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

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The importance of the astrometry of the natural satellites

- The knowledge of dynamics of natural satellites help to understand the formation and evolution of the solar system
- Ground based astrometry of giant planets is possible only through their satellites (natural or artificial = space probes)
- The internal structure of the natural satellites may be understood through the dynamics (tidal effects, …)

We need:

- Accurate observations of the satellites:
  - To build accurate dynamical models of the satellites in order to go from the positions of the satellites to the center of mass of the system
  - To translate the observed positions of the satellites to the center of mass of the system
- In both cases, we need observations spread over a long interval of time

- How Gaia will help?

Which accuracy for the observations ?

- 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)
  - Space probes: accuracy 5 km (➔ needs 3 years of observations)
  - GAIA: 5 to 10 km (➔ needs 3 to 10 years of GAIA)

Attention: due to the bad repartition of the observations with time, all types of data are useful…

Ephemerides extrapolation: are very accurate observations necessary?

- The accuracy of the dynamical models does not depend only on the accuracy of the observations but on the length of the period of observations

- This may be tested through the extrapolation of the ephemerides

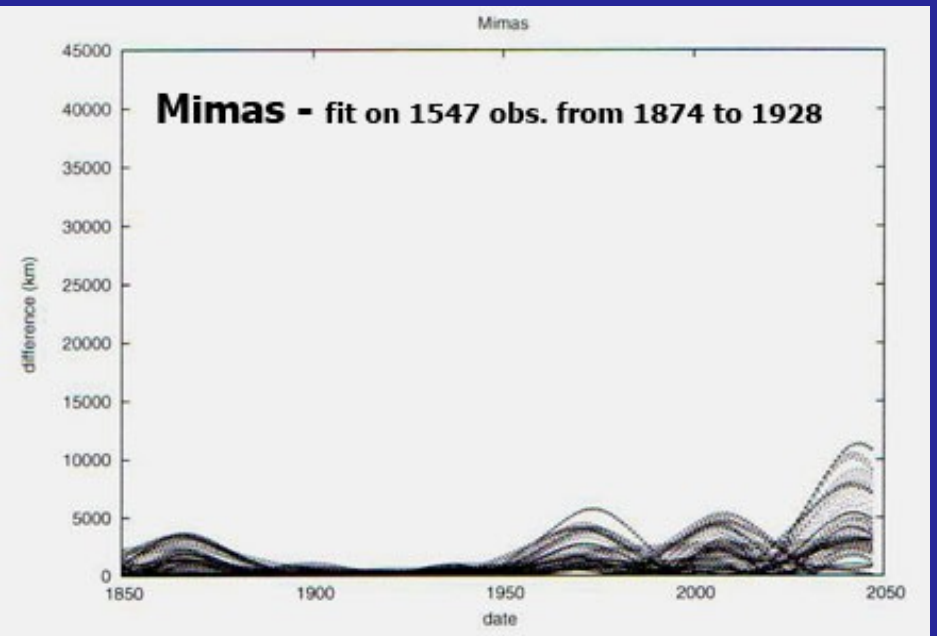
- How to extrapolate the external error to a period in the future where no observation is available? The use of the errors on the initial conditions needs that the law of errors be known (biases, …) that is not the case… So, the « random hold-out » method is preferable, even providing larger errors (Desmars 2007).

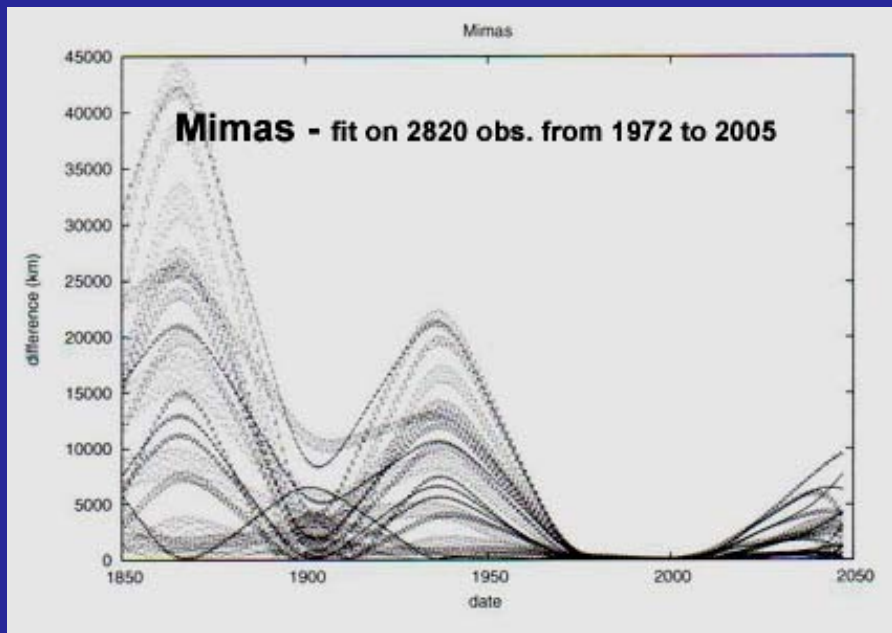
The extrapolated accuracy of the ephemerides

- Several ephemerides based upon the same set of observations deduced by random hold-out

