Precise CCD positions of Galilean satellite-pairs

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ABSTRACT
In this paper, we present 526 precise CCD positions of Galilean satellite-pairs of Jupiter, which have been extracted from 441 CCD frames captured by a 1-m telescope at the Yunnan Observatory from 2002 to 2010. The four Galilean satellites (Io, Europa, Ganymede and Callisto) are used to calibrate the CCD field of view by comparing their pixel positions with their theoretical positions computed from two modern ephemerides of the Galilean satellites, L2 and JUP230, which have been developed by the Institut de Mécanique Céleste et de Calcul des Éphémérides and the Jet Propulsion Laboratory, respectively. In this paper, we focus on the relative position of a pair of satellites with short separation (less than 85 arcsec) for good internal precision. The mean (O − C) (observed minus computed) values of all these satellite-pairs in right ascension and declination are found to be no larger than 6 mas and 2 mas, respectively, for each ephemeris. The estimated precision for one single observation is better than 30 mas in each direction.

Key words: methods: data analysis – astrometry – planets and satellites; general.

1 INTRODUCTION
Although the Galilean satellites of Jupiter have been observed for more than 400 yr since their discovery, there is always great interest in their dynamics and planetary physics and this research is ongoing, with an obvious example being the recent results concerning tidal dissipation (Lainey et al. 2009). The observations used in Lainey et al. (2009) include old observations (Arlot 1982), mutual events (Arlot et al. 2009), modern CCD observations (Stone 2001) and space observations (Mallama, Aelion & Mallama 2004). Furthermore, more observations (including new reductions of old observations; see De Cuyper et al. 2009; Robert et al. 2011) with high precision are needed to investigate the planetary physics of this small solar system.

As first discovered by Pascu (1994) from photographic observations, the positional measurement of two short-separation satellites (as shown in Fig. 1) has a high external precision, called a precision premium. This was also confirmed by CCD imaging with some experimental observations (Peng et al. 2008a). In this paper, we give all the positional measurements that have been extracted from 441 CCD frames captured by a 1-m telescope at the Yunnan Observatory from 2002 to 2010, with special attention given to the photocentric offset. The paper is arranged as follows. In Section 2, we describe all the CCD observations in detail and we also explain the image-processing techniques for the pixel-positional measurements of the Galilean satellites (and Jupiter). In Section 3, we give the data reduction and analysis including the solution of the calibration parameters, light scatter models and the results of the positional measurements. The format of the published observations is described in Section 4. Finally, we give some conclusions in Section 5.

2 OBSERVATIONS AND IMAGE PROCESSING
2.1 Observations
From 2002 to 2010, 10 nights of observations delivered 441 CCD frames with the 1-m telescope at the Yunnan Observatory (longitude E102°47’18”, latitude N25°1’30” and height 2000 m above sea level, i.e. IAU code 286). Table 1 lists the specifications of the telescope and the CCD cameras.

During the observations, a Johnson B-type filter was mainly used to control the exposure time (1–10 s). A Johnson I-type filter was also used once for contrast while the exposure time was short (i.e. less than 1 s). Because our former PI CCD, which had a resolution of 1024 × 1024 and was attached to the 1-m telescope, aged quickly after 2006, a new CCD with a resolution of 2048 × 2048 was used to replace it. However, in the experiments from 2006 to 2008 using the new CCD, we encountered a readout problem that prevented us from observing the Galilean satellites. As a result, we have no useful observations during that period of time. The observations are listed in Table 2. In the last two rows of Table 2, the same
satellite-pair of 1–2 was observed on the same night but with different CCD orientations (see Table 3).

2.2 Image processing for the pixel positions of Jupiter and its Galilean satellites

To measure the raw pixel position, we use the techniques described in Peng et al. (2008a). We give only the outline of these techniques. Interested readers can refer to Peng et al. (2003) or Peng et al. (2008b) for more details. For the pixel position of Jupiter, our technique involves isolating the disc of Jupiter by creating a subimage. We then choose the threshold brightness and convert the subimage into a binary representation, detecting the edge with an ellipse using a least-squares method. The pixel position of a satellite was determined based on a modified moment analysis, after correcting for the brightness of the halo around Jupiter. It is well known that the centroid of the image of Jupiter is difficult to measure accurately, especially in its non-zero phase. Therefore, in this paper, we are concerned only with the Galilean satellites.

