The astrometry of the natural planetary satellites applied to their dynamics before and after Gaia

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Abstract

The natural planetary satellites are observed since centuries in order to understand their dynamics and their evolution. A high level astrometric accuracy is necessary for this purpose. The arrival of Gaia makes necessary to perform the ground based observations in the scope of the future data provided by Gaia. About 50 observations by Gaia of each satellite will be available, and the Gaia star catalogue will allow to reduce the astrometric observations with a high level accuracy. This is true for observations made at the present time, made in the future and made in the past thanks to a new reduction of old observations such as photographic plates. We analyze the different status of the satellites depending on the system of which they belong. This will decide the astrometric observing programs of the natural planetary satellites for the next years.

Key words: celestial mechanics, natural satellites, astrometry, GAIA

1. Introduction

Astrometric observations of the natural planetary satellites are regularly performed. The frequency of the observations depends on the satellites, on their revolution around their planet, on the periodic perturbing terms and on the dynamical models used. The arrival of Gaia leads us to make new plans for the observing programs and the reduction of the observations.

2. The astrometry of the natural planetary satellites

1) Purpose. The astrometry of the natural planetary satellites has several goals. The knowledge of their dynamics help us to understand the formation and evolution of the solar system and the internal structure of the natural satellites may be understood through the dynamics: tidal effects and dissipation induce an acceleration in their motions which is detectable through the astrometric observations (Lainey et al. 2009).

We have to note also that the astrometry of the giant planets is possible only through their satellites (natural or artificial i.e. space probes). Only the satellites are observable and the position and motion of the planets are deduced from the ephemerides of the satellites (Robert et al. 2011). For these purposes, we need accurate astrometric observations of the satellites to build accurate dynamical models in order to go from the positions of the satellites to the position of the planet, i.e. to translate the observed positions of the satellites to observed positions of the center of mass of the system. In both cases, we need observations spread over a long interval of time depending on the velocity of the satellites in order to model completely the dynamics of the satellites. How Gaia will help? Is it the same for all satellites?

2) The needed accuracy of the observations. An astrometric observation is valuable only if its accuracy is sufficient to model all dynamical effects. For example, for the large satellites of Jupiter, the smallest dynamical effects such as tidal forces are of 100m per year in longitude (acceleration) i.e. 45 km after 30 years and 500 km after one century, then this effect is mesurable with:

Eclipses by Jupiter: accuracy 500 km (needs at least 100 years of observations)

Old photographic plates: accuracy 300 km (needs at least 75 years of observations)

CCD images: accuracy 150 km (needs 50 years of observations)

Mutual events: accuracy 15 km (needs 17 years of observations)

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Space probes: accuracy 5 km (needs 3 years of observations)

GAIA: 5 to 10 km (needs 3 to 10 years of GAIA observations)

Of course, we need a large number of observations spread on a long interval of time and, due to the bad repartition of the observations of the same type with time, all types of data are useful.

3) Sampling the observations. The Gaia observations will be made on an interval of time limited to 5 years. Is this duration sufficient? In order to know the necessary length of this interval of time, we simulated observations and built ephemerides. Then, it appeared that one century of ground based observations is equivalent to 5 years of Gaia observations (Desmars 2009a, 2009b). The accuracy of the dynamical models does not depend only on the accuracy of the observations but also on the length of the period of observations. This may be tested through the extrapolation of the ephemerides depending on the sampling of observations used to fit the theoretical model of motion. For example, for Mimas, we split the set of available observations (Desmars 2009c) into two sets: the first one gathering 1547 observations made on a 50 years interval of time (1874-1928), the accuracy of which being 0.30 arcsec and the second one gathering 2820 observations made on a 30 years interval of time (1972-2005) the accuracy of which being 0.15 arcsec. We then built ephemerides using each set, and extrapolated each ephemerides on the period of the other set of observations. We were able to see which ephemerides were the closer to the observations. One should infer that the large number of more accurate observations will provide the smallest error for the ephemerides but in fact the contrary occurs. As seen on figure 1, the ephemerides made with the old less accurate observations are better than the other one. This comes from a short period term (70 years) in the motion of Mimas which is better described by observations made on a 50 years period than on a 30 years one.

