixel sensitivity variations. As the strong variance of light caused by the planet can systematically bias the positions of the inner satellites, we paid much attention to the problem of the reduction of the background from the planet. An area around the satellite of approximate width of about 30 × 30 arcsec was interpolated using the surrounding background distribution. Because of the presence of the Lyot stop the distribution of Jupiter's glare is nearly azimuthally symmetric (see Schneider & Trauger 1995) and depends only on the radial distance from Jupiter. Therefore the interpolation was done in polar coordinates centered at Jupiter. Finally the background with the interpolated areas was subtracted from the original image.

Figures 1, 2 show the images of the inner satellites and Jupiter's ring after the background reduction procedure. A two-dimensional Gaussian fit on a small area around the image was applied to determine the center of the satellite.

We obtained and processed 10 images of the astrometric standard cluster $\chi$Per (see Evstigneeva et al. 1991), in order to estimate aberrations of the optical system of the Two-Channel Focal Reducer which displaces the star images on the frame. The most significant aberration seems to be a distortion that moves the centre of the images about 0.3 pixel on the edges of the frame. The geometric corrections due to the distortion were applied to all the data. The rigorous methods to obtain the celestial coordinates $\alpha$ and $\delta$ of the satellites from the measured inter-satellite coordinates $\Delta X$ and $\Delta Y$ may be found elsewhere (see, for example, Hertzsprung 1912; van de Kamp 1967; Kiselev 1989). Some Galilean moons are imaged through black glass on almost every frame. They were used as the reference points forming the reference direction on the frames. To obtain the array scale $M$ and orientation angle of the north-south axis of the CCD array $\theta$ with respect to celestial reference frame we got the precise ephemeris positions of the Galilean satellites from HORIZONS

**Table 2.** Mean residuals (O–C) and their rms errors in arcsec for the two observational sets.

| Satellite | Year | (O–C) $\alpha$ | $\sigma$ | (O–C) $\delta$ | $\sigma$ |
|---|---|---|---|---|---|
| Thebe | 1999 | −0.02 | ±0.16 | −0.06 | ±0.12 |
| Amalthea | 1999 | 0.03 | 0.10 | −0.06 | 0.05 |
| Amalthea | 2000 | −0.07 | 0.22 | −0.06 | 0.18 |
| Metis | 1999 | −0.29 | 0.24 | 0.08 | 0.25 |
| Metis | 2000 | −0.15 | 0.32 | 0.04 | 0.27 |
| Adrastea | 2000 | −0.15 | 0.88 | 0.11 | 0.62 |

Ephemeris System (Giorgini et al. 1996 and at URL http://ssd.jpl.nasa.gov/horizons.html), provided by JPL. We used JPL's JUP100 tabulation for the observations made in 1999 and JPL's JUP166 for the 2000 year observations. The array scale was corrected for differential refraction and differential aberration to first order (Kiselev 1989). We used the appropriate images of each night to determine the scale $M$ and the orientation angle $\theta$ to account for temperature variation and occasional rotation of the telescope baseplate during the observations. The positions of Thebe and Amalthea are referred to those of the Galilean moons, the positions of Metis and Adrastea are tied to Thebe or Amalthea if there are no Galilean moons in the frame. All the observed positions are calculated in the ICRF/J2000 reference system.

## 4. Results

We provide the intersatellite coordinates $\Delta\alpha * \cos(\delta)$ and $\Delta\delta$ in electronic form (http://www.mao.kiev.ua/ast/c4_txt.htm). The mean residuals (O–C) of the observed and theoretical positions of Thebe, Amalthea, Adrastea, Metis and the rms errors of these residuals for each observational set are presented separately in Table 2. The number of the observed positions corresponds to the number of frames in Table 1. We preferably used Io as reference because this satellite appears on most of our frames. The results reported by Mallama et al. (2000) show that the rms difference between Io's observed position and its position predicted by Lieske's E5 ephemeris is 62 km if expressed as along-track distance. This corresponds to 0.02 arcsec at Jupiter's mean opposition distance. In addition, use of the Galilean satellites as astrometric reference may systematically shift the derived positions of the small moons since the changing solar phase angle and the non-uniform albedo of the satellite surface produce an offset between the satellite's photocenter and its center-of-figure. As Mallama et al. (1993) have shown such systematic shift may amount to more than 300 km for the Galilean moons. In order to estimate the range of the photocentric offsets during our observation made between $-5.4°$ and $+2.1°$ solar phase we used Mallama et al.'s (see above) data for each observational night. The shift between photocenter and center-of-figure fall into the range from about −0.03 to 0.02 arcsec for Io. Performing repeated measurements of our frames with different methods of background subtraction as well as using different Galilean moons as reference we estimate our measurement accuracy to about 0.1 arcsec for Amalthea and somewhat higher for the other inner satellites. As our measurement accuracy is lower than the shift between photocenter and center-of-figure this effect was not taken into account. This has the additional advantage that our data can be considered as truly experimental.