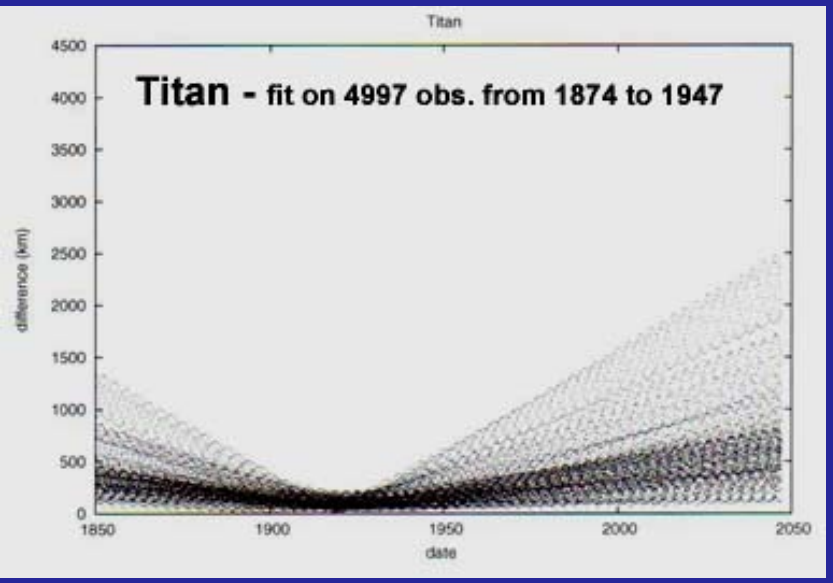
- This shows the importance of long period observations preferred to short period with better accuracy

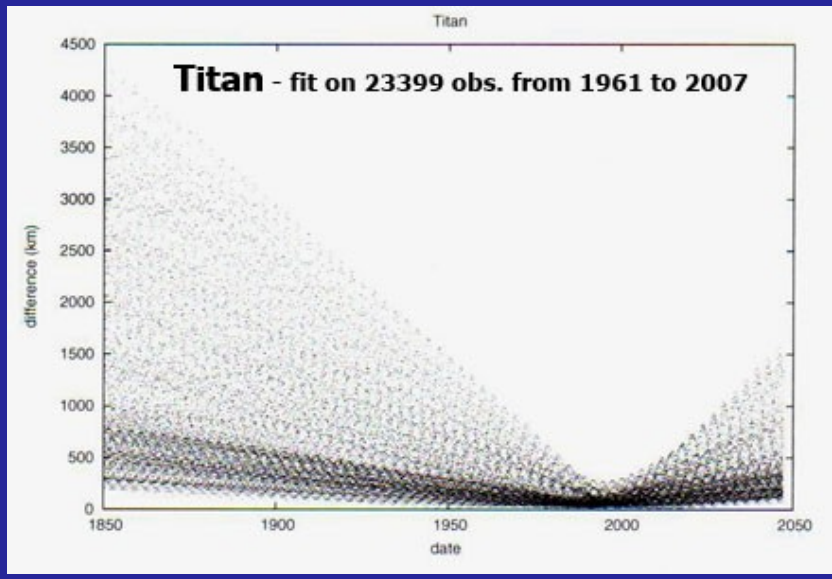
Case of Mimas: 50 years – 1547 obs. (accuracy: 0.30")
preferable to 30 years – 2820 obs. (accuracy 0.15")
due to short term libration (70 years)





Same with Titan 4997 obs. on 73 years
preferable to 23399 obs. on 46 years





So, the interest of Gaia observations will not be the 50 observations of the natural satellites themselves made during the mission.

So, what will be the interest of Gaia observations for natural satellites purpose?

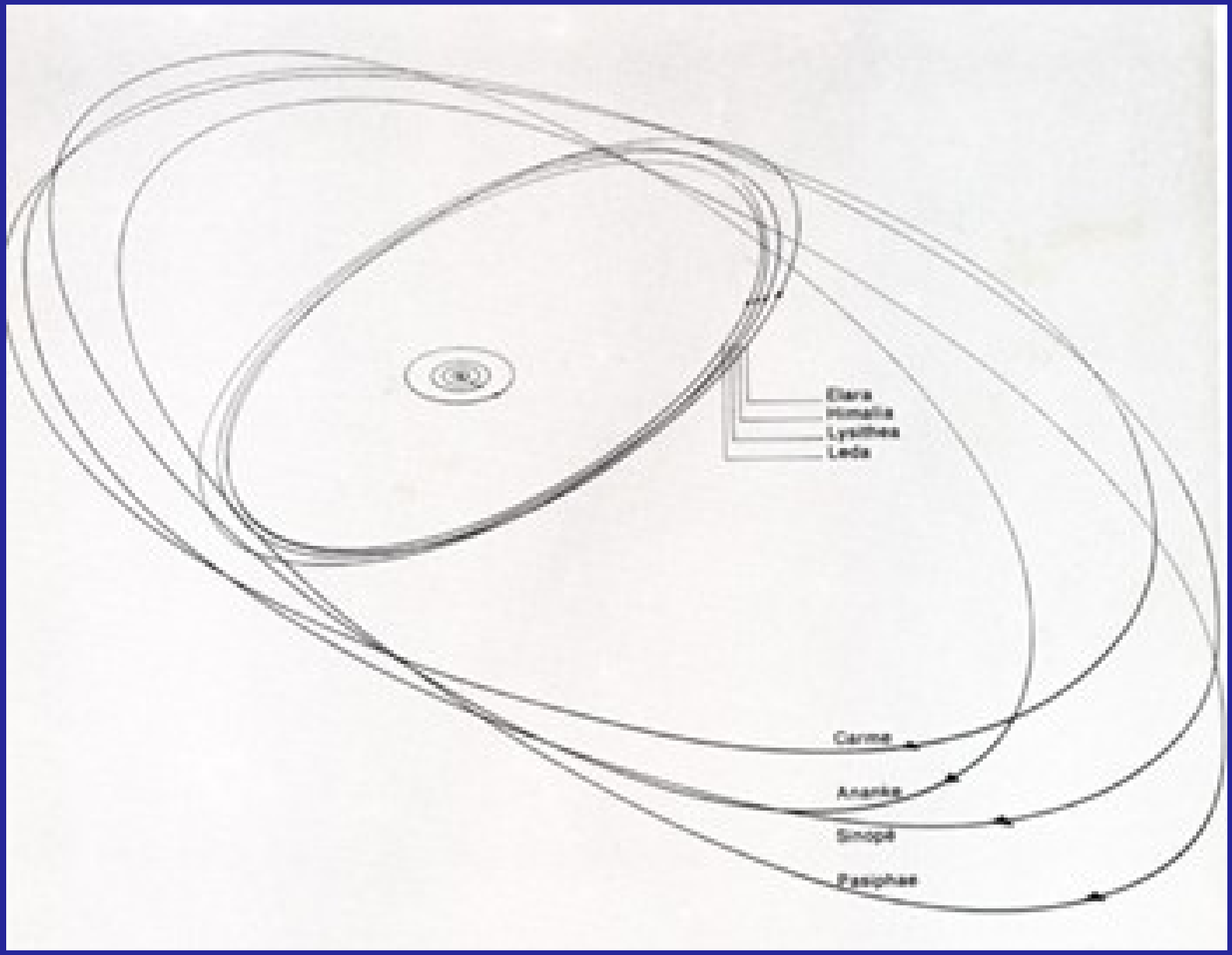
Before Gaia:

