Testing ephemerides with old data

-l'influence des observations anciennes sur la qualité des éphémérides-

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Modeling the dynamics and building ephemerides

Step 1: Dynamical model

Planet's gravity field (C_{np}, S_{np} coefficients)
Rotation
Precession

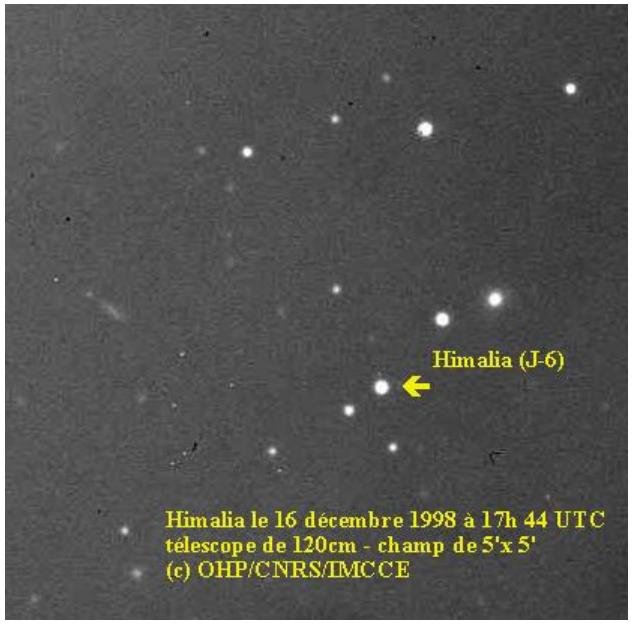
Satellites gravity field
J_2, C_{22} coefficients (if known)

« Equations of motion »
numerical/analytical/synthetic

Sun and other planets
as mass points

t^2 term in the longitude
Tides raised by the satellites on the planet
(Martian, Galilean moons)

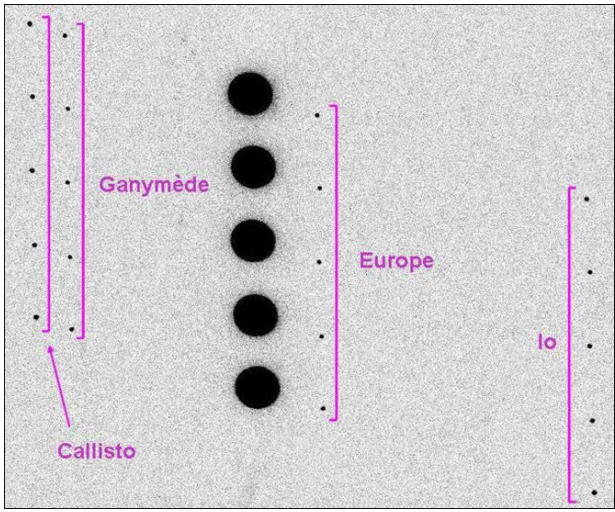
Modeling the dynamics and building ephemerides



Step 2: Observations

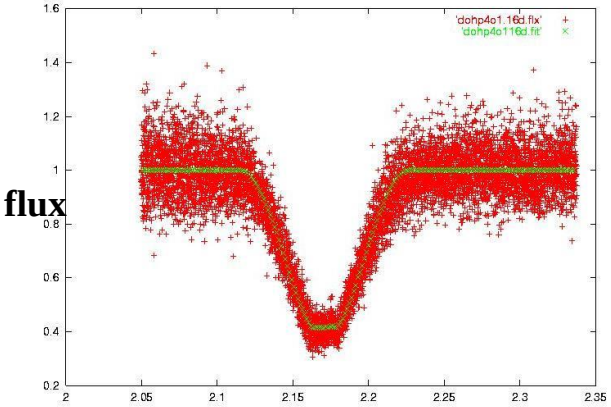
Corrections of:

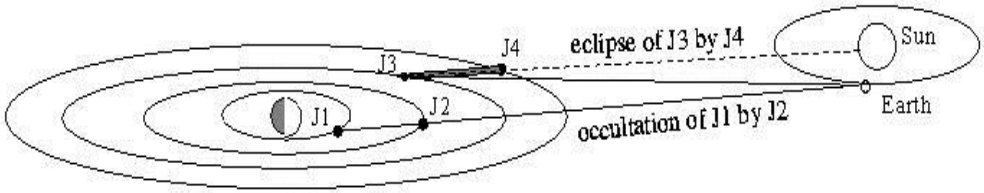
-time scale
-frame
-aberration
-light time



Astrometric observations

Few different kind,
but many different format!