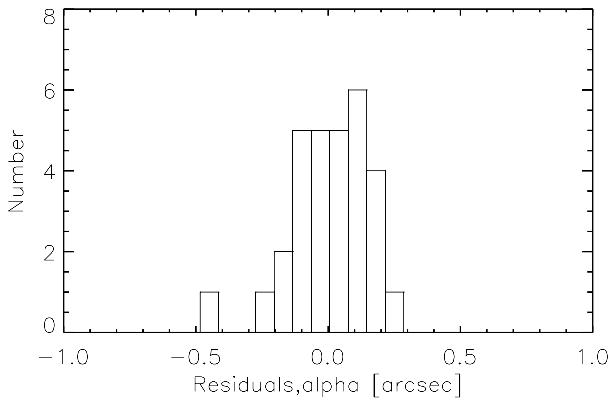


**Fig. 3.** Histogram of the distribution of the residuals (O–C) for $\alpha$ of Amalthea.

The JPL's JUP120.DE405 ephemeris positions of the inner satellites have been taken from HORIZONS Ephemeris System. As follows from Table 2, the standard deviations of the residuals for Metis and Adrastea are higher than those for Amalthea and Thebe. The measurement errors for these satellites are larger because these moons are fainter and disturbed by the Jupiter's ring.

The histograms of the right ascension residuals of all satellites are plotted in Figs. 3–6. The residuals of Thebe and Amalthea display a normal distribution. This is not the case for Methis and Adrastea.

To find a possible systematic influence on our observations of Metis and Adrastea, the dependence of the residuals of position on the orbital longitude of the satellite was examined. Observations near the eastern elongation were used, because of a lack of images on the west side of Jupiter. The differences (O–C) for Thebe, Adrastea and Metis are plotted versus the orbital longitudes in Figs. 7–9. Amalthea's positions were not analysed because they are far from elongations. Since we had got many eastern images of Metis, the differences (O–C) were averaged within five degree intervals of the orbital longitudes for the two observational sets (1999, 2000) separately. Each point has an uncertainty in the range from about 0.1 to 0.2 arcsec.

A second order polynomial was used to fit the residuals. All three satellites display a dependence of (O–C) on the orbital position. Besides of inaccurate orbital elements the stronger dependence of Adrastea and Metis is perhaps caused by radial variations of the ring brightness. As shown in Figs. 1, 2 the densest point of the ring