Then the question of the use of the observations of the natural satellites by Gaia is appropriate.

3. The astrometric reduction before Gaia: accuracy of catalogues

Before Gaia, we performed the astrometric reduction by linking the catalogued stars present in the field. Then, the accuracy will depend on the field recorded together with the studied object. Small fields have less distorsion due to optics but they contain less catalogued stars. For example, a good catalogue published in 1997 after the astrometric satellite Hipparcos contains only 120000 stars until magnitude 12.4 with an accuracy better than one mas. The Tycho catalogue deduced from the Hipparcos mission contains 2500000 stars until magnitude 16 but with an accuracy not better than 60 mas due to proper motions. Small fields needing fainter stars, some catalogues intent to compile a larger number of stars: the USNO SA2 contains 526000000

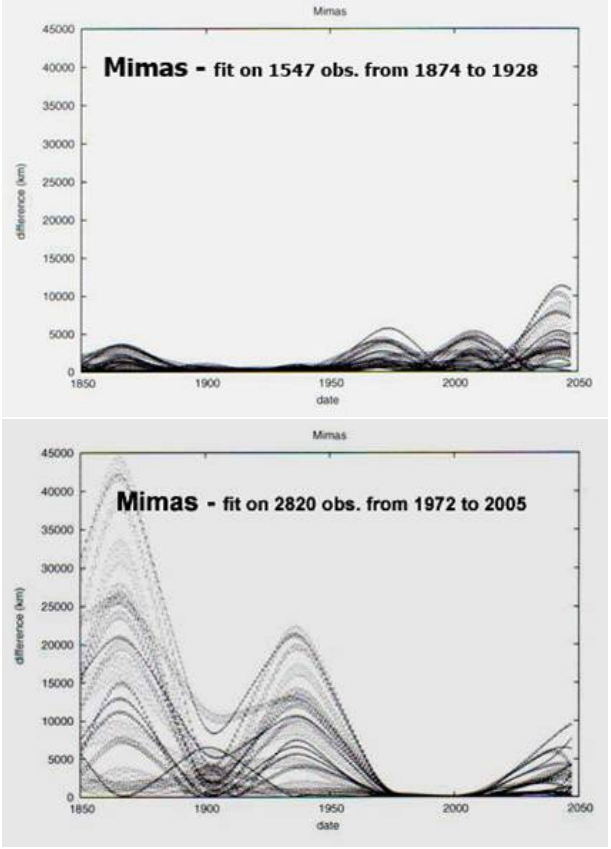

Fig. 1. Accuracy of extrapolated ephemerides depending on the observations used for the fit

stars with an accuracy not better than 150 mas. It is preferable, when the field is not too small to use the UCAC2 catalogue containing 48000000 stars with magnitude from 7.5 to 16 with an accuracy around 50 mas. One will understand easily that the Gaia catalogue will replace all the older catalogue for astrometric reduction.

4. The satellites observed by Gaia: the possible accuracy

We know that Gaia will observe all natural satellites the magnitude of which being from 8 to 20 with an accuracy around one mas. Each object will be observed 50 times during a 5-year period, a little less for satellites close to their planet due to possible occultation or blooming due to the bright primary. The accuracy and the interest of these observations will depend on the object:

-large objects extensively observed from Earth since years and observed by space probes will not take a large benefit from Gaia direct observations,

-small objects close to the primary, difficult to observe from ground based observatories, will take benefit from Gaia direct observations,

-small outer satellites far from their planet are similar to asteroids. Gaia observations will be valuable providing accurate positions, photometry and shapes of the objects.

Table 1
Usefulness of the Gaia data depending on satellites: + means usefulness

satellites	period	Gaia observations		Gaia catalogue
small, close to the planet	hours	+++	difficult ground based observations	+
large observed by Gaia	days	-	obs. on long time interval	+++
large not observed by Gaia	days	no	improvement of ground-based observations	+++++
outer irregular mag < 20	years	++++	getting shape and precise observations by Gaia	+++
outer irregular mag > 20	days	no	improvement of ground-based observations	+++++

Table 1 provides an estimation of the interest of the Gaia direct observations depending on the satellites.