The mutual events (occuring each 6 years)

Photometric observations

Modeling the dynamics and building ephemerides

Step 3: Fit

Observations

Theory: modelisation

Integration of partial derivatives

Linear system approximation
➔Least squares method

$$\left(\mathbf{r}_i'^{(k)} - \mathbf{r}_i^{(k)}\right) = \sum_{l=1}^{6N+M} \frac{\partial \tilde{p}_{i_a}^{i}}{\partial c_l}(\mathbf{c}) \cdot \Delta c_l + O((\Delta c_l)^2)$$

unknown

Determination of initial conditions or constants of the motion

Modeling the dynamics and building ephemerides

Interpolation

Polynomials of time

Chebychev polynomials

Fourier analysis

Mixed functions

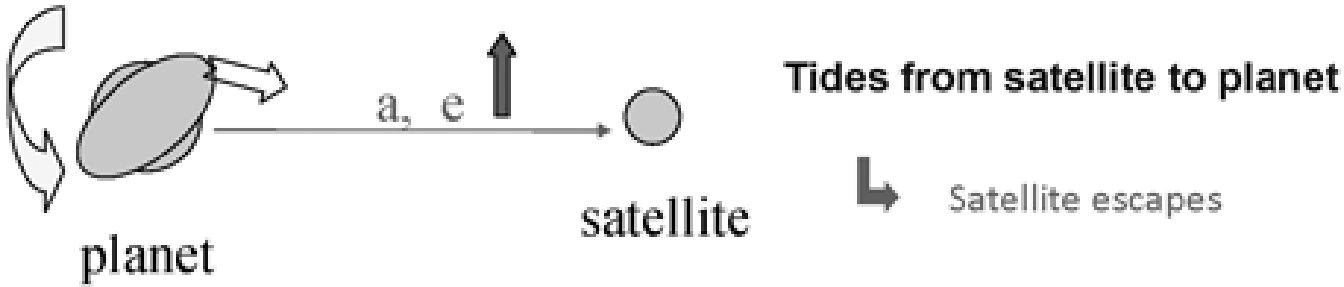
Step 4:
Making a representation on a defined interval of time

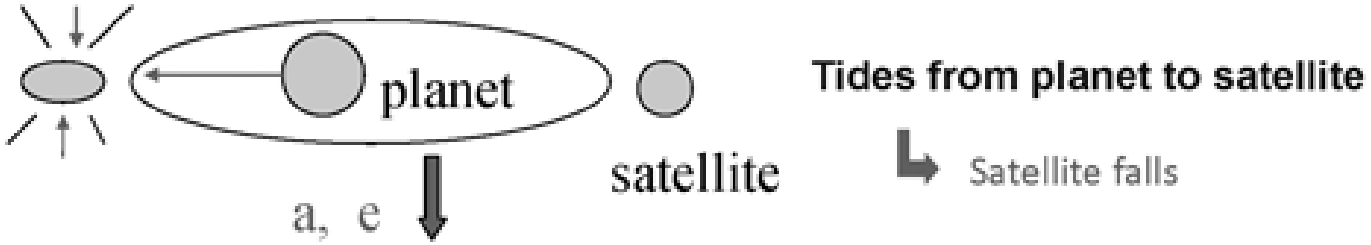
« EPHEMERIDES »

➔extrapolation
➔space navigation

Dissipation of energy inside the icy satellites is difficult to model

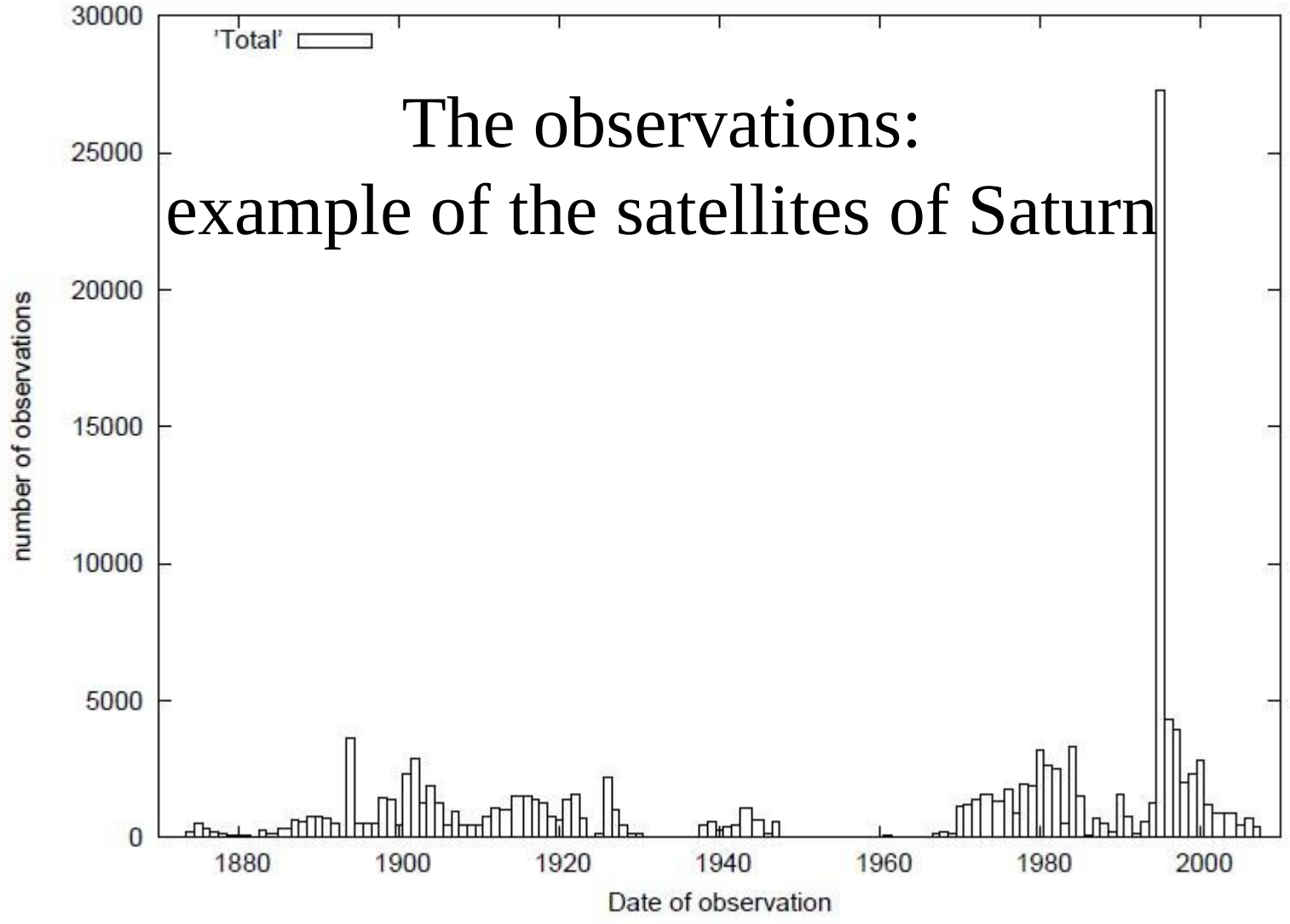
- Measurement of a cumulative drift in the motion in longitude ➔ astrometry + ephemerides



