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NAROO PROGRAM : ANALYSIS OF USNO GALILEAN OBSERVATIONS 1967-1998

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Abstract. The New Astrometric Reduction of Old Observations (NAROO) program is dedicated to the measurement of astrophotographic plates and the analysis of old observations for scientific purposes. One of the main objectives is to provide accurate positional measurements of planets and satellites to improve our knowledge of their orbits and dynamics, and to infer the accuracy of the planet and satellite ephemerides. We digitzed 553 astronegatives of the Galilean satellites taken with the McCormick and the U.S. Naval Observatory 26-inch refractors from 1967 to 1998, resulting in 2650 individual observations. We measured and reduced these observations through an optimal process that includes image, instrumental, and spherical corrections using Gaia-DR3 catalogue to provide the most accurate equatorial (RA, Dec) ICRS positions. We compared the observed positions of the satellites with the theoretical positions from different planetary ephemerides and satellite ephemerides. 4819 positions of the Galilean satellites have been determined with an accuracy of 55 mas or 160 km at Jupiter, indicating that the limits of the photographic techniques were now reached.

Keywords: Astrometry - Ephemerides - Instrumentation: high angular resolution

1 Introduction

The New Astrometric Reduction of Old Observations (NAROO) facilities have been built as a unique center dedicated to the measurement of astrophotographic plates and the analysis of old observations for scientific purposes (Robert et al. 2021). The framework is the study of the dynamics of Solar System bodies, in particular, that require astrometric observations sampled over a long time span to quantify the long period terms which may help to analyze the evolution of the motion. One of the main objectives of the NAROO program is to provide accurate positional measurements of planets and satellites to improve our knowledge of their orbits and dynamics, and to infer the accuracy of the planet and satellite ephemerides.

We obtained the large photographic plate archive of the Galilean satellites taken at the U. S. Naval Observatory (USNO) from 1967 to 1998 for remeasurement and reanalysis. In fact, most of these plates had been measured with the USNO automatic StarScan measuring machine (Zacharias et al. 2008), reduced by the trail/scale scheme (Pascu 1977) and used by Jet Propulsion Lab (JPL) for the navigation of the Voyager and Galileo space probes to successful reconnaissance with the Jovian system. The expectation was that the astrometric positions of the planets, as well as the Galilean satellites, could now be obtained to the absolute limits of the photographic technique.

2 Measurement and reduction

We selected 553 photographic plates to be transmitted at Meudon and digitized with the NAROO machine. Each plate contains four to six exposures shifted in the declination direction. The exposure times of the photographic plates are 20-60 s. The field of view is 57 arcmin on the x-axis and 43 arcmin on the y-axis. Figure 1 shows the center of the digitized (positive) USNO Galilean plate No. 21014, which is a typical digitized image. Five 20 s exposures of the Jovian system were taken with the USNO 26-inch refractor on 18 June 1994. Non visible

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by eye, the small special filter covers the planet and satellites, reducing their light and providing a measurable image of Jupiter and the Galileans. From left to right, Callisto, Ganymede, Europa, Jupiter, and Io. North is up, east to the left.

