A Giant Step: from Milli- to Micro-arcsecond Astrometry
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Astrometry of the solar system: the ground-based observations

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Abstract. The main goal of the astrometry of solar system objects is to build dynamical models of their motions to understand their evolution, to determine physical parameters and to build accurate ephemerides for the preparation and the exploitation of space missions. For many objects, the ground-based observations are still very important because radar or observations from space probes are not available. More, the need of observations on a long period of time makes the ground-based observations necessary. The solar system objects have very different characteristics and the increase of the astrometric accuracy will depend on the objects and on their physical characteristics. The purpose of this communication is to show how to get the best astrometric accuracy.

Keywords. astrometry, solar system: general, ephemerides, occultations

1. Introduction

The astrometry of solar system objects is very specific since these bodies have a proper motion very fast and since they are, most of the time, not a point source but larger bodies with surface effects either depending on the structure of the object and/or on the phase angle. Note that we are interested in the astrometric position of the center of mass of the object and that we are observing, most of the time, its photocenter. Because of the large number of very different bodies in the Solar system, the observational techniques are also numerous in order to get the best astrometric accuracy. We will review the different techniques used by the observers and emphasize the ones providing the best accuracy and easily usable worldwide even with small telescopes.

2. Purpose of the solar system astrometry

Contrary to stars, the solar system bodies have proper motions very fast needing very complicated models for their motion. Celestial mechanics provide the tools to get the best dynamical models needing astrometric observations of the center of mass of the objects to fit the theoretical model to observations and to determine the parameters of the motion. Unfortunately, these motions, even very fast, have very long periodic terms depending on the motion of all the planets that require the observations to be spread regularly over a long period of time. So, the solar system astrometry should be made every day covering the orbits of all the objects. Theoretical models and astrometric observations will provide ephemerides of the solar system objects in order to help the preparation and the exploitation of the observations made either by space probes or by ground-based telescope. The ephemerides are also useful for the near-Earth objects on the orbits which could be a hazardous to the Earth. The determination of the scale of the solar system, its formation and evolution also need astrometric observations. The knowledge

Table 1. Observational techniques and their accuracy.

Technique	Accuracy	Objects	Comments
VLBI	2 to 10 mas	objects visited by space probes	all
Radar	10 to 100 m	Near-Earth objects	possible for Jupiter
LLR	1 to 3 cm	The Moon	
Transit circle	50 to 100 mas	magn. 6 to 15	except Mercury, venus and Mars
Scanning tel.	50 to 100 mas	until magn. 20	except the planets
Tangential focal plane	20 to 2000 mas	all	except the planet
Planets through sat.	20 to 50 mas	Giant planets	only Jupiter and Saturn
AO, IR	a few mas (relative)	inner satellites	objects close to primary
Photometric mutual events eclipses	1 to 30 km (1 to 10 mas) 500 km (150 mas)	main planetary satellites, asteroids Galilean satellites, Titan	occultations

of the dynamical reference system requires a good knowledge of the motions in the solar system. A better accuracy of the observations will allow us to make discoveries in the dynamics of the objects or in their physical structures. In fact, the non gravitational forces, not taken into account in theoretical models, can be detected from astrometric observations. Same, the tidal forces modify the orbits of the objects and astrometric observations will show the deviation of the real orbit relative to the theoretical one based upon a model not including these tidal forces. This shows the challenge to increase the accuracy of the astrometric observations of the solar system objects.

3. The different techniques of observation and their accuracy

Each technique of observations has its own precision and accuracy. Note that we must avoid to mix precision and accuracy. The precision is internal to the technique of observations and is calculated from the rms of observational residuals, made during a short period of time in which the residuals are not supposed to change. The accuracy is more difficult to determinate. It will be calculated from the residuals provided by a theoretical model, the precision of which being better than the one of the observations. We have to notice than the accuracy may be given either in angular units (arcsec or mas) or in distance unit (kilometers) depending on the technique itself.

- VLBI observations of space probes

The observations through differential VLBI are the most accurate but need to receive a radio signal from a space probe. The positions are relative to the nearby radio sources and linked to ICRF. The Deep Space network of the JPL is used for that purpose (Folkner *et al.* 1996, Standish 2000).

- Direct observations by space probes

Space probes take pictures of the objects that they are visiting with stars in the background: knowing the position of the probe, these pictures yield astrometric data. These observations (mainly the planetary satellites) are very rare but are added to the available series of data for dynamical purpose (see for example Jacobson 2004).

- Radar observations

Radar observations may be performed only for nearby objects and have been made for Near-Earth objects allowing to measure the distance to the Earth. Since the radar data

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have an accuracy until 10 times better than optical observations, this technique should be used more extensively for the calculation of the orbits of NEO (Ostro 2002).