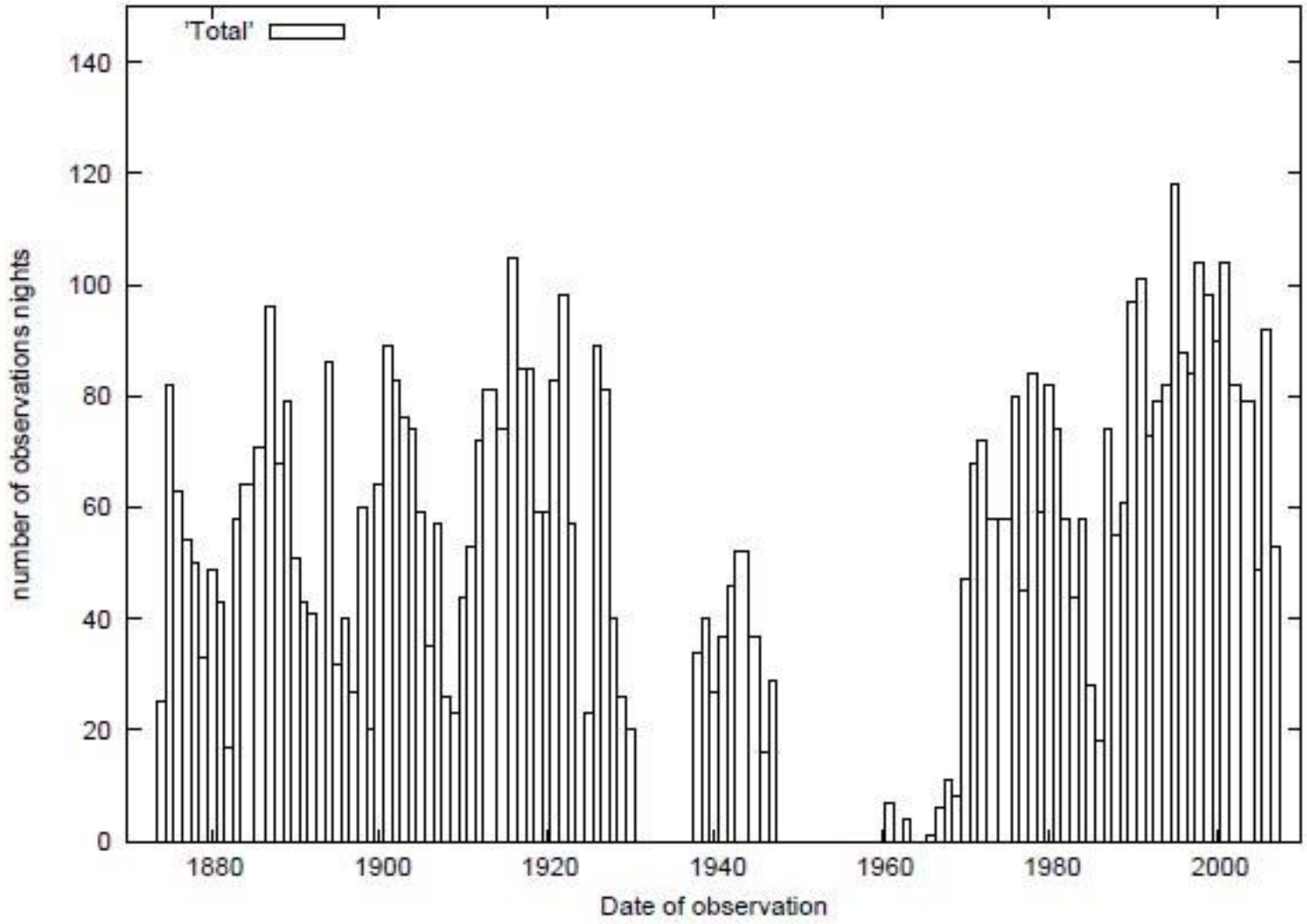


- Need of observations on a long interval of time

The observations: example of the satellites of Saturn



Number of observations by opposition



Histogramme du nombre de nuits d'observations à chaque opposition

satellites	période de temps	nombre de données
S-1	1874-2012	3087
S-2	1874-2012	7963
S-3	1874-2012	12508
S-4	1874-2012	12855
S-5	1874-2012	12750
S-6	1874-2012	11103
S-7	1874-2012	5311
S-8	1874-2012	10648
tous S-1-2-3-4-5-6-7-8	1874-2012	76225
S-10, S-11	1966-2000	188
S-12	1980-1996	286
S-13, S-14	1981-1996	90
S-16, S-17	1994-2002	410
tous S-12-13-14-16-17	1966-2002	974
S-9	1904-2017	6049
de S-18 à S-52 et autres	2000-2015	1419
tous S-9-18-...	1904-2017	7468

outer➔
irregular

Satellites of Mars
Galilean satellites of Jupiter

satellites	période de temps	nombre de données
M-1 M-2	1877-2011	4134

satellites	période de temps	nombre de données