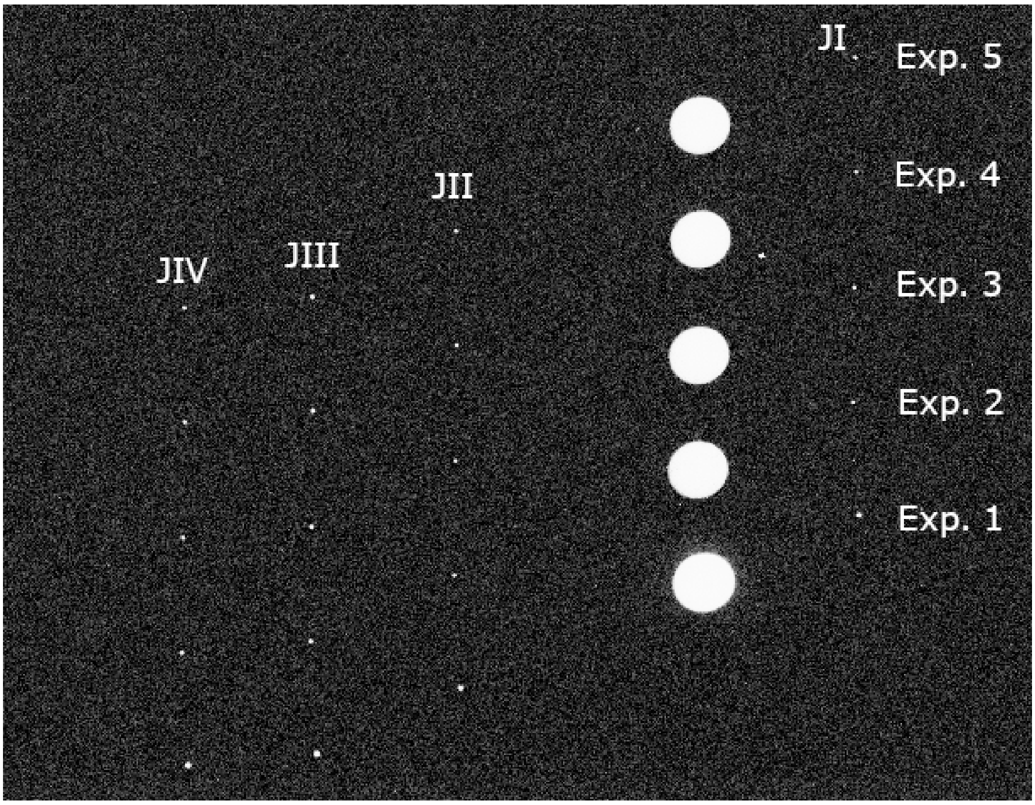

Fig. 1. Center of the digitization (positive) of the USNO 26-inch Galilean plate No. 21014. Five exposures shifted in the declination direction, from left to right: Callisto, Ganymede, Europa, Jupiter, and Io. North is up, east to the left.

2.1 Positioning results

We re-processed the analysis of the 553 NAROO images using the Gaia-DR3 reference star catalogue (Gaia Collaboration et al. 2016, 2022) to compare the positions of the Galilean satellites with their theoretical computed positions given by the INPOP21a planetary ephemeris (Fienga et al. 2021) and newest NOE-5-2021-JUP satellite ephemerides. All of the Gaia reference stars and the satellite images were centered using the shapelet decomposition method (Refregier 2003). This concerns 1145 positions of Io, 1178 positions of Europa, 1274 positions of Ganymede, and 1222 positions of Callisto. We also computed 1355 positions of Jupiter as the barycenter of the observed satellites, when at least two of them were available on the same date. The distributions of the (O-C)s and residuals in equatorial right ascension and declination are provided in Table 1. It shows the difference of (RA, Dec) coordinates for individual satellites, hence the observed positions versus positions calculated from INPOP21a and NOE-5-2021-JUP models with NAROO digitizations.

The key point is that the NOE-5-2021-JUP/INPOP21a rms (O-C) for all observations is 54.1 mas for Io, 53.0, mas for Europa, 57.2 mas for Ganymede, and 54.3 mas for Callisto. These average rms (O-C)s and residuals correspond to our observation accuracies over twenty-six oppositions in the series, or 31 years. The main improvement consisted in using the Gaia-DR3 star catalogue for the positioning of the stellar references for the astrometric reduction. In fact, we were able to decrease the residuals by about of 7 mas in both right ascension and declination, by comparison to the same analysis using the UCAC2 catalogue (Zacharias et al. 2008). With regard to the quadratic differences between the average residuals, we may conclude that we eliminated an error contribution about of 28 mas, indicating that our first measurements were degraded by unmodeled uncertainties. This result is consistent with the expected mean error of 15-30 mas of the UCAC2 catalogue, and we may deduce that the error contribution of the Gaia DR3 catalogue is negligible for our needs,

Table 1. Details of the equatorial mean (O-C)s and residuals for the Galilean satellites in mas, according to NOE-5-2021-JUP and INPOP21a ephemerides, with NAROO digitizations.

Satellite	$\overline{(O-C)}_{\alpha\cos\delta}$	$SEM_{\alpha\cos\delta}$	$\sigma_{\alpha\cos\delta}$	$\overline{(O-C)}_{\delta}$	SEM_{δ}	σ_{δ}
		+/−	+/−		+/−	+/−
JI	-4.8	1.6	55.7	0.3	1.5	52.5
JII	-0.5	1.5	53.3	-0.1	1.5	52.7
JIII	-2.4	1.6	57.0	1.0	1.6	57.4
JIV	-1.0	1.6	56.2	0.9	1.5	52.5
Average	-2.1	0.8	55.6	0.5	0.8	53.9

as expected. Finally, we may conclude that astrometric positions derived from photographic plates could now be obtained to the absolute limits of the photographic technique since our results are very close to those derived from mutual phenomena techniques (Emelyanov et al. 2022).

2.2 *Atmospheric limitations*

With Fig. 2, we investigate the astrometric limitation in external precision due to the atmosphere. Lindegren (1980) discussed the influence on the astrometry of the wave-front distortion due to the atmospheric turbulence, and he expressed the mean astrometric error as a function of the measured angle between two objects. Thus, we plotted rms residuals in the (satellite-satellite) separations against the separations for Io, Europa, Ganymede and Callisto. For comparison, we also plotted Lindegren's function above.