- LLR (Lunar Laser Ranging)

The LLR is used only for the Moon thanks to the reflector put on the Moon first by Apollo 11. The ranging was made from several sites but only McDonald observatory, USA and Grasse Observatory, France, produced observations regularly and over decades (Dickey *et al.* 1994). The accuracy was about 20 cm at the beginning and now is a few centimeters. An improvement of this accuracy should be possible in the future thanks to the technical progress.

- Optical ground-based observations

In nearly all techniques described above, the optical ground-based observations are performed over centuries and are efficient since photographic plates allowed to record the data. The advantage of this technique is to be easily available at any time – important for solar system objects that need a continuous survey. The lower accuracy is replaced by the large number of observations and by their distribution over the time. Different techniques were developed in order to increase the astrometric accuracy as we will see below. Table 1 provides some comparisons between several optical ground-based observational techniques for the Galilean satellites and for the Uranian satellites. The photometric observations of occultations have the same accuracy for both systems but is better for the Uranian satellites since the accuracy is in kilometers at a very large distance.

Even if some non optical techniques provide a high level of accuracy, ground-based observations are necessary for several reasons:

-many objects are not visited by space probles making impossible VLBI or Doppler observations

-radar observation is a powerful technique but only the objects near the Earth can be observed even though the farther objects are reachable but with difficulties.

-objects for which a long period of observations is possible only with optical ground-based observations (objects beyond the main asteroid belt).

4. The meridian transit circle

The meridian transit circle observes the culmination of an object and measures directly its right ascension and declination. The automatic transit circles use a CCD target in TDI mode i.e. the CCD scans the sky rebuilding an image which may be very long. All the objects present in this strip are linked together. Each transit circle may be associated to its own star catalogue determining its absolute accuracy. Bright objects (magnitude from 6 to 15) have been extensively observed for many years and provide useful data (Stone 2001, Rapaport *et al.* 2002). These instruments have limits: small aperture, large pixels, small declination (at large declinations, the strip is not rectangular). A way to solve these problems is to use scanning telescopes along great circles of the celestial sphere such as LINEAR, working automatically, providing the majority of the asteroidal observations.

Table 2 provides the rms of the residuals of observations of Uranus and its satellite Oberon made at Flagstaff and at Bordeaux.

5. Tangent-plane astrometry

The most classical astrometric observations consist in making an image in the focal plane of the telescope. During most of the XXth century, photographic plates were made extensively either with short focus instruments or with long focus ones. Unfortunately, the star catalogues were poor and too few stars from these catalogues were present on the

Table 2. Rms of the residuals of transit circle observations in arcsec.

	FASTT				Bordeaux			
	Oberon		**Uranus**		**Oberon**		**Uranus**	
Year	R.A.	DEC	R.A.	DEC	R.A.	DEC	R.A.	DEC
1997					0.16	0.09	0.05	0.08
1998	0.15	0.14	0.12	0.15	0.11	0.18	0.09	0.09
2001	0.15	0.13	0.13	0.14	0.26	0.23	0.06	0.11
2002	0.13	0.11	0.16	0.11	0.11	0.31	0.08	0.09
2004	0.11	0.10	0.11	0.14	0.13	0.24	0.08	0.14
2005					0.22	0.28	0.08	0.25

Table 3. Characteristics of the main astrometric star catalogues.

Year	**Name**	**Number of stars**	**Limit magnitude**	**Accuracy in mas**	**Accuracy in proper motion**	**Origin**
1997	Hipparcos	120 000	12.4	< 0.78	< 0.88 mas/yr	obs. from space
2000	Tycho 2	2 500 000	16	25 to 100	< 2.5 mas/yr	from Tycho and 143 sources
1998	USNO A2	526 280 881				
2005	GSC II	1 billion	19.5	360		Schmidt plates
2003	USNO B1	1 billion	21	200		Schmidt plates
2004	UCAC2	48 000 000	7.5 to 16	20 to 70	1 to 7 mas/yr	CCD imaging
2004	Bright stars	430 000	< 7.5			Hipparcos + Tycho2
2005	Nomad	1 billion				compilation of best entries
2006	Bordeaux	2 970 674	15.4	50 to 70	1.5 to 6 mas/yr	$+11deg >$DEC$> +18deg$
2003	2MASS	470 000 000	16	60 to 100		Infrared K
2015	Gaia	1 billion	20	< 0.01		obs. from space

long-focus photographic plates because of the small number of stars in the catalogues at that time. Consequently, only relative astrometric positions were provided through reductions based upon the trail-scale method (Pascu 1996).

