A new reduction of old observations: a challenge for the next decade

Jean-Eudes Arlot

A new reduction of old observations: a challenge for the next decade

J.E. Arlot (IMCCE/CNRS/observatoire de Paris)

Introduction: looking to the past of the Solar system

The solar system objects are fast moving objects, needing to build accurate dynamical models in order to make ephemerides and to predict the positions of these objects in the future. More, the building of such dynamical models helps to understand the formation and the evolution of the objects of the solar system. For that purpose, astrometric observations of their positions are made since years. Because of the progress of the observational techniques, the astrometric accuracy of the observations is increasing, years after years. However, even the more recent observations are very accurate, old data are still useful. Using only the recent good data does not allow to build long term theories as it has been shown (Desmars 2009) and old observations are still used for fitting the theoretical models. We may wonder how old the observations should be to be kept for our present models. Two criteria have to be taken into account. First, the accuracy of the old observations should be equivalent to the amplitude of the periodic small effects to be modelized and quantified: this will help to decide which observations are still useful to be kept. Second, this accuracy should be better than cumulated effects due to secular terms. This criterium will increase dramatically the number of interesting observations. The experience obtained from the present dynamical models shows that the best micrometric visual observations from the middle of the XIXth century are still useful as the observations of eclipses of the Galilean satellites made during the XVIIIth century. However, because of recent knowledge, we are able to improve the accuracy of these old data, mainly by correcting the time scale, making them more useful. We will see below how these improvements might increase in the next future thanks to the Gaia data.

Purpose of the astrometry of solar system objects: the interest of old observations

Astrometry of solar system objects is necessary in order to provide numerical values to the parameters of the dynamical models built by celestial mechanics. Then, ephemerides could be made for several purposes:

- Space navigation
- Impact hazard assessment
- Space and ground based observations

The search for gravitational or non-gravitational small effects for the dynamical models are closely related to the astrometric accuracy and allows progresses in:

- Dynamics, stability, evolution, scale of the solar system
- Physics of the surface and internal structure of solar system objects
- Gravitational and relativistic studies
- Reference systems

For these goals, old data have specific interests:

- The interest of old observations is for the fitting of parameters of a “time-dependant” model.
- Old astrometric observations are necessary for:
  - Making of ephemerides accurate on a long interval of time with a better modeling of long periodic terms
  - Studying the evolution of solar system and quantifying accelerations coming from tidal effects

We will provide below some examples of the interest of old observations.

Ephemerides extrapolation

Extrapolating the ephemerides in the future has been a challenge never solved. In fact, when fitting the dynamical model on the observations, we calculate the external error for the period of the observations only , so, how to extrapolate the external error to a period in the future where no observation is available? We use several methods but, in fine, this extrapolation depends on the use of old precise observations enlarging the period of validity of the ephemerides. This shows the importance of long period observations preferred to short period with better accuracy. As shown in Desmars et al. (2009), in the case of Mimas, the first satellite of Saturn, 1547 observations made on a 50-year interval of time with an accuracy of 0.30 arcsec is preferable to 2820 observations made on a 30-year interval of time with an accuracy of 0.15 arcsec'. This is mainly due to a short term libration of 70 years. Fast periodic motions need long observing period of time.

The evolution of the solar system:

<u>The natural planetary satellites</u>. The evolution of the solar system may be deduced from the dynamical models describing the motion of solar system objects. However, this evolution is characterized by some parameters which have to be validated by the observations. Long term scenarios of evolution may be validated only by observations made at the present time on a very small interval of time. Enlarging this interval of time could be very useful. For example, secular terms are more easy to estimate through an interval of time during which the cumulated effect is detectable. For example, the tidal effects on the satellites of the giant planets may be observed only after one century of observations. The thermal equilibrium of Io has been demonstrated through the analysis of a large set of astrometric observations of the Galilean satellites (Lainey et al. 2009). Same, the geysers on Enceladus found an explanation after the analysis of numerous astrometric observations (Lainey et al. 2012). It is possible to go further, either for these satellites showing a scenario of formation and evolution with more accurate astrometric observations made on a longer interval of time or for other bodies such as the Uranian moons for which the astrometric observations are more rare and less accurate since their distance to the Earth is larger.