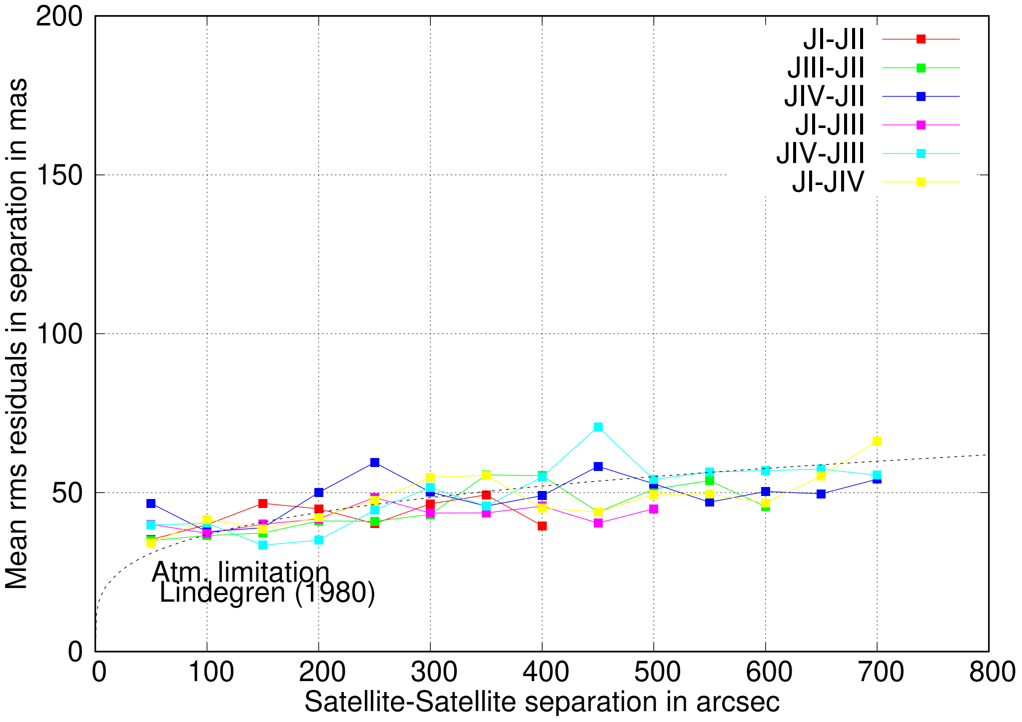

Fig. 2. Mean rms residuals in the (satellite-satellite) separations according to NOE-5-2021-JUP ephemerides. The x-axis shows the satellite-satellite separation and the y-axis the mean rms residuals in separation. Atmospheric limitation is given by Lindegren (1980).

Lindegren's function is referenced to the measured angle between two objects near the zenith and would not apply exactly to our observations, but this comparison is a first approach to assess the quality of our results. The curves for all satellite pairs are near coincident, and there is no excess variance in the separations. We may conclude that we have reached the limit in precision for these observations based on the Gaia-DR3, and confirm that we g-have reached the limits of the photographic techniques here.

2.3 The case of Amalthea

We compared the positions of the Galilean satellites with their theoretical computed positions given by the INPOP21a planetary ephemeris and former NOE-5-2010-JUP satellite ephemerides. In fact and by its definition, NOE-5-2010-JUP satellite model did not introduce the motion of the inner satellites. Their influence was taken into account by adding their mass to that of Jupiter. Thus, considering that Io is the main Galilean disturbed by the gravitational potential of the inners, we should be able to detect such an additional signal in its (O-C)s, in particular. We performed a frequency analysis of these data normalized by the Earth/satellite distance to reduce extra signals (motion of the observer, planetary ephemeris...) over 31 years, at the known frequencies of the four inner satellites. We assumed that the measured signals corresponded to variations in longitude since we were looking for mass estimations. Therefore, we were able to extract a 0.5016 ± 0.0022-days periodic signal of 20 ± 2 km of magnitude.

Table 2. Comparison of the mass of Amalthea.

Source	Amplitude (km)	Mass (.10^{18}kg)
USNO plates	20.00 ± 2	2.00 ± 0.20
Galileo	—	2.08 ± 0.15

Table 2 shows the comparison between the mass of Amalthea we estimated from our observations, and the mass that was calculated from Galileo flybys by Anderson et al. (2005). Both results are in the same order of magnitude. The differences are mainly due to the hypotheses of our estimation method. Although, our measuring error is a resulting indicator of these uncertainties. The key point is that we confirm that direct observation is not the only way to determine the physical characteristics of celestial bodies, and a new analysis of photographic plates could help to get more information about various bodies to contribute to a more fundamental physics.

3 Conclusions

We analyzed a full series of astrophotographic plates of the Galilean satellites taken at USNO from 1967 to 1998. Using the NAROO machine for the digitization and the Gaia-DR3 reference star catalogue allowed us to increase the precision and more important, to finally reach the limit in astrometric accuracy for the photographic technique. Thus, we were able to provide astrometric (RA, Dec) ICRS positions of the satellites, allowing us to deduce positions of the planet indirectly, with overall rms residuals of about 55 mas or 160 km at Jupiter.

We confirm the high interest in continuing the analysis of old observations, especially photographic plates, in the framework of the NAROO program. Since digitization time is reserved for external users, we remind that the NAROO machine is available for researchers to digitize their own collections following our call for proposals, issued every six months via our project website at `https://naroo.imcce.fr/`.

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