Ground based CCD observations reduced with star catalogues such as UCAC2

Reduction with the star catalogue link method:
a field of 12 minutes of degree

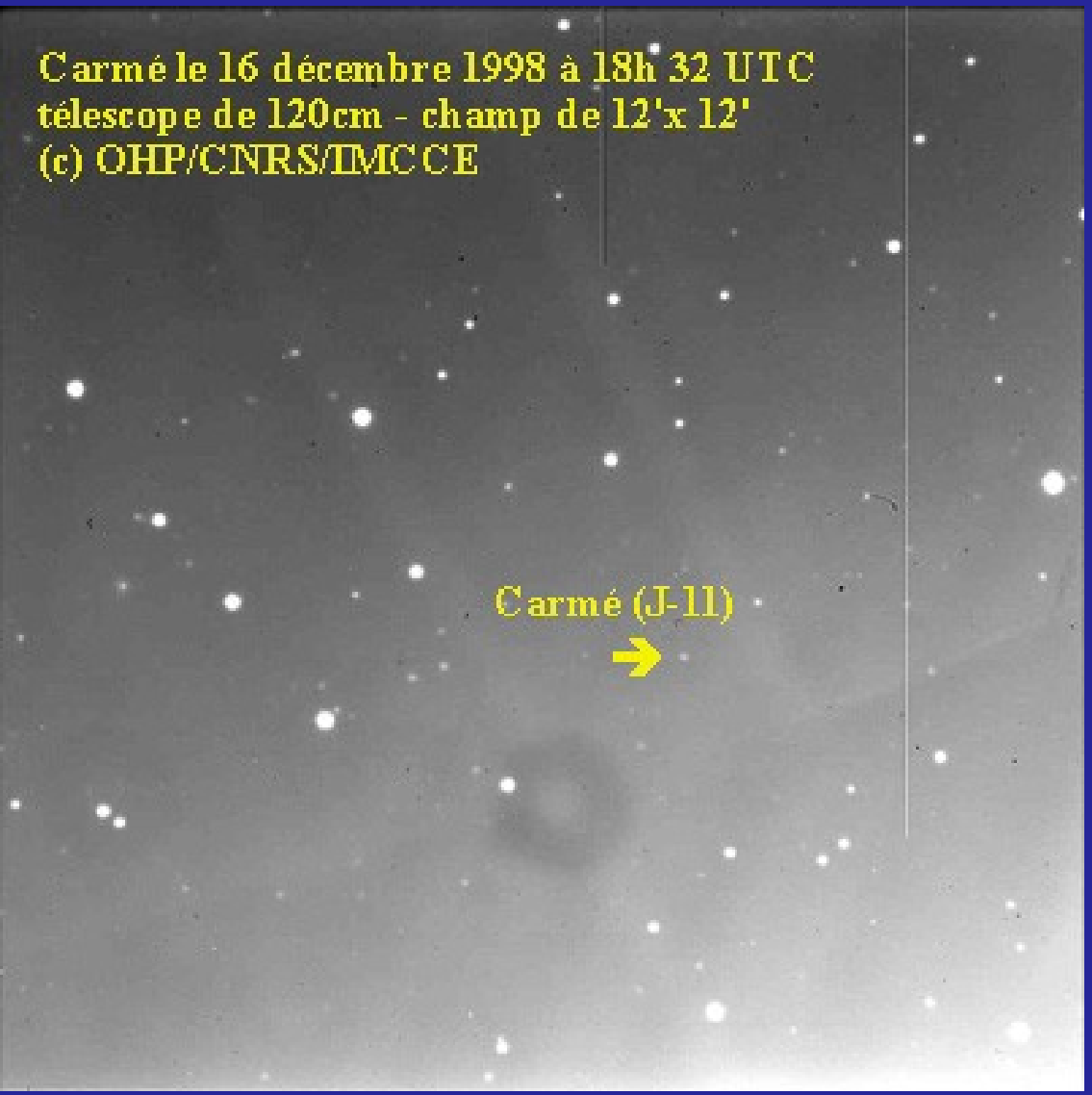
The GAIA catalogue of stars will provide very accurate positions for many more stars

Natural Planetary Satellites



Outer satellites of Jupiter: two families

Outer satellites of Jupiter and Saturn



Family of Himalia:

Semi-major axis around 10 Mkm
Inclination around 20°

Family of Pasiphae:

Semi-major axis around 20 Mkm
Inclination around 140°

For slow satellites (period more than one year), 50 direct Gaia observations made upon a 5 years period will be valuable.
The shape of these asteroid-like objects will be determined.