3 REDUCTION AND ANALYSIS OF OBSERVATIONS

Normally, there is no astrometric reference star (in brightness and in number) appearing in the field of view for the astrometric calibration of the Galilean satellites. This is because of the small field of view and the relatively short exposure times. It is well known that for the astrometry of Saturnian satellites, the four bright satellites (Tethys, Dione, Rhea and Titan) are used to compute the scalefactor and orientation of the CCD field of view (Harper et al. 1997; Vienne et al. 2001). This is because the four bright satellites usually have the best theoretical positions among the eight major satellites of Saturn. Along the same line of thought, we resort to a modern Galilean ephemeris for the Galilean satellites to calibrate the CCD field of view by solving two parameters (i.e., the scalefactor and the orientation of the field of view). Although these parameters might not be accurate enough for the positional measurement of the long-separation satellite-pairs, they could be precise enough for the positional measurement of short-separation satellite-pairs. This is because the error existing in the solved calibration parameters has a direct proportional effect on the separation of the two satellites. Moreover, we have a precision premium for small separation observations with an external precision of 0.01 arcsec, as first discovered by Pascu (1994). This precision makes these observations of short-separation satellite-pairs comparable to mutual events, with the additional advantage that 50-arcsec separations occur much more frequently than mutual events – averaging about 50 times per month (Pascu 1994). Pascu and his collaborators performed experiments with their Speckle interferometer to measure the close approaches of the Galileans (Mason et al. 1999) and their preliminary results are promising. Actually, Lindegren (1980) derived the classical equations of the internal precision of two objects in a small field of view:

\[ m.e.(\text{arcsec}) = 1.3 \theta^0.25 T^{-0.5}. \]  

(1)

Here, \( \theta \) (s) \( \gg 3000 \) (rad) is the integration time in s. Obviously, the shorter the separation of the two observed objects, the less the mean error. In addition, if a field of view is not very small, its geometric distortion cannot be neglected. (For example, on the Hubble Space

Table 3. Calibration parameters – the scalefactor (arcsec pixel\(^{-1}\)) and orientation (deg) of the CCD chip – computed by DE405+L2 ephemerides (and DE405+JUP230 ephemerides for the figures in parentheses).

<table>
<thead>
<tr>
<th>Subset</th>
<th>( N )</th>
<th>Scalefactor</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>020104</td>
<td>133</td>
<td>0.373611</td>
<td>179.526 (179.528)</td>
</tr>
<tr>
<td>030218</td>
<td>71</td>
<td>0.373634</td>
<td>179.884 (179.885)</td>
</tr>
<tr>
<td>030220</td>
<td>19</td>
<td>0.373768</td>
<td>179.875 (179.873)</td>
</tr>
<tr>
<td>030227</td>
<td>15</td>
<td>0.373565</td>
<td>179.463 (179.462)</td>
</tr>
<tr>
<td>030228</td>
<td>15</td>
<td>0.373553</td>
<td>179.428 (179.429)</td>
</tr>
<tr>
<td>040104</td>
<td>20</td>
<td>0.373535 (0.373545)</td>
<td>179.565 (179.566)</td>
</tr>
<tr>
<td>050106</td>
<td>60</td>
<td>0.373632 (0.373669)</td>
<td>178.996 (178.987)</td>
</tr>
<tr>
<td>050107</td>
<td>14</td>
<td>0.373567 (0.373567)</td>
<td>178.953 (178.949)</td>
</tr>
<tr>
<td>091221</td>
<td>40</td>
<td>0.209479 (0.209492)</td>
<td>179.996 (179.997)</td>
</tr>
<tr>
<td>101230(1)</td>
<td>15</td>
<td>0.209401 (0.209397)</td>
<td>-91.053 (-91.053)</td>
</tr>
<tr>
<td>101230(2)</td>
<td>33</td>
<td>0.209345 (0.209341)</td>
<td>178.887 (178.888)</td>
</tr>
</tbody>
</table>

Table 2. Data subsets corresponding to the observational dates. \( N \) denotes the number of measured satellite-pairs, \( PA \) is the solar phase angle (deg), \( ZD \) is the zenith distance (deg), \( SP \) is the satellite-pair (1, 2, 3 and 4 represent Io, Europa, Ganymede and Callisto, respectively) with a short separation and MS is the mean separation (arcsec) of the satellite-pair.