J-1	1891-2015	4785
J-2	1891-2015	3767
J-3	1891-2015	4229
J-4	1891-2015	4108
tous J-1-2-3-4	1891-2015	16889

plates + CCD

Eclipses

Phénomènes.	période de temps	nombre d'observations
satellites galiléens		
éclipses	1652-1983	16802
occultations	1836-1972	4411
phénomènes mutuels	1973-2015	2383
satellites Amalthée et Thébé de Jupiter		
phénomènes mutuels	2009-2015	8
satellites de Saturne		
phénomènes mutuels	1980-2009	113
satellites d'Uranus		
phénomènes mutuels	2007-2008	41
grand total	1652-2015	23750

Outer irregular satellites of Jupiter

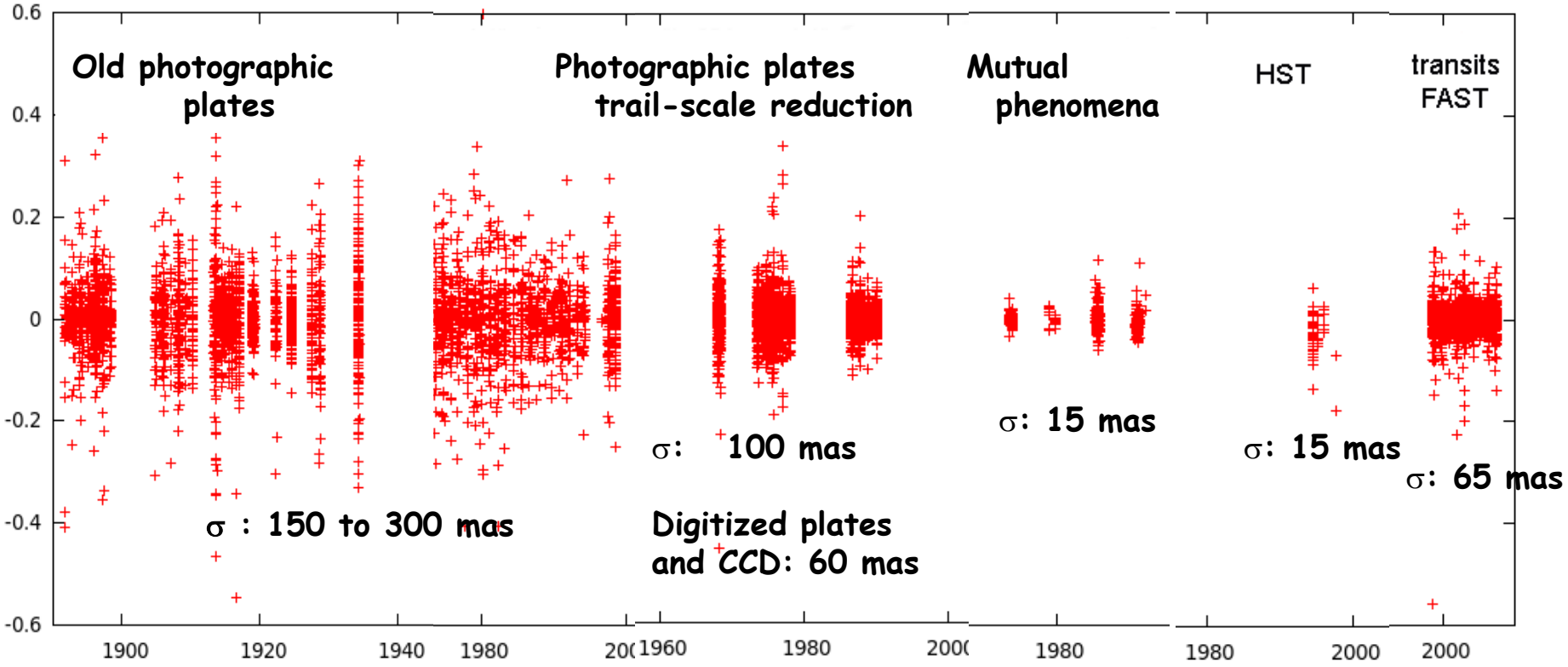
satellites	période de temps	nombre de données
J-5	1954-2015	712
J-14	1981-2015	740
J-15	1988	48
J-16	1988-2000	178
tous J-5-14-15-16	1954-2015	1478
J-6 J-7 J-8 J-9 J-10 J-11	1894-2018	11930
J-12, J-13	1951-2018	1179
J-17 à J-49 et autres	1975-2018	2176
tous J-6-7-8-9-10-11-12-13-17	1894-2018	15285