Main satellites of Saturn

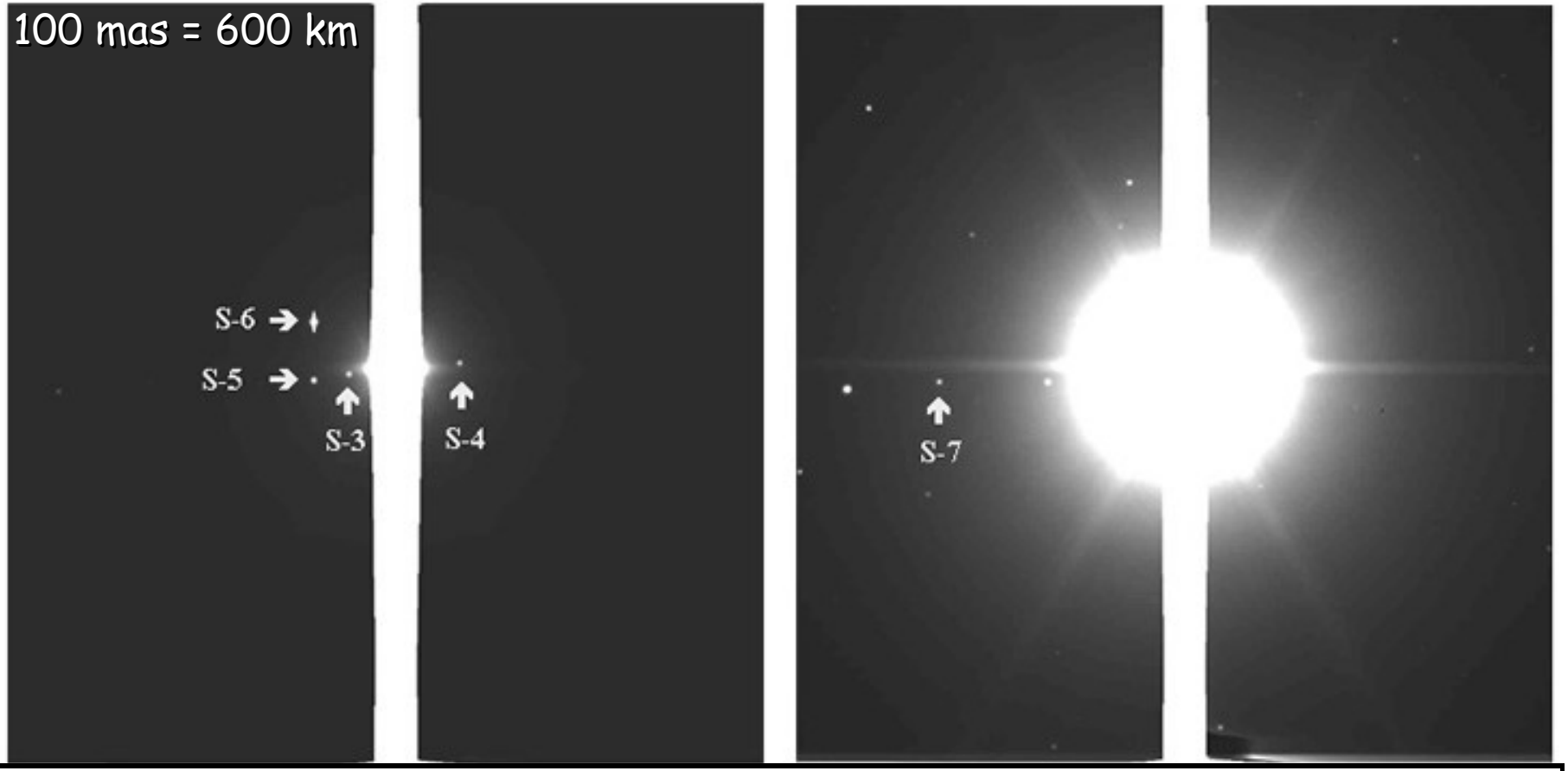


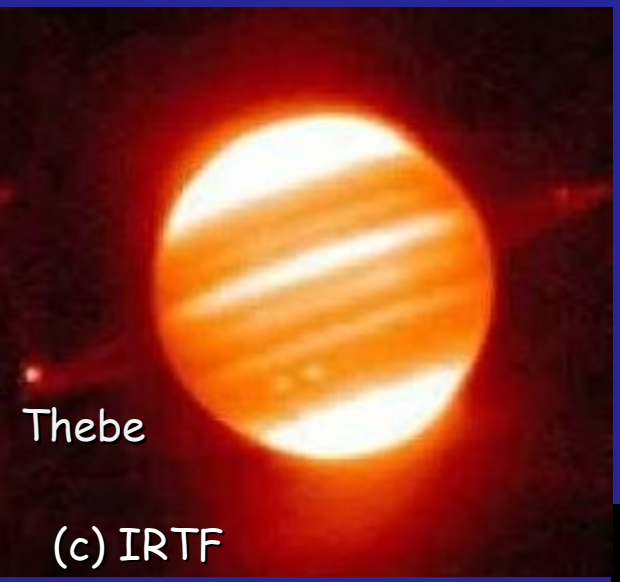
Image from Observatoire de Haute Provence with 1.2m telescope

Direct observations by Gaia not more valuable than old data since the satellites are moving fast with many perturbations.
Need more than 10 observations per year

Faint small satellites close to the planet

- Need of filters or coronographs
- Too few reference stars➔ use of the main satellites