<table>
<thead>
<tr>
<th>Subset</th>
<th>( N )</th>
<th>Filter</th>
<th>( PA )</th>
<th>( ZD )</th>
<th>( SP )</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>020104</td>
<td>133</td>
<td>B</td>
<td>0.75</td>
<td>18.5–2.8</td>
<td>1–3</td>
<td>22.8</td>
</tr>
<tr>
<td>030218(1)</td>
<td>71</td>
<td>B</td>
<td>3.40</td>
<td>6.7–11.7</td>
<td>1–2</td>
<td>41.2</td>
</tr>
<tr>
<td>030218(2)</td>
<td>71</td>
<td>B</td>
<td>3.40</td>
<td>6.7–11.7</td>
<td>3–4</td>
<td>18.9</td>
</tr>
<tr>
<td>030220</td>
<td>19</td>
<td>I</td>
<td>3.70</td>
<td>9.4–8.3</td>
<td>1–2</td>
<td>6.9</td>
</tr>
<tr>
<td>030227</td>
<td>15</td>
<td>B</td>
<td>5.14</td>
<td>19.3–21.4</td>
<td>1–2</td>
<td>14.1</td>
</tr>
<tr>
<td>030228</td>
<td>15</td>
<td>B</td>
<td>5.31</td>
<td>37.6–42.2</td>
<td>1–4</td>
<td>6.7</td>
</tr>
<tr>
<td>040104(1)</td>
<td>20</td>
<td>B</td>
<td>9.50</td>
<td>27.4–21.0</td>
<td>1–2</td>
<td>83.5</td>
</tr>
<tr>
<td>040104(2)</td>
<td>20</td>
<td>B</td>
<td>9.50</td>
<td>27.4–21.0</td>
<td>2–4</td>
<td>12.5</td>
</tr>
<tr>
<td>050106</td>
<td>60</td>
<td>B</td>
<td>10.39</td>
<td>35.9–33.4</td>
<td>1–4</td>
<td>24.9</td>
</tr>
<tr>
<td>050107</td>
<td>14</td>
<td>B</td>
<td>10.39</td>
<td>44.7–41.7</td>
<td>1–4</td>
<td>35.6</td>
</tr>
<tr>
<td>091221</td>
<td>40</td>
<td>B</td>
<td>9.22</td>
<td>49.2–53.2</td>
<td>1–4</td>
<td>24.6</td>
</tr>
<tr>
<td>101230(1)</td>
<td>15</td>
<td>B</td>
<td>7.84</td>
<td>29.6–30.1</td>
<td>1–2</td>
<td>16.8</td>
</tr>
<tr>
<td>101230(2)</td>
<td>33</td>
<td>B</td>
<td>7.84</td>
<td>30.7–32.2</td>
<td>1–2</td>
<td>23.3</td>
</tr>
</tbody>
</table>

Table 1. Specifications of the telescope and CCD cameras.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length</td>
<td>1300cm</td>
</tr>
<tr>
<td>( F ) ratio</td>
<td>13</td>
</tr>
<tr>
<td>Diameter of primary mirror</td>
<td>100cm</td>
</tr>
<tr>
<td>CCD field of view</td>
<td>6.4 \times 6.4 arcmin(^2) (2002–2005)</td>
</tr>
<tr>
<td></td>
<td>7.1 \times 7.1 arcmin(^2) (2009–2010)</td>
</tr>
<tr>
<td>Size of pixel</td>
<td>24 \times 24 \mu\text{m}^2 (2002–2005)</td>
</tr>
<tr>
<td></td>
<td>13.5 \times 13.5 \mu\text{m}^2 (2009–2010)</td>
</tr>
<tr>
<td>Size of CCD array</td>
<td>1024 \times 1024 (2002–2005)</td>
</tr>
<tr>
<td></td>
<td>2048 \times 2048 (2009–2010)</td>
</tr>
<tr>
<td>Angular extent per pixel</td>
<td>0.37 arcsec pixel(^{-1}) (2002–2005)</td>
</tr>
<tr>
<td></td>
<td>0.21 arcsec pixel(^{-1}) (2009–2010)</td>
</tr>
</tbody>
</table>
3.1 Computation for theoretical positions