<u>The « pre-discoveries » of Pluto</u>

Pluto has been discovered in 1930 so that we observed only an arc of its orbit. The semi major axis of its orbit is not well defined. How to enlarge the set of observations? The presence of Pluto on old observations performed before its discovery in 1930 has been shown: these “pre-discoveries” are essential in order to improve the dynamics of Pluto but we need to make a new accurate astrometric reduction of images made far in the past, when reference star catalogues were not confident. Here occurs the problem of the reduction of old observations that we will have to solve.

<u>Near Earth objects</u>

Near Earth objects (NEA) are observed on a very short interval of time for most of them. We may try to follow them in order to improve their ephemerides and extrapolation in the future but the lack of observations in the past encourage us to try to find pre-discoveries on old observations. In fact, due to their fats motion, “old” corresponds, for NEA, only to a few years so that the reduction problem is easy to solve and the astrometric accuracy will be sufficient for our purpose.

<u>Observations of the planets</u>

The planets, especially the giant planets are difficult to observe for astrometric purpose: their center of mass which is the moving point described by the laws of celestial mechanics, is not easily observable because of a thick atmosphere and a phase effect difficult to model. The satellites are easier to observe: their figure is simpler without atmosphere and we may suppose that their center of mass is the center of the figure. Then, their ephemerides will provide exactly the position of the center of mass of the planet. However, in the past, the satellites were observed referred to their primary but with a new reduction, we will be able to get RA and DEC of the satellites and then going back to the center of mass of the system that will provide new observations of the planets in the past.

What is an old observation?

As evidence, an old observation is an observation made in the past and our purpose is to see how such an observation may bring original information nowadays. This observation may have been reduce and have provided astrometric positions which have been used and which may still be used in the fit of dynamical models today. How to obtain more now?
A new reduction may be interesting thanks to new reference star catalogues including more accurate stars than in the old catalogues used for the first reduction. However, we have to be sure to have a genuine original observation under the form of a plate or a numerical image with all needed metadata such as the date in a time scale linkable to UT, the exposure time, information on the instrument (aperture, focal length), information on the support (plates, CCD, filter, …). Then we will be able to re-reduce this observation and to obtain new positions for a past epoch.

What about measurements without the observation itself?
In some case, we may get the measurements without the original observation. We need information on the date, the instrument, the reference frame, the corrections applied to the measurements. We will be able to perform not really a new reduction, but to make corrections to the original reduction. For example, if we know the reference stars and the catalogue used, corrections may easily be made.
Table 1 provides the different types of observations performed and indicates if the improvement through a new reduction is possible.

Technique	Present accuracy	Objects	Improvement
Transit circle	50 ➔ 100 mas	mag 6-15	probably
Scanning telescope	50 ➔ 100 mas	➔ mag 20	possible
Focal plane images	20 ➔ 2000 mas	all	yes
AO, IR	a few mas (relative)	inner objects	yes : through more faint reference stars available
Photometric events	1 ➔ 10 km (relative)	main planetary satellites, asteroids	no, depends on size of objects
Gaia	0.1 ➔ 1 mas	mag 7 ➔ 20	50 obs./5 years
Space probes	2 ➔ 10 mas	objects visited by space probes	yes for observations referred to stars

Table 1

A new reduction

The interest of a new reduction of old observations is obvious: modern techniques of measurements and new algorithms for centroiding (automatic instead of manual) may be more efficient. Positions in a recent reference system should be easier to link to modern observations. New reference star catalogues contain more stars (table 2) with a better astrometric accuracy. The arrival of the Gaia catalogue will complete the possibilities. However, we should not use the classical reduction methods with the Gaia catalogue since it would be accurate to less than one mas. Many small effects neglected until now will be worth to be corrected in order to keep all the accuracy for the final positions. A more complete reduction algorithm should include a better refraction model (including differential and zenithal refraction), correct small effects such as coma and take into account color effect in refraction or magnitude effect (plates).