➔

The extrapolation of ephemerides is so bad for some satellites that they are lost after a few years without observations

satellites	période de temps	nombre de données
U-1	1983-2011	3778
U-2	1983-2011	4140
U-3	1983-2011	5016
U-4	1983-2011	5975
U-5	1983-2011	2507
tous U-1-2-3-4-5	1983-2011	21416
U-6 à U-15	1994-2004	65
U-16 à U-20	1984-2016	900
N-1	1877-2016	4996
N-2	1949-2017	1814
N-1 N-2	1877-2017	6810
N-3 à N-8	1991-2009	159
N-9 à N-13	1999-2017	382
P-1	1992-2006	78
P-2, P-3	2002-2011	46
tous P-1-2-3	1992-2011	124

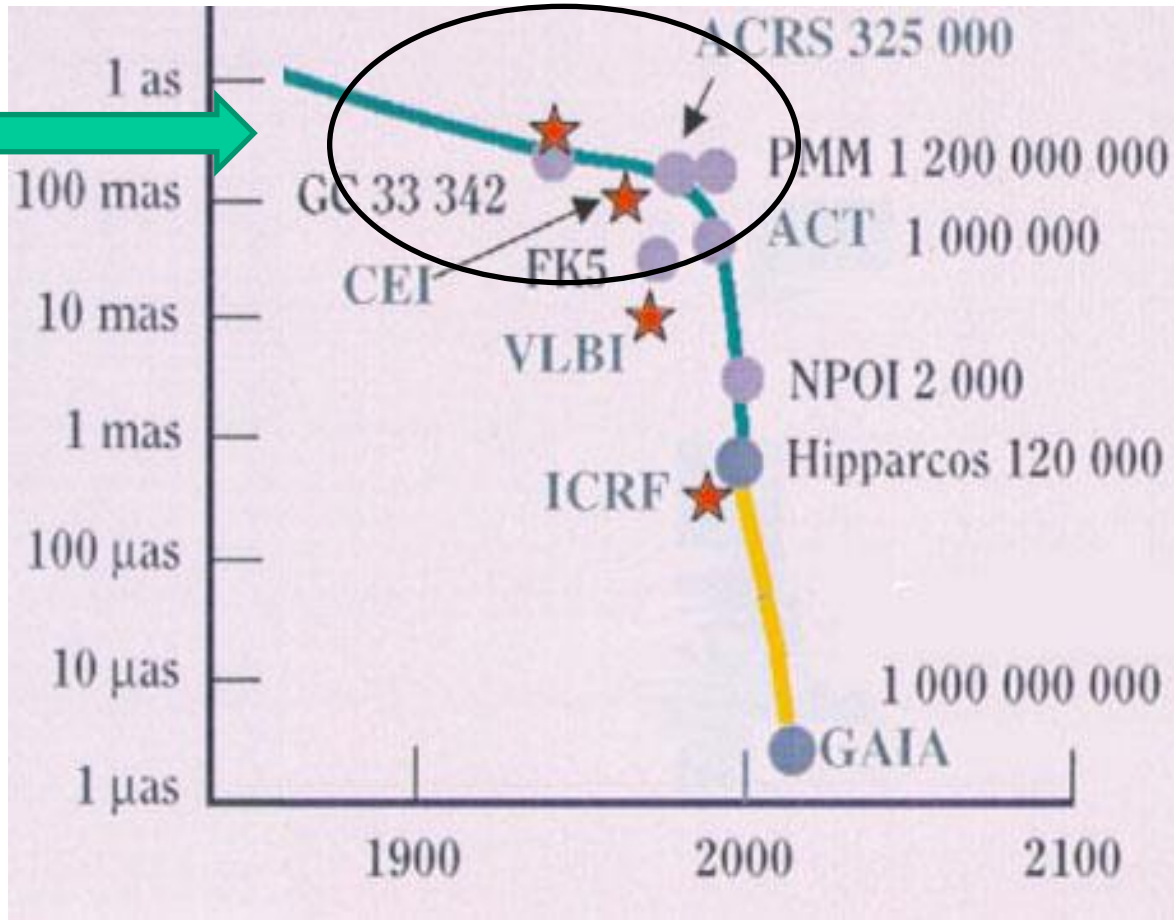
Compared accuracy of the observations



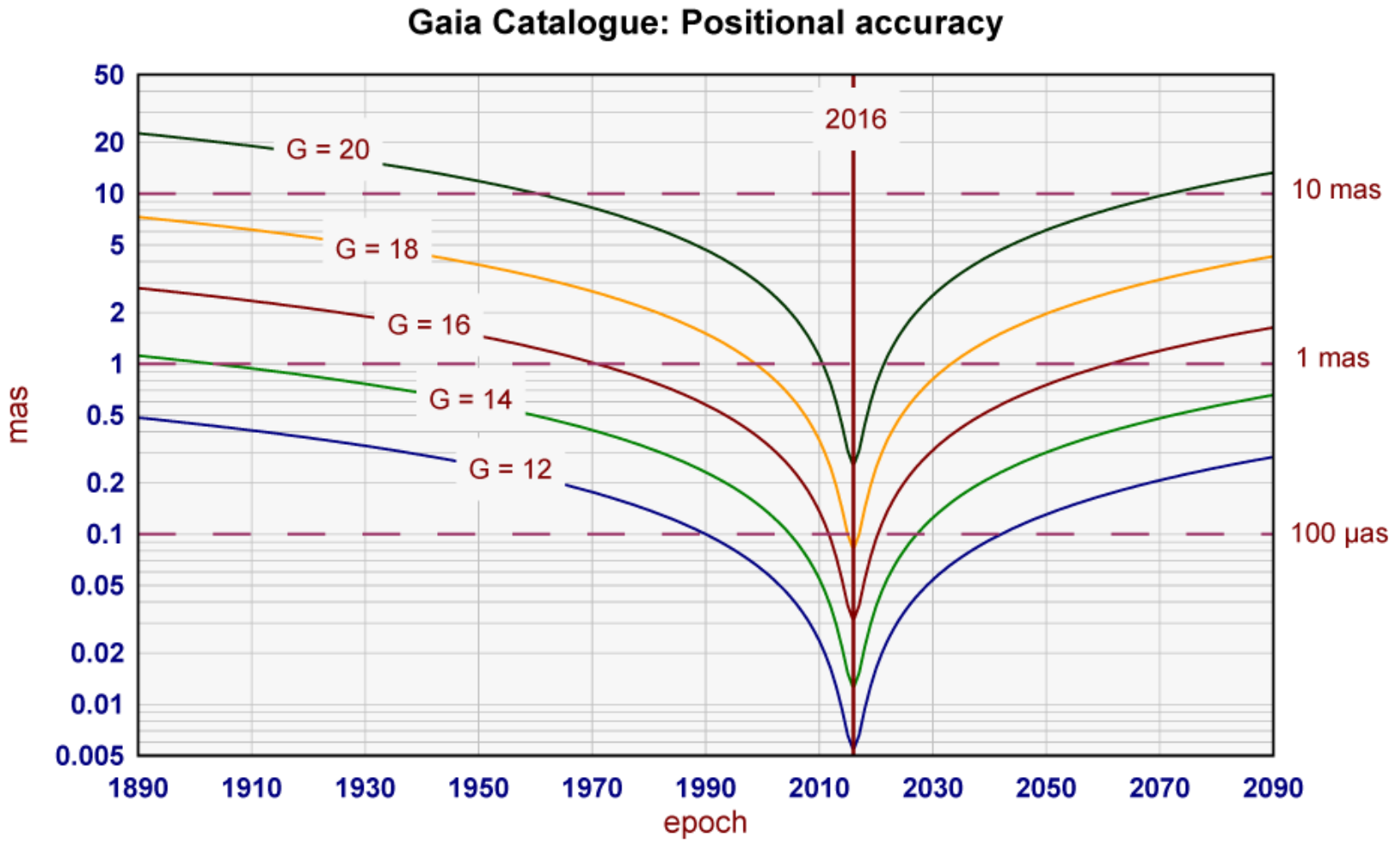
Old reductions might be improved (300 mas ➔ 50 mas)

Catalogues used for the reduction

- Most of the astrometric observations used until today were made and reduced with a 100 mas-1000 mas accuracy for catalogues and solar system dynamics