5. Future astrometric reduction using the Gaia star catalogue

Future observations will use the Gaia catalogue for the astrometric reduction. The accuracy of the astrometric observations will not depend on the Gaia star catalogue but on the telescope used, the receptor, the measuring algorithm, the signal/noise ratio, the size of the object, the knowledge of its surface and shape. The Gaia catalogue will contain one billion stars until magnitude 20, so even a small field (a few arcmin) will contain a sufficient number of stars for the reduction.

Old observations will also take benefit from the Gaia astrometric star catalogue. A new reduction of old observations has to be studied and old observations have to be chosen carefully, depending of their quality and of the scientific need.

Figure 2 provides an image taken by the Cassini space probe, showing Enceladus and Dione against a field of a few stars. These stars are used for the astrometric reduction and allow to obtain positions of the two satellites with an accuracy of 10 km, mainly due to the uncertainty of the star catalogue. When doing the reduction with the Gaia catalogue, the uncertainty will decrease to 100 meters. Only the difficulty to measure the positions of the satellites will increase the uncertainty up to 1 km. However, the improvement is sufficiently important to justify a new reduction.

Figure 3 provides an image of the scan of the central part of a photographic plate taken in 1974 at USNO and showing several exposures of the Galilean satellites of Jupiter.

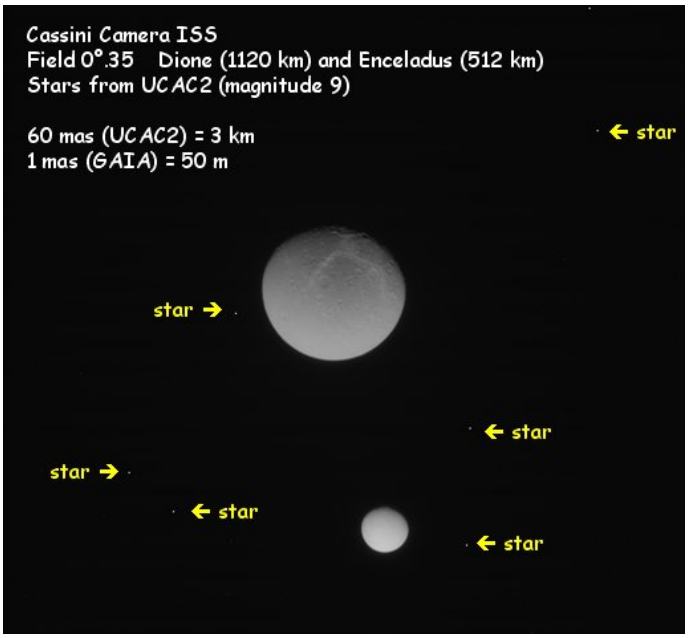

Fig. 2. Dione and Enceladus observed by the Cassini space probe: the astrometric reduction uses the stars present in the field.

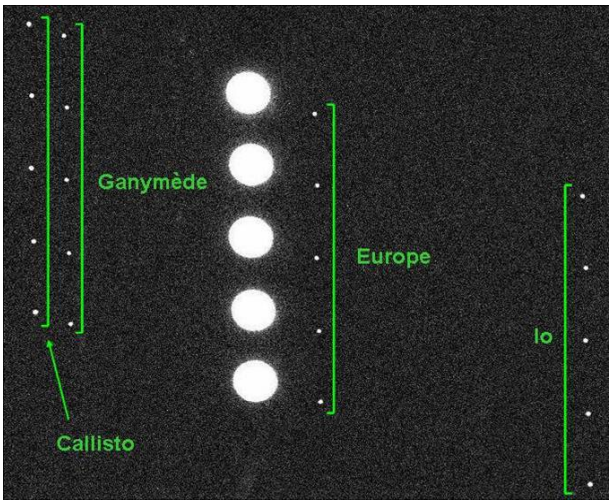

Fig. 3. The center of a photographic plate of the Galilean satellites made at USNO in 1974