Year	Name	Nb of stars	Magnitude limit	Accuracy mas	Accuracy p.motions	Origin
1997	Hipparcos	120 000	12.4	< 0.78	< 0.88 mas/y	obs. from space
2000	Tycho 2	2 500 000	16	< 60	< 2.5 mas/y	from Tycho and 143 sources
1998	USNO A2	526 280 881				
2001	GSC II	19 000 000		360		Schmidt plates
2003	USNO B1	1 billion	21	200		Schmidt plates
2004	UCAC 2	48 000 000	7.5 ➔ 16	20 ➔ 70	1 ➔ 7 mas/y	scans
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 ➔ 70	1.5➔6 mas/y	+11° > δ > +18°
2003	2MASS	470 000 000	16	60 ➔ 100		Infra red K
2015	GAIA	1 billion	20	< 0.01 mas		obs. from space

Table 2

Compared accuracy of different observations

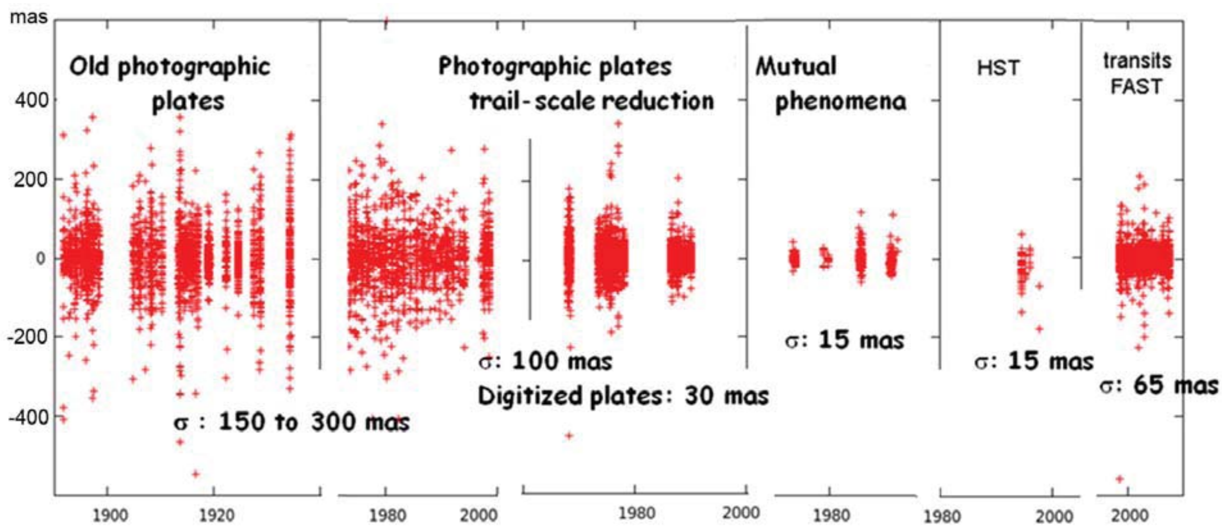

Figure 1

Figure 1 provides as an example, the rms of the residuals to the best model of several types of observations of the Galilean satellites of Jupiter. At least, a new reduction should reduce the rms of the residuals of the old photographic plates to 30 mas as it is with the recent ones. With the Gaia catalogue, the improvement should be larger and possible for all direct focal plane imaging.

__Problems to be solved for old observations__

Old observations were reduced with the reference star catalogues available at the time of the observations and the correction possible to make easily nowadays is a zonal correction by comparing reference star catalogues. Our goal is to go further and to reduce again the original observation. The first experiences made with the UCAC2, 2-MASS, Tycho-2 or USNO B1 have shown the problem of the proper motion of the stars: going back more than 30 years does not allow to improve the accuracy of the reduction. The future Gaia reference star catalogue should solve this problem by providing proper motions more accurate and allowing to go back about one century in the past.
A new reduction should solve most of the problems of inaccuracy of the old data. We just have to check the quality of the original observation on photographic plates. In some case, we will have just the old measurements of all objects present on the plate: if the manual measurements were confident, a new reduction should be useful.