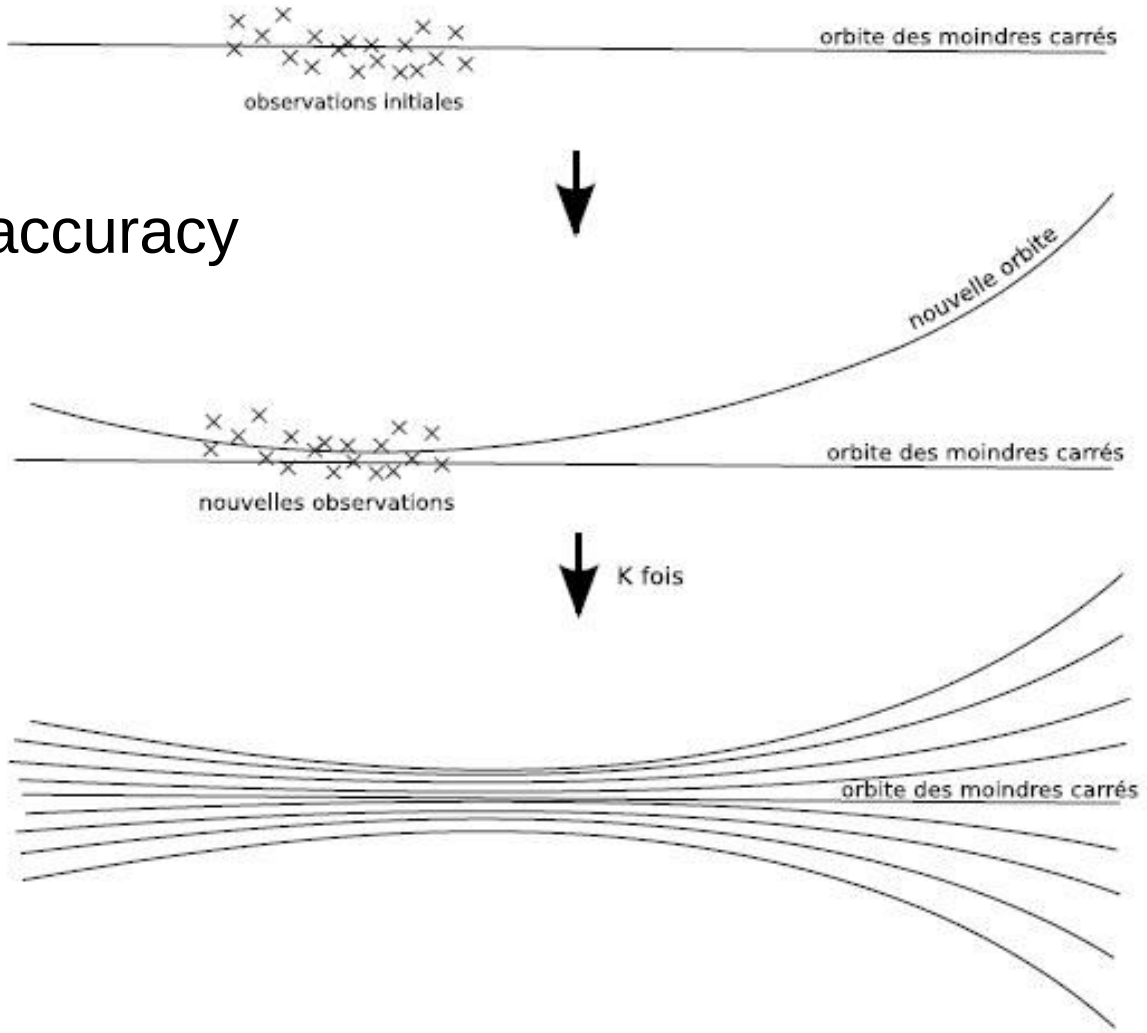


Proper motions of the Gaia reference stars allow reducing past observations



Extrapolation of ephemerides

precision and accuracy

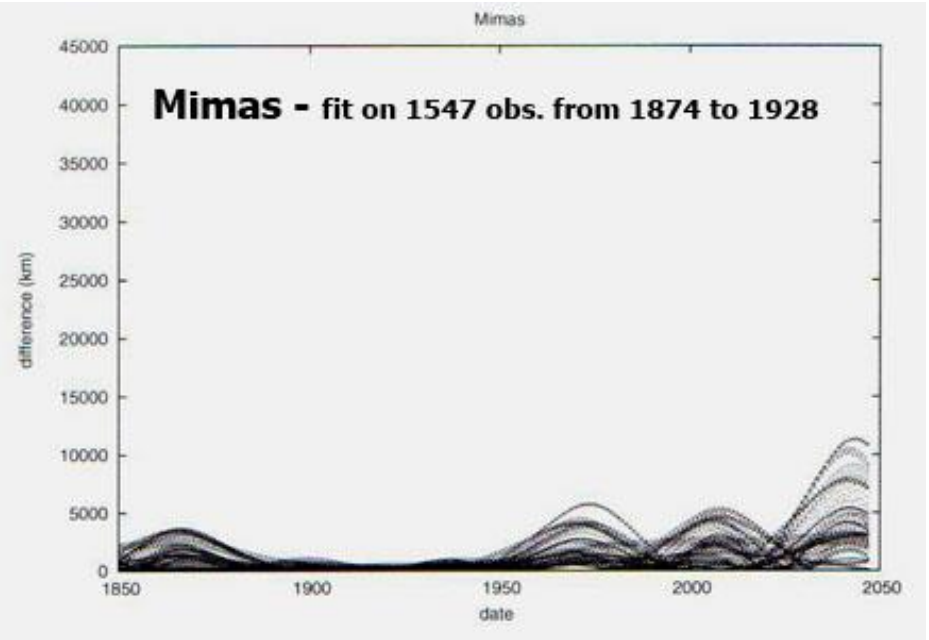


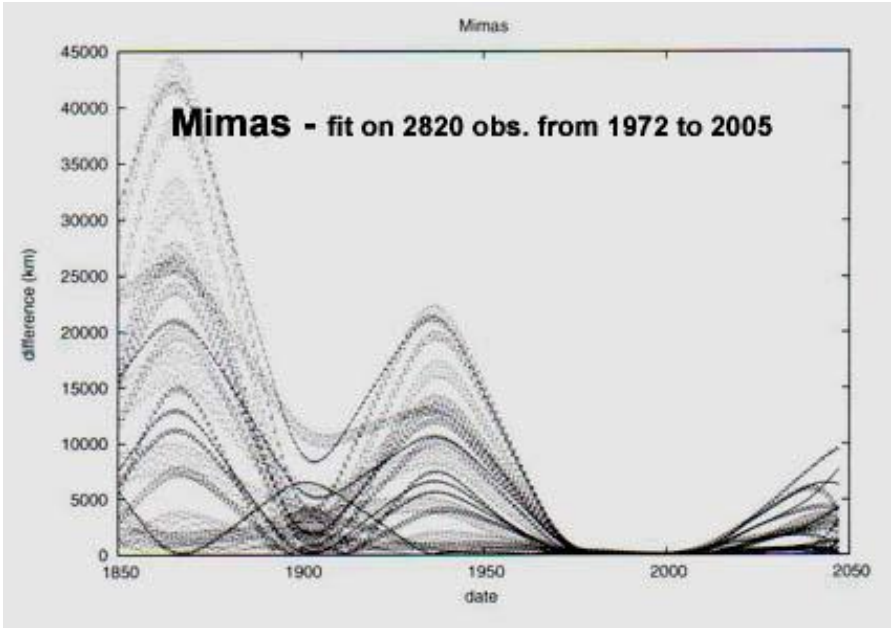
Observations supposed to be independant with gaussian errors

Fig. 7.2: Principe des méthodes MCO et du bootstrap

Another example: mean term ephemerides with extrapolation for preparing space missions

- Ephemerides are valod only on the period of observations
- The extrapolation of the positions is even better than the observations are distributed over a very long time interval even with a poor precision





Results: comparison re-reduced observations with ephemerides

- The analysis was made with observations made during the period 1967-1995
- UCAC catalogues did not allow to go further in the past

Test of planetary ephemerides (Jupiter)
Evolution of residuals for 1967-1995
in α and in δ (in mas)

	$\overline{(O-C)}_{\alpha\cos\delta}$	$\sigma_{\alpha\cos\delta}$	$\overline{(O-C)}_{\delta}$	σ_{δ}
DE421	-1.7	63.0	40.0	73.1