At present, there are two modern ephemerides for the Galilean satellites of Jupiter, which have been developed by the Institut de Mécanique Céleste et de Calcul des Éphémérides (IMCCE) and the Jet Propulsion Laboratory (JPL). L1 (Lainey, Duriez & Vienne 2004a; Lainey, Arlot & Vienne 2004b), and its updated version L2 (derived from Lainey et al. 2009), which have been developed by the IMCCE, are available at http://www.imcce.fr/sat/. JUP230 is the latest ephemeris of the JPL, which can be found at http://ssd.jpl.nasa.gov/. Based on the same Jupiter theory in DE405 (Standish 1998), the geocentric apparent positions (in J2000) and the geocentric ranges of the four Galilean satellites are first retrieved. Then, all other positional effects, such as the atmospheric refraction, diurnal parallax, diurnal aberration and central projection, are incorporated into the theoretical positions. Finally, for the photocentric offset from the centre of mass, we compared three scatter models: the uniform bright model, the Lambertian model (Lindegren 1977) and the Lommel–Seeliger model (Batrakov et al. 2002), the measured raw pixel positions of the Saturnian satellites (Shen et al. 2001; Vienne et al. 2001; Peng, Vienne & Shen 2002), the mean observed minus computed values in right ascension and declination, mean observed minus computed values in right ascension and declination, respectively. SD denotes the standard deviation for each observation data set. In Parts A and B, the reference theories are L2 and JUP230, respectively. The last row for each part is derived from all observations.

3.2 Solution of calibration parameters

Similar to the determination of the calibration parameters using Saturnian satellites (Shen et al. 2001; Vienne et al. 2001; Peng, Vienne & Shen 2002), the measured raw pixel positions of the Galilean satellites are compared with their theoretical positions to derive the scalefactor and the orientation of the CCD field of view. All satellite-pairs are used to calculate these calibration parameters using the weight scheme in Peng (2003). Table 3 lists the derived parameters. It is found that the parameters derived from two different ephemerides have only small differences. Even for satellite-pairs separated by as much as 83.5 arcsec (i.e. the subset 040104), the positional variations caused by different calibration parameters are less than 3 mas in each direction. Therefore, the calibration parameters from any ephemeris are accurate enough to derive the O − C (observed minus computed) values for a shortly separated satellite-pair. The inclusion of the short satellite-pair for calibration might be confusing. Logically, it might be unreasonable to use a short satellite-pair to calibrate. However, because of the relatively small weight solution, the effect of their inclusion can be neglected. Table 4 shows the different calibration parameters when the short satellite-pair is included and when it is not. It can be seen from the table that the greatest difference in the solution of separation is less than 0.5 mas for the subset 040104(1), with the largest separation of 83.5 arcsec. Therefore, all satellite-pairs can be safely and conveniently included in the calculation of the calibration parameters. In the experiment, the Lambertian model (Lindegren 1977) is used to compute the photocentric offset of each satellite.
3.3 Phase effect for different light scatter models

A phase effect is the shift of the measured photocentre to the centre of mass (or centre of centroid). According to Lindegren (1977), a spherical object and the scattering of light on its surface follows the reciprocity principle (i.e. the phase shift is along the bisector of the directions toward the observer and the Sun). This can be given in differential coordinates (Standish et al. 1992; Hestroffer 1998) by

\[
\begin{pmatrix}
\Delta \alpha \
\Delta \delta
\end{pmatrix}
= \begin{pmatrix}
\sin \theta_s \\
\cos \theta_s
\end{pmatrix} C(i) \sin(i/2) \phi/2,
\]

where \( \phi \) is the apparent diameter of the satellite, \( i \) is the solar phase angle and \( \theta_s \) is the position angle of the subsolar point in the tangential plane. Here, three simple models are adopted for the Galilean satellites: the Lambertian sphere (Lindegren 1977), the uniform brightness (Hestroffer et al. 1995) and the Lommel–Seeliger law (Batrakov et al. 1999). Detailed equations can be found in Hestroffer (1998).

Because only the relative positional difference between two satellites, rather than that between a satellite and a star, is considered here, and because the two satellites concerned have almost the same phase angle, these have a differential phase shift that depends only on their related radii. Fig. 2 shows the calculated positional differences from different light scatter models for all the short-separation satellite-pairs considered. It is shown that the differential phase shift in right ascension (rarely larger than 0.01 arcsec) is usually larger than that in declination for all our observations. The differential phase shifts in both directions are even smaller when the Lommel–Seeliger and Lambertian models are compared.