__Some problems of the reduction__

Most of the small objects of the solar system were discovered and observed with Schmidt telescopes on Schmidt plates. Obtaining a good astrometric accuracy with Schmidt plates was not easy. However, most of the stars will be included in the Gaia catalogue (until magnitude 20) so that we could have about 50000 stars to perform the reduction! A good model of the field should be possible for the field calibration.
We have to note that solar system objects are fast moving in either rich or poor field (figure 2 below 10x10 arcmin until magnitude 20): so, be careful to select observations easy to reduce. The photographic plates made with most of the astrograph do not contain stars until magnitude 20 and may have not enough stars to perform a good reduction.

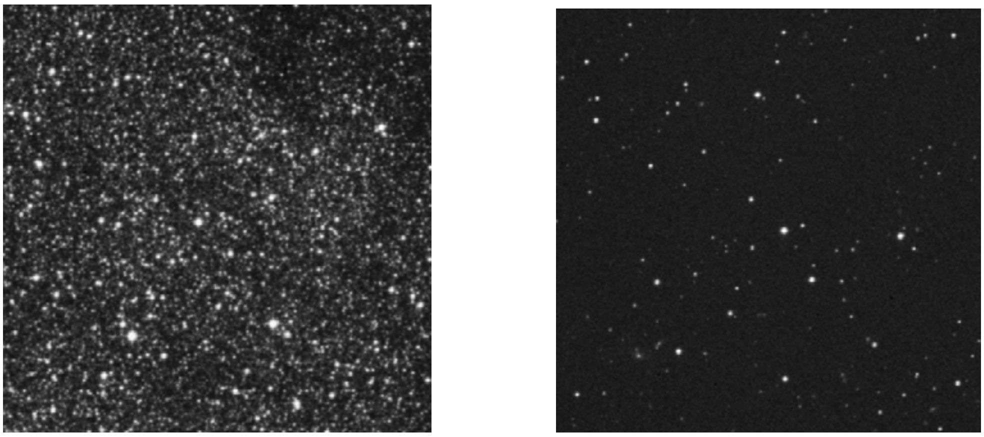

Figure 2

Photographic plates

<u>Digitizing the plates</u>. A new reduction of photographic plates needs to digitize the image and measure the positions of stars and objects. Scanning the plates to get numerical images which will be analyzed by computers needs to be very careful in order to be sure of the astrometric accuracy. It is pure metrology: we have to calculate the errors of measurement all along the process:

- motion of the XY table
- distortion of the optics to get the image
- geometry of the CCD or CMOS target
- making of the fits file

The cumulated error should be smaller than the astrometric accuracy of the reference star catalogue. It has been shown that the total measuring error should be less than 100 nm (Robert et al. 2011).

Selecting the plates. The available photographic plates are very numerous and we will have to select only the more interesting. The criteria could be as follows:

- plates in good shape
- objects needing observations in the past
- dates for which the sampling of observation is very poor or inexistent

Plates were made, most of time by short focus astrograph (Carte du Ciel or instrument with a focal length less than 4 meters), by normal astrograph (focal length between 4 and 7 meters), by long focus astrograph (focal length larger than 7 meters) or by Schmidt telescopes. Note that long focus instrument provide small field. They were used in the past in order to increase the astrometric accuracy in relative astrometry (too few catalogue stars) but all stars will be in the Gaia catalogue allowing a RA/DEC reduction.

Metadata. It is necessary to get all the needed metadata such as the instrument, focal length, filter, sensitivity of the emulsion, date of the exposure, exposure time, site of observation, accuracy of the time scale referred to the Universal Time. One datum missing may make the plates useless.