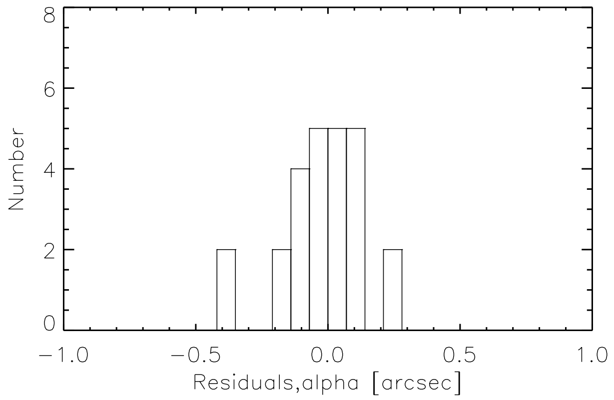


**Fig. 4.** Histogram of the distribution of the residuals (O–C) for $\alpha$ of Thebe.

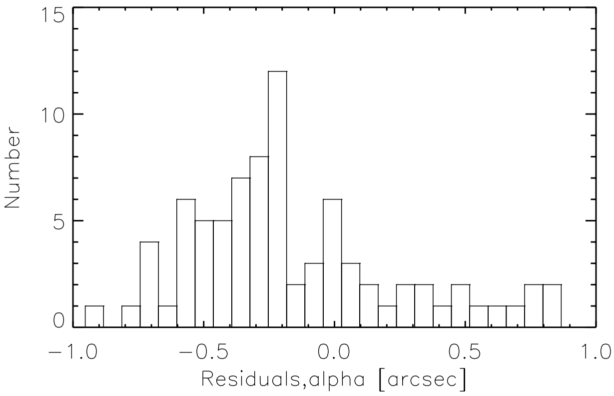


**Fig. 5.** Histogram of the distribution of the residuals (O–C) for $\alpha$ of Metis.

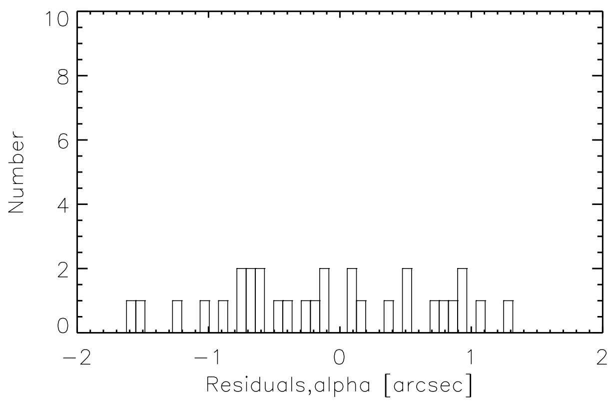


**Fig. 6.** Histogram of the distribution of the residuals (O–C) for $\alpha$ of Adrastea.

appears at about 1.70 $R_j$ (where $1R_j = 71398$ km) and may shift the centre of the satellites. No fine structure was previously detected at this distance, however (Ockert-Bell et al. 1999; McMuldroch et al. 2000; Meier et al. 1999). The residuals of the positions obtained from two observational sets with slightly different viewing geometry of the ring are in good agreement (the ring opening angles were 3.36° in November 1999 and 3.15° in November 2000).

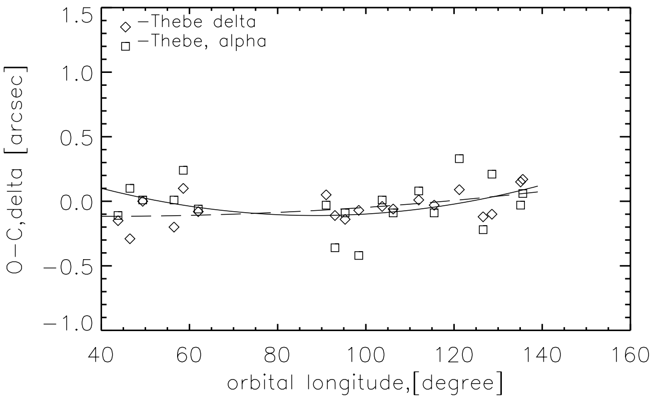


**Fig. 7.** Thebe: dependence of (O–C) on the orbital longitude of the satellite.

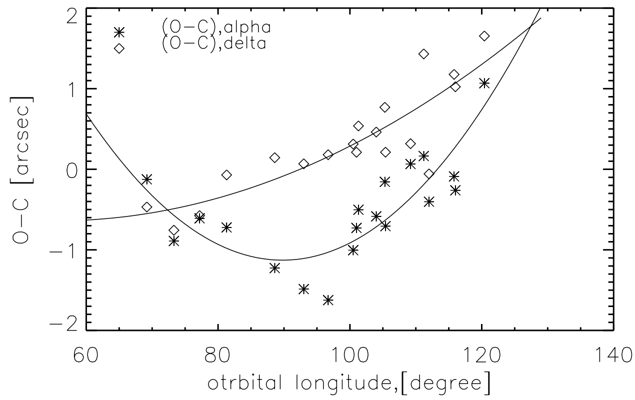


**Fig. 8.** Adrastea: dependence (O–C) on the orbital longitude of the satellite.

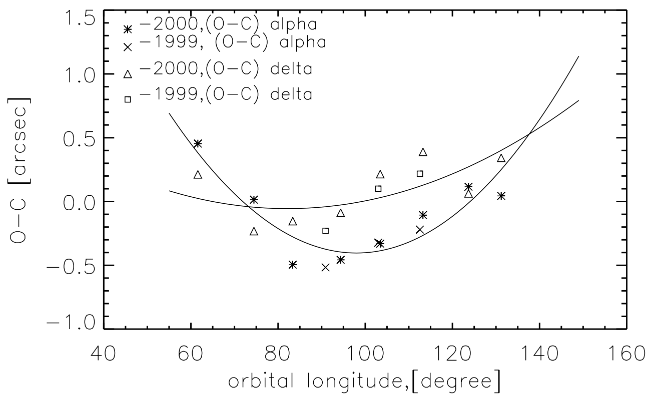


**Fig. 9.** Metis: dependence (O–C) on the orbital longitude of the satellite.

## 5. Summary

We presented 253 intersatellite astrometric CCD positions of Thebe, Amalthea, Adrastea and Metis obtained during the 1999 and 2000 Jovian oppositions. The special technique of our observations and data reduction permits us to obtain a positional accuracy of about 0.1–0.2 arcsec for Thebe and Amalthea and 0.2–0.9 for Metis and Adrastea. The residuals of the observed and theoretical positions of Metis, obtained from different years of observation, agree well. A strong dependence of Metis and Adrastea residuals on the orbital position in right ascencion and declination was found. The factors influencing the observed positions of these inner satellites are not clear now, and additional observations under a different viewing geometry of the ring system may be needed.

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