These satellites are difficult to observe because there are too bright (which is the reason why Gaia will not observe them). The plates include a few stars which were not catalogued at the time of the observation. Recently, these plates were scanned and reduced with the UCAC2 catalogue providing very accurate and interesting results for the satellites and for the planet Jupiter (Robert et al. 2011). Making a new reduction with the Gaia catalogue will increase again the astrometric accuracy allowing to reach small effects in the orbital motion that is needed and provides interesting results (Lainey et al. 2009). Figure 4 shows the present accuracies of the observations of the Galilean satellites. All the old photographic observations will have the accuracy of the measurement on the receptor after a new reduction with the Gaia catalogue, i.e. an accuracy between 2 and 10

mas.

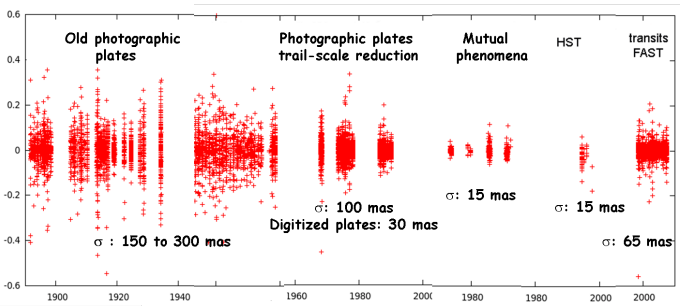

Fig. 4. Accuracy of the different types of observations of the Galilean satellites: using the Gaia astrometric star catalogue, the accuracy of photographic plates will become around 10 mas

6. What to do during the next years?

After the arrival of Gaia data, we first will use the 50 GAIA observations and second, we will use the Gaia star catalogue for the reduction of the new CCD astrometric observations. Then, we will re-reduce old observations: a long work of searching and selecting old observations among several hundreds of thousands plates spread in observatories worldwide. Metadata should be available to perform a new reduction. All of this will allow to gather valuable data leading to a better dynamical modeling of the solar system object, to a better measurement of tides effects and to a better knowledge of the evolution of the system. Table 1 estimates the interest of Gaia direct observations and Gaia star catalogue depending on the satellites.

7. Conclusion

The usefulness of the Gaia data for the natural satellites study will depend on the satellites. We have to be prepared to the arrival of the Gaia data. The observations made at the present time must take into account this future arrival. Because of the high velocity of most of the natural planetary satellites, we must never stop observing even if the reduction should be made with the Gaia catalogue: an observation not made is a missing observation. The sampling of observational data is crucial. More, we should think as soon as possible to what old data should be re-reduced with the Gaia astrometric star catalogue. Due to the high accuracy of positions and proper motions, the Gaia astrometric catalogue will be good enough even for old observations made one century ago, when the photographic plates appeared. We will be able to observe in the past that will bring valuable information for the natural satellites study purpose.

References

Desamrs, J.: 2009a, Precision d'extrapolation des ephemerides dans le systeme solaire. PhD, Paris Observatory, Paris.

Desmars, J., Arlot, J.-E., Arlot, S., Lainey, V., Vienne, A.: 2009b, Estimating the accuracy of satellites ephemerides using the bootstrap method. A&A **499**, 321.

Desmars, J., Vienne, A., Arlot: 2009c, A new catalogue of observations of the eight major satellites of Saturn (1874-2007). A&A **493**, 1183.

Lainey, V., Arlot, J.E.., Karatekin, O., Van Hoolst, T.: 2009, Strong tidal dissipation in Io and Jupiter from astrometric observations Nature **459**, 957.

Robert, V., De Cuyper, J.P., Arlot, J.E., de Decker, G., Guibert, J., Lainey, V., Pascu, D., Winter, L., Zacharias, N.: 2011, A new astrometric reduction of photographic plates using the DAMIAN digitizer: improving the dynamics of the Jovian system. MNRAS (early on line paper).