At the end of the XXth century, CCD technology appeared, allowing to capture images electronically which then are analyzed by computers. In fact, the early CCD chips were very small compared to photographic plates and, at the beginning, only relative astrometry was possible. However, the size of the CCD chips has increased along with the number of reference stars in catalogues, so that a sufficient number of astrometric stars are now available even in a small field. Table 3 provides a list of the main star catalogues and their characteristics, used in astrometric reductions.

5.1. *Direct CCD imaging*

CCD imaging provides, most of the time, small 3 to 12 arcmin fields. Thanks to the now available star catalogues, it is possible to find enough astrometric stars for the reduction (cf. Table 3). The accuracy of the measurement depends on several criteria:

- sampling of each image in pixels (the FWHM should be larger than 2.5, i.e. seeing and the pixel size must be adequate);
- signal/noise ratio must be high enough for centroiding of the image;
- atmospheric absorption must be taken into account for moving objects observed at

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Table 4. Residuals and rms (in mas) from a re-reduced photographic plate made in 1994.

Date in JD	**Io** in R.A.	(O-C) in DEC	**Europa** in R.A.	(O-C) in DEC
2449521.577894	-41	-22	-43	+15
2449521.578356	-59	-24	-6	-23
2449521.578877	+15	-4	-6	-83
2449521.579456	-46	+44	+44	+22
mean (O-C)	-33	-2	-3	-2
rms (O-C)	43	28	31	45

small elevations above the horizon, far from the meridian transit with long exposures. The photocenter moves towards the zenith, contrary to the images of fixed stars (this effect is very different from refraction).

5.2. *Photographic plates*

Nowadays, photographic plates are no more in use in spite of the possibility of a very large field which are now made using mosaics of CCD chips. The low sensitivity of photographic plates has led to their abandonment for astronomical purpose. However, it appears to be important to scan the old photographic plates and to reduce them with the new star catalogues. This is equivalent to observing in the past with the benefit of getting "new" observations at the time when it is not possible to make them anymore. Several attempts were made showing the importance of this method (Pascu *et al.* 2005). Pluto, which has not been yet observed over a complete orbit, has a motion not very well understood. The reductions of old plates should add new data useful for such a purpose (see Table 4).

5.3. *Small field astrometry*

Some solar system objects, such as small satellites very close to their host planet, are difficult to image because of the brightness of a planet. Several techniques may be used in order to get measurable images. The goal is to make the image of a planet faint enough to minimise a halo of light overlapping with the target object. Two methods allow to get such astrometric images:

- adaptive optics: in fact, the brightness of a planet per square arcsec is similar to the one of the satellites and the large contrast between the planet and its satellite comes from the seeing effects. The light of a satellite is spread out over the detector while the light of a planet is concentrated on the same pixels. To solve this problem, it is useful either to observe in a site with a very good seeing or to use adaptive optics.

- infrared observations: we note that the giant planets are not that bright at specific infrared wavelengths where the light from the Sun is absorbed by the atmosphere of planet. Observations in the K-band allows us to get measurable images very close to the planet. Figure 1 shows an image of the Uranian satellites in the K-band: from left to right: Titania, Ariel, Miranda, Umbriel, Uranus, Oberon. The planet, usually very bright compared to its satellites, here is quite dark.

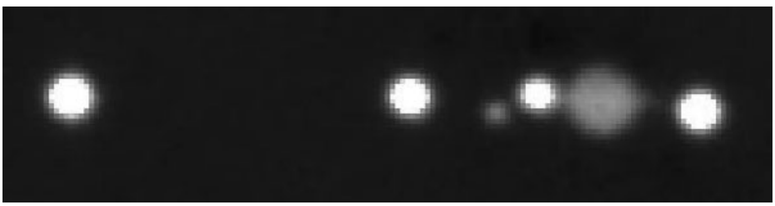

Figure 1. The system of Uranus in the K-band (c) ESO-NTT.

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Table 5. Rms of the residuals of pseudo-observations of Saturn in arcsec.

	via Titan		via Hyperion	
Year	R.A.	DEC	R.A.	DEC
1999	0.05	0.10	0.17	0.25
2001	0.04	0.10	0.22	0.34
2003	0.05	0.09	0.26	0.19
2004	0.03	0.12	0.25	0.36
2006	0.08	0.08	0.17	0.28

5.4. *Close approaches of stars*

Another technique of observation possible even with a small field is the observations at close approach of a solar system object to a star, the position of which is known. Even without any other stars in the field, it is possible to use the motion of an object to calibrate the field, making a series of short exposures during the close approach. Even if the position of a solar system object is not known very well, its angular velocity can be predicted to a high accuracy. Relative position with respect to a star can be deduced with a high precision (Souchay *et al.* 2007).