- Gaia observations valuable when possible



above Jupiter

at right: Saturn

(c) F. Colas, J. Lecacheux PIC du MIDI

Star catalogues available for the reduction

Year	Name	Nb of stars	Mag limit	Accuracy mas	Accuracy pr motions	Origin
1997	Hipparcos	120 000	12.4	< 0.78	< 0.88 m/y	obs. from space
2000	Tycho 2	2 500 000	16	< 60	< 2.5 m/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 m/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 m/y	$+11° > \delta > +18°$
2003	2MASS	470 000 000	16	60 → 100		Infra red K
2015	GAIA	1 billion	20	< 0.01 mas		obs. from space

After Gaia:

Ground based CCD observations will continue

Reduction with the star catalogue link method:
a field of 12 minutes of degree

The GAIA catalogue of stars will provide very accurate positions:
all stars until mag 20

The error in position will be the error of measurement (depending on the object –size and surface- and on the receptor –size of pixels and S/N ratio)

After Gaia:

Re-reduction of observations from space probes of the natural satellites

(Saturn ➔ Cassini; Jupiter ➔ Galileo)

- Reducing astrometric observations made by space probes

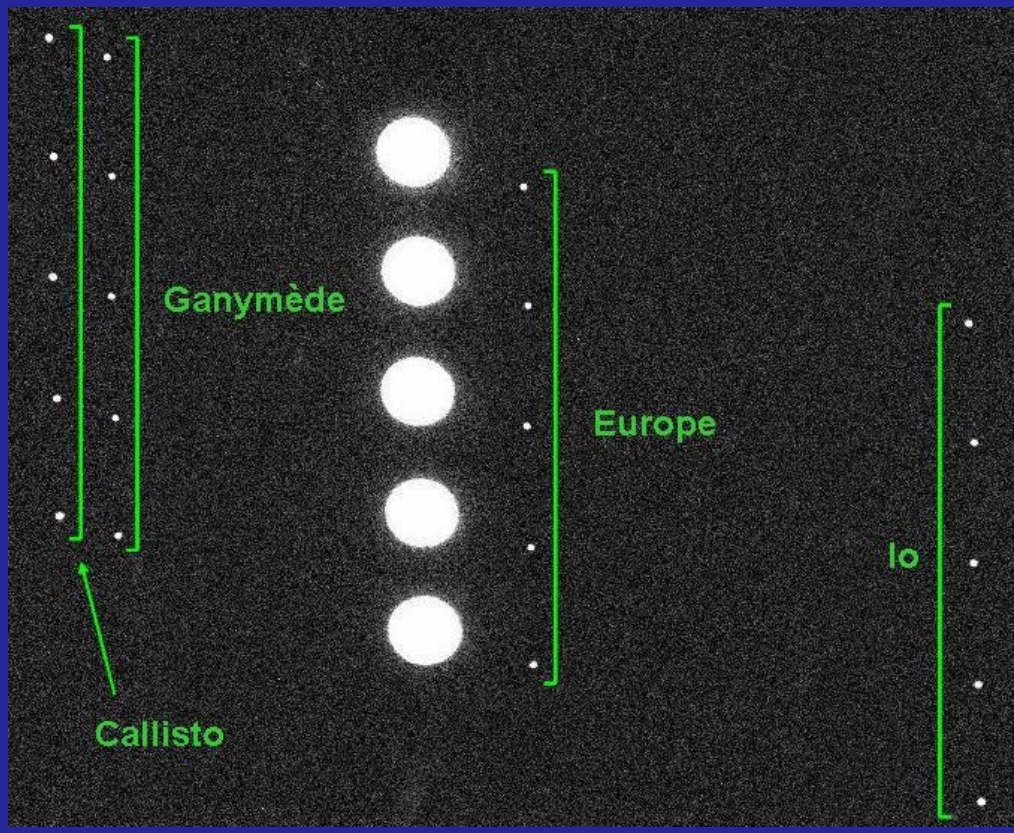
➔ accuracy: 10 km ➔ 1 km


Cassini Camera ISS
Field 0°.35 Dione (1120 km) and Enceladus (512 km)
Stars from UCAC2 (magnitude 9)
60 mas (UCAC2) = 3 km
1 mas (GAIA) = 50 m
star
star
star
star
star
star

- **After Gaia:**
- **Re-reducing old photographic observations**

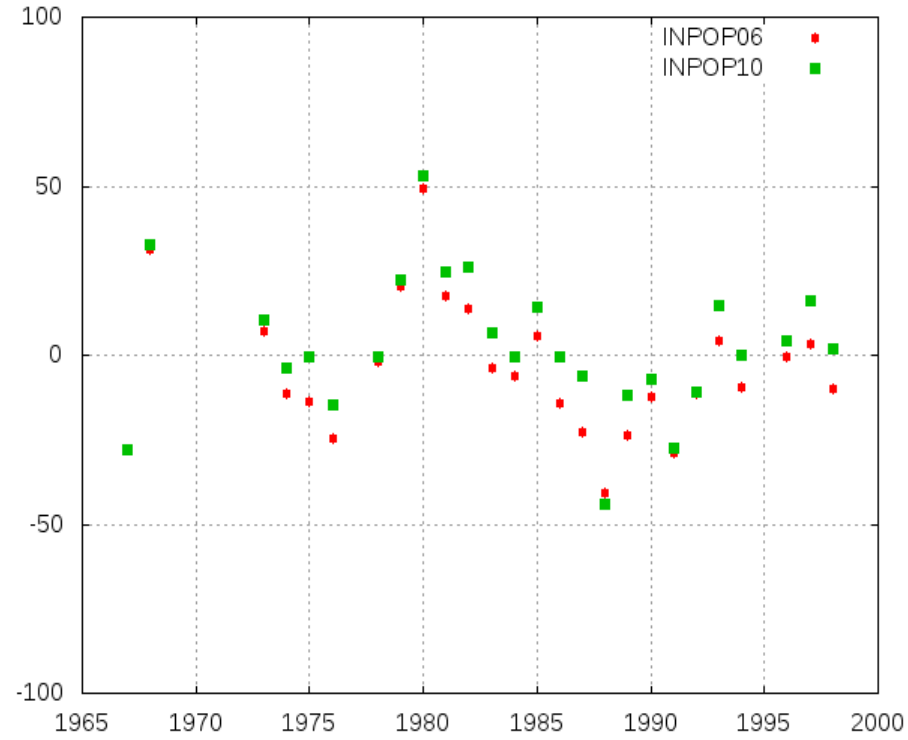
  - Observing in the past: re-reducing old observations : photographic plates reduced with UCAC2 (at the present time) or (to come) GAIA