Ground based CCD observations made in the 1980's

These observations are old observations! Most of time, the field was very small and only relative positions were extracted. It is worse than with long focus photographic plates. However, the Gaia catalogue will contain enough stars for the reduction of small fields providing that the exposure was long enough to catch faint stars which were useless at the epoch of the observations. If stars are numerous enough for a complete astrometric reduction, the measurement could be not only better than the previous ones but also it will provide RA and DEC positions when only relative positions were provided. Figure 3 shows a poor field with stars until magnitude 20. Old CCD observations had, most of time, fields around 3 arcmin.

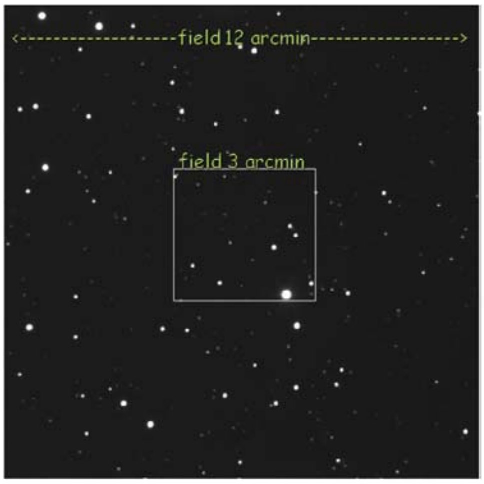

Figure 3

Space probes observations are old observations!

The astrometric positions provided by the space probes come from images containing the solar system object and reference stars. The accuracy is very good since the space probe is very close to the observed object. The figure 4 (Tajeddine 2012) shows an image from the space probe Cassini near Saturn. The UCAC2 catalogue is used for the astrometric reduction. Because of the small number of

Figure 4

Observing in the past: how to select observations to be re-reduced?

First, the observations must be available under the format of fits file, either after digitizing photographic plates or after finding files in CCD observations archive (most of the large telescopes have archives on line, full of interesting images).
Second, a new reduction could bring new information and a better astrometric accuracy
Third, the selection must be made through scientific purposes. Note that it will not be possible to re-reduce all the old data, even the original observation is available. Below, one will find some examples concerning the natural planetary satellites:

- Satellites of Mars:

3000 observations are available from 1877 to 1988 (14 per year per satellite)
Examine old observations in order to see if a new reduction is possible
Need to digitize plates from 1990's in order to eliminate gaps

- Galilean satellites of Jupiter:

12000 observations are available from 1891 to 2001 (27 observations per year per satellite)
Need to digitize old plates from 1890's in order to improve old data and all un-reduced observations
Need to reduced data formerly in intersatellites into RA and DEC

- Main satellites of Saturn

50641 observations are available from 1874 to 2003 (49 observations per year per satellite)
Need to digitize plates from 1920's to eliminate gaps
Need to reduced data formerly in intersatellites into RA and DEC

Conclusion: the NAROO project

In conclusion it appears that many new results may arrive soon from a new reduction and analysis of well-chosen old observations. The Gaia reference star catalogue is not yet available but a lot of work is necessary, the present catalogues allowing preparing new astrometric reduction algorithms. It will be useful to organize collaboration between interested laboratories since all the fields of research covered by this project should be shared worldwide. Among the first goals to be started, we may emphasize:
- inventories of:

photographic plates identifying the storage places and the location of the metadata
archives of CCD observations

- selections of plates to be analyzed
- choice of criteria and parameters for digitization making the files useful for several purposes
- preparation of the reduction programs taking into account the increase in accuracy
- making tests with available plates on available digitizing machines with present catalogues
- preparing specific databases for files of digitized plates through the standards of the Virtual Observatory.

We have a challenge for the next years: astrometry will change with the arrival of the Gaia reference star catalogue and we have to be ready for the exploitation of all the old data which contain information not yet used and necessary for many scientific purposes.

References

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

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

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

Lainey V., Karatekin O., Desmars J., Charnoz S., Arlot J.E., Emelyanov N., Le Poncin-Lafitte C., Mathis S., Remus F., Tobie G., Zahn J.P.: 2012, Strong tidal dissipation in Saturn and constraints on Enceladus thermal state from astrometry, The Astrophysical Journal 752, 14

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 415, 701.

Tajeddine R.: 2012, private communication