DE423	-1.8	62.8	38.1	71.5
INPOP06	-6.1	63.0	37.4	71.6
INPOP08	44.1	69.3	47.8	91.6
INPOP10	3.0	62.8	37.4	71.1
EPM08	-2.3	63.1	37.6	71.3

Moyennes et dispersions des (O-C) en (RA,Dec), en mas.

Test of planetary ephemerides (Mars)
Evolution of residuals for 1967-1995
in α and in δ (in mas)

Satellites de Mars	$\overline{(O-C)}_{\alpha\cos\delta}$	$\bar{\sigma}_{\alpha\cos\delta}$	$\overline{(O-C)}_{\delta}$	$\bar{\sigma}_{\delta}$
INPOP08	2,3	59,8	2,6	57,8
INPOP10	3,2	59,8	2,8	57,8
DE421	2,3	59,7	2,7	57,8
DE430	2,6	59,7	2,7	57,8

Planet Saturn and satellites in RA and DEC

The residuals in RA and DEC are calculated using INPOP10 for Saturne and the JPL SAT351 ephemeris for the satellites

Objects	RA	DEC
Residuals	(mas)	(mas)
All satellites	-13	+20
Enceladus	-47	-33
Tethys	+3	+27
Dione	-55	-12
Rhea	-7	+51
Titan	-18	+23
Hyperion	+15	+23
Iapetus	+10	+12
Dispersion	100	72

Conclusion:
choosing the observations to be re-reduced

- A regular sampling of the orbits
- A large base of time
- Complementarity with spatial data
- Promote data for Uranus and Neptune
- Search pre-discoveries to enlarge the time basis