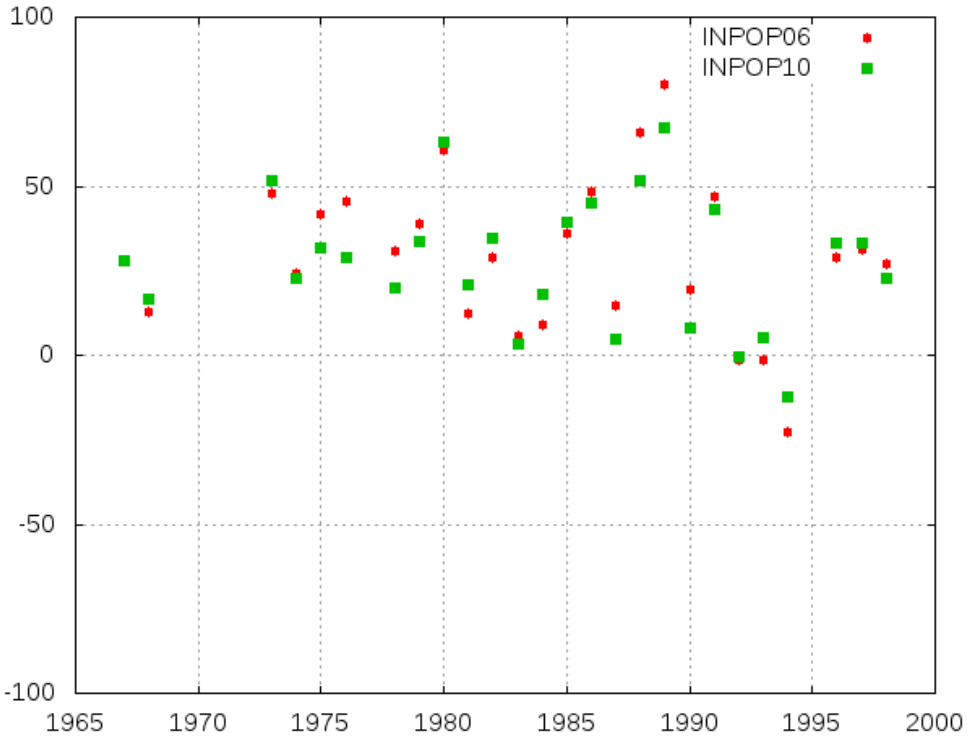
  - The Galilean satellites



Scanner DAMIAN of the Royal Observatory of Belgium
(accuracy 70 nanometers i.e. less than 2 mas
➔ Needs a better star catalogue –waiting for GAIA)