5.5. *Pseudo-observations of planets*

Pseudo-observations of a planet consists in observing a satellite of the planet and following its positions through the ephemerides of the satellite. This method is used in some specific cases:

- the center of mass of a planet is not easy to observe because of a thick atmosphere (the case of Jupiter) or of the presence of a bright ring (Saturn);

- the ephemerides of satellites are more precise than the observations of planet ifself (the case of Galilean satellites and some Saturn's main satellites).

This method is interesting for Jupiter and Saturn if we have sufficient observations of absolute positions (right ascension and declination) of satellites. Table 5 shows the rms of the residuals of pseudo-observations of Saturn through Titan and Hyperion from transit circle observations. It is clear that the accuracy of this method depends on the satellite used for this purpose. It is known that Hyperion is more difficult to observe than Titan with a transit circle and that Hyperion has an ephemeris of less accuracy than Titan.

6. Photometric astrometry of mutual phenomena

During the years, astrometry consisted in the measurement of angles on the celestial sphere. Radar observations recently introduced the direct measurement of a distance between the observer and the object. However, other ground-based observations are able to provide distances between solar system objects: the occultations and eclipses.

The first phenomena observed for an astrometric purpose were the eclipses of a Galilean satellite by Jupiter. Observing the disappearance of a satellite in the shadow of Jupiter corresponds to a specific geometric configuration of the system Jupiter-satellite. Numerous observations are made when the configuration is changing with time, allowing to build a model of the motion of the satellites. The first dynamical model of the Galilean satellites was made thanks to observations of eclipses. Unfortunately, the astrometric accuracy (cf Table 1) may not be better than 100 mas because of the Jovian atmosphere. In contrast, the satellites have no atmosphere and their mutual occultations and eclipses can be accurately observed. The occurrence of such events corresponds to the equinox on the planet since all main satellites belong to the equatorial plane of a planet. The predictions of these events started in the 1970's when computers made possible such calculations. Predictions are now regularly made using the best dynamical models since the events are very sensitive to calculations (Arlot, 2002). Coordinated campaigns of observations allow to get numerous observations used for planetologic purpose (study of the surfaces) and for astrometry. The photometric observations provide often light curves which appear to be not symmetrical. This asymmetry is a source of information and allows to increase the accuracy of the relative positions deduced from the observations through the knowledge of the surface of objects. Note that the measures are in kilometers, more precise than in angle especially for remote objects. (Vasundhara *et al.* 2003, Emelianov and Gilbert 2006, Kaas *et al.* 1999).

Occultations of stars can provide accurate positions of the object relative to a star. However, these occultations are too rare to be extensively used for astrometric purpose. The main goal in this case, is to measure the size of an object.

7. Towards a higher astrometric accuracy

How to improve the accuracy of the Solar system object astrometry? We may ask for more space probes to be put around the Solar system objects but it is clearly a very limited option. Radar observations should be intensified for near-Earth objects since the distance provided by a radar are of a high accuracy, allowing to fit very accurately the dynamical models.

There are also other ways to improve the accuracy of observations: celestial mechanics predicts the position of the center of mass of an object and observations provide the position of a photocenter. An improvement is possible by studying the surface of the objects. First, the phase effect should be taken into account not only in its geometric effect but also in the reflected light, depending on the nature surface material. Several laws of diffusion and reflectance are helpful for this purpose, such as Hapke's laws (Hapke 1993). For some objects such as the main satellites of giant planets, the albedo maps may improve the astrometric accuracy of observations.

Another question is the arrival of Gaia. When the Hipparcos data arrived, a substantial progress was made and the interest in new data was expressed (Fienga *et al.* 1997). But would Gaia make useless all the old observations? A paper by Desmars (Desmars 2005) has shown that even very accurate observations made during a short period of time will not replace a set of numerous but less accurate observations made over a long time span period of time. Gaia will provide 50 observations on a period of 5 years for each solar system object with an accuracy of 0.1 to 1 mas, depending on the object. His conclusion was that Gaia will not bring more accuracy for objects extensively observed more than a century with a fairly good astrometric accuracy.

However, the interest in Gaia for the Solar system objects will be its catalogues of stars which will allow to re-reduce the old observations. We will be able to observe in the past with accuracies not reachable at the time of observations. In chapter 5.2 we have shown that re-reductions of photographic plates is very powerful even with the present-day catalogues. The arrival of Gaia catalogues will substantially increase the benefit of re-reduction of old observations.

8. Conclusion

The astrometry of the solar system may be improved by taking into account the physical characteristics of the objects. The arrival of new star catalogues such as Gaia will allow to re-reduce old observations providing much better data from the past. The observational effort must be continued in order to improve the quality of dynamical models for the motion of solar system objects.

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