3.4 Results of positional measurements

With the calibration parameters given in Table 3, we can compute the formally mean \((O - C)\) values and their corresponding standard deviations for each subset of observed short-separation satellite-pairs. We can see from Table 5 that the mean \((O - C)\) values in each direction are usually small, and the largest value is \(-59\) mas from the JUP230 theory in right ascension. In declination, the largest mean \((O - C)\) value is \(-55\) mas from the L2 theory. On the whole, the mean \((O - C)\) values in both directions are less than 10 mas. For the L2 theory, the standard deviations for all data are the same in both directions, but they are distinctly different for JUP230. More observations are needed to investigate this difference. Figs 3 and 4 show all \((O - C)\) values against the observational dates and the solar phase angles, respectively.

4 DATA FORMAT OF OBSERVATIONS

In this paper, all the observations are presented in the following format (see Table 6).

- ID is the data set identification. For all the observations, it runs from 1 to 13.
- JOJR is the measured objective in the form of JO with respect to JR. Here, 1, 2, 3 and 4 represent Io, Europa, Ganymede and Callisto, respectively.

**Figure 2.** Positional difference resulting from different light scattering models. The left panel shows the difference between the uniform and Lambertian models, and the right panel shows the difference between the Lommel–Seeliger law (denoted L–S) and the Lambertian model.

**Figure 3.** The relation between \((O - C)\) and observational dates. The left panel is in RA and the right panel in Dec.
The relation between \((O-C)\) values in each direction are no larger than 60 mas in right ascension for JUP230. On the whole, the mean \((O-C)\) values in right ascension and declination are 6 mas and 2 mas for any ephemeris. The observational precision in each direction is estimated at better than 30 mas for one single observation.

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REFERENCES


5 CONCLUSIONS

In this paper, we have presented 526 precise positions of short-separation Galilean satellite-pairs made by the 1-m telescope at the Yunnan Observatory. The observations are extracted from 441 CCD frames taken from 2002 to 2010. The reduction of the observations is performed by comparing the pixel positions of all four Galilean satellites in the field of view with their theoretical positions, based on two modern ephemerides: L2 from the IMCCE and JUP230 from the JPL. The analytical results show that the mean \((O-C)\) values for most observational sets are quite small; at the same time, the largest is less than 60 mas in right ascension for JUP230. On the whole, the mean \((O-C)\) values in each direction are no larger than 6 mas in right ascension and 2 mas in declination for any ephemeris.

T is the type of CCD used. 1 denotes a CCD resolution of 1024 \(\times\) 1024 and 2 denotes 2048 \(\times\) 2048.

Yr, Mon and Day give the recorded middle exposure moment in the form of a year, month and day fraction of each CCD frame in UTC (the light time is not corrected).

Obs is the IAU observatory code from the Minor Planet Center.

DA and DD are the observed positional differences in sense of objective (JO) minus reference (JR) in right ascension and declination, respectively. These are geocentric apparent positions in J2000 and are really astrometric, because all significant astrometric corrections have been removed. Unlike observations normally used in \((\Delta \cos \delta, \Delta \delta)\), \(DA = \Delta \alpha (= \sigma_0 - \alpha_0)\) and \(DD = \Delta \delta (= \delta_0 - \delta_0)\) are adopted. Here, the subscripts ‘o’ and ‘r’ correspond to JO and JR, respectively. Both units are arcsec.

Da and Dd are the \((O-C)\) values (arcsec) in right ascension and declination in the form of \((\Delta \alpha \cos \delta, \Delta \delta)\) for the two satellites considered. Here, the computed positions are derived from the ephemeris L2 (Lainey et al. 2009).

Ox and Oy are the raw pixel positions for objective (JO) in the x and y (in pixels) directions, respectively.

Rx and Ry are the raw pixel positions for reference (JR) in the x and y (in pixels) directions, respectively.

Furthermore, the centre pixel position of the CCD frame is nearly at the pixel (511.0, 511.0) for the former CCD with the resolution of 1024 \(\times\) 1024 and at (1023.0, 1023.0) for the new CCD with the resolution of 2048 \(\times\) 2048.

Table 6. Extract from the observations. This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the on-line journal (see Supporting Information). A portion is shown here for guidance regarding its form and content. The units of DA and DD (the observed positional differences in right ascension and declination, respectively) are arcsec. The same units are also used for Da and Dd, the \((O-C)\) values in right ascension and declination for the two satellites considered. (Ox, Oy) and (Rx, Ry) are the raw pixel positions for objective and reference, respectively.
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SUPPORTING INFORMATION

Additional Supporting Information may be found in the on-line version of this article.

Table 6. The observations.

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