Residuals in RA and DEC on Jupiter's positions for several oppositions





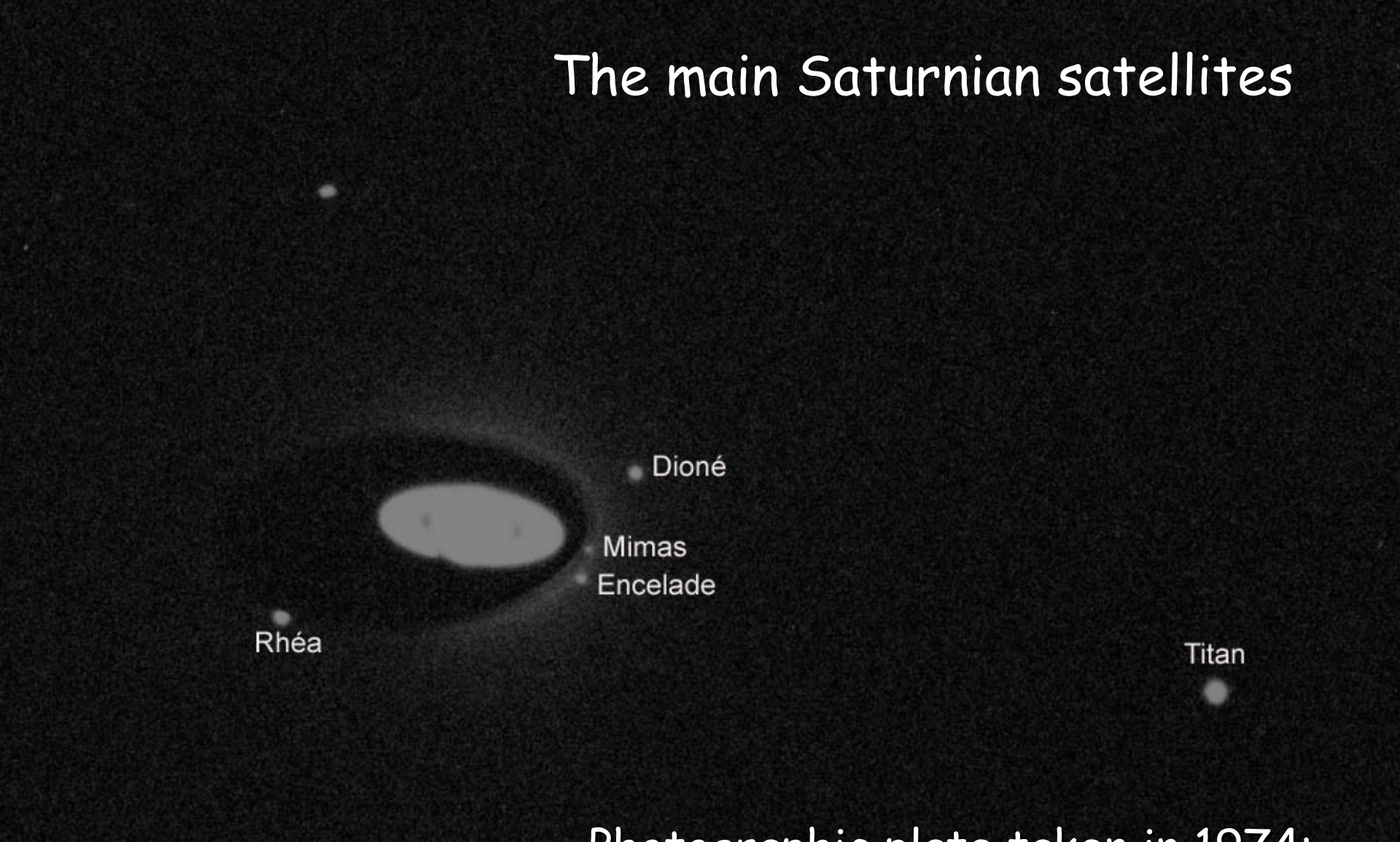
In RA : average near 0 mas

In DEC : average near 20 mas from 0 to 50 mas depending on the ephemeris used

A shift from star catalogues or from bad old observations?

After Gaia: a definitive solution to this shift in declination

The main Saturnian satellites

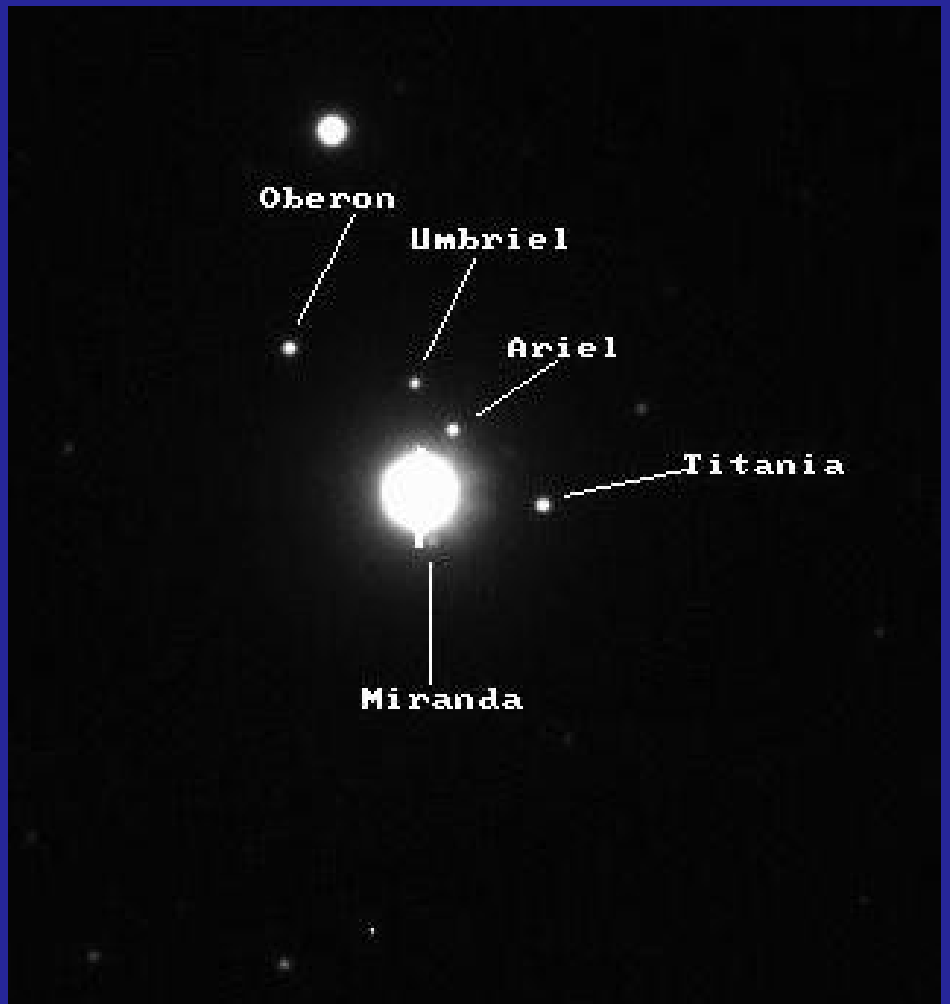


Photographic plate taken in 1974:

Mimas = S-1; Enceladus = S-2;
Dione = S-4; Rhea = S-5; Titan = S-6

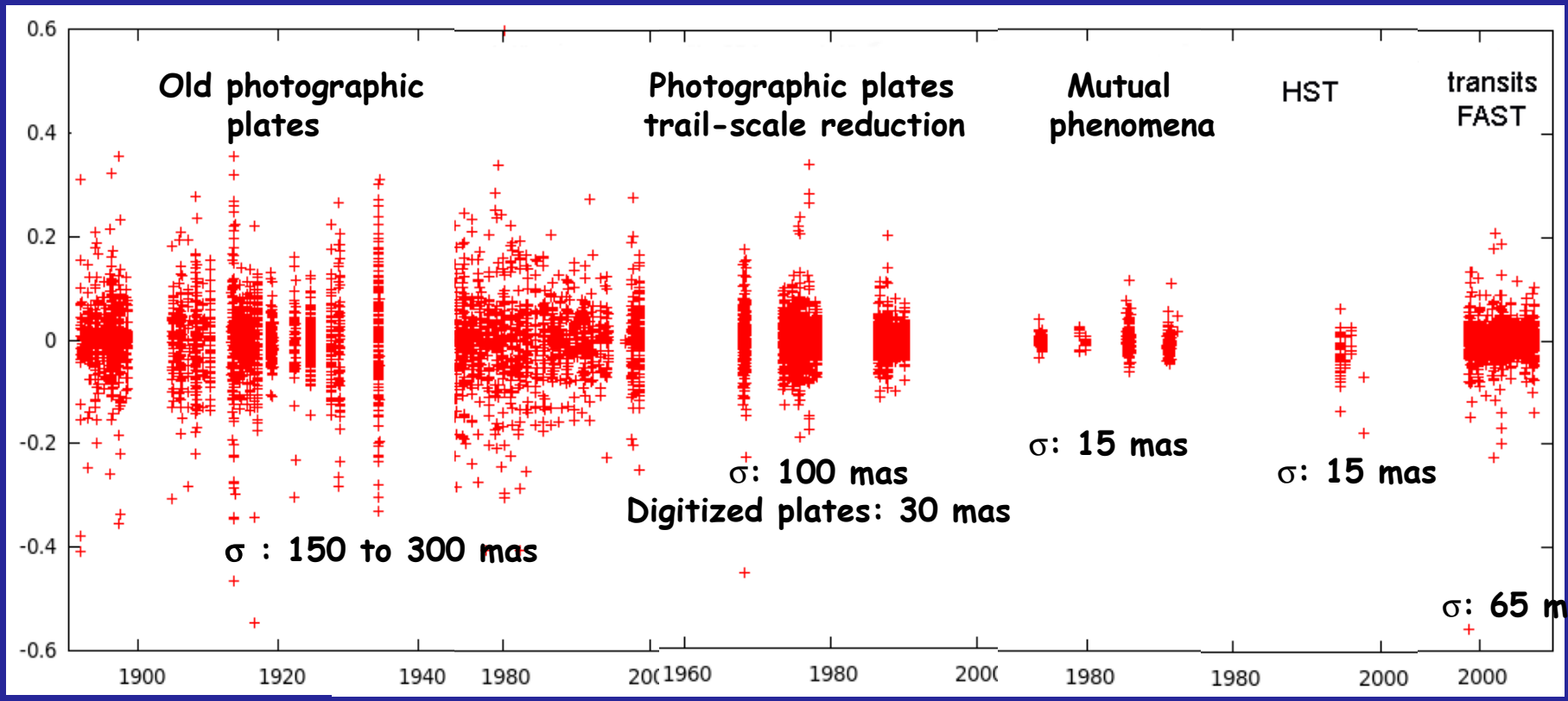
The Uranian satellites: a poor accuracy with direct imaging

➔ taking the opportunity of the mutual events
➔continuing with GAIA which will provide valuable data
➔ using the GAIA catalogue for CCD astrometric observations



100 mas = 1200 km

Before GAIA: compared accuracy of the observations (from 15 to 300 mas)



After GAIA: accuracy = precision of the measurement on the receptor (from 2 to 10 mas)

Before GAIA: best observational accuracy (optical)

Intersatellite positions

Example: case of the Galilean satellites of Jupiter

Type of observation	Standard deviation in mas	Standard deviation in km
Eclipses by Jupiter	150	450
Short focus photographic plates	150	450
Long focus photographic plates – trail scale method -	100	300
Automatic transit circle	65	200
Long focus digitized plates – UCAC2	30	80
CCD obs. – UCAC2	50	150
Mutual events	15	40
HST	15	40
Space probes	3	8
GAIA catalogue	0.05	0.15

After Gaia: only the error of measurement i.e. a few mas

A problem to be solved: surface effects on the satellites

•For the « large » objects (with an apparent diameter larger than 0.5 arcsec), it is possible to improve the correction photocentre-centre of mass thanks to albedo maps and a better modeling for the phase (60 mas maximum for Ganymede)

Jupiter and Ganymede
as seen from Pic du Midi
➔

After GAIA: for all satellites

Use of the 50 GAIA observations

+ re-reduction of old astrometric observations with the GAIA catalogues

+ new CCD observations reduced with the GAIA catalogue

= better dynamical modeling of the solar system object allowing to measure tides effects and to understzand the evolution of the system

But the results will depend on the satellites

Interest of Gaia depending on the satellites

Satellites	Period in	Obs. Gaia		Gaia catalogue
Small, close to the planet	hours	+++	Difficult ground based observations	+
large, observed	days	-	Long periods and fast motion	+++
large, not observed	days	no	Improvement of ground-based observations	+++++
outer irregular mag<20	years	++++	Getting shape and precise observations	+++
outer irregular mag>20	years	no	Improvement of ground-based observations	+++++

Great interest for satellites difficult to observe from the ground

Conclusion: preparing the future: after Gaia era

- For natural fast moving satellites, GAIA will be useful through its astrometric catalogue
- Before and after Gaia, never stop observing satellites since they move fast:
  - Preparing future observations
  - Improving accuracy
- Search for old photographic plates of high quality:
  - For scanning and new reduction
  - For fast objects as satellites
  - Observing in the past with today accuracy