European Satellite Partnership for Computing Ephemerides
FP7-ESPaCE Program
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Ephemerides of Martian, Saturnian and Uranian SAT

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DOCUMENT CHANGE RECORD

Issue	**Date**	#	**Description of the modification**	**Reason of the modification**
V 1.0	15/04/2015	1	Version 1 from IMCCE	

Content:

1. **Ephemerides of Martian satellites**
2. **Ephemerides of Saturnian satellites**
3. **Ephemerides of Uranian satellites**

The ESPaCE ephemerides benefit from NOE numerical code that was successfully applied to the Mars, Jupiter and Uranus systems. It integrates the full equations of motion for the centre of mass of the satellites and solves for the partial derivatives of the system. This latter set of equations allows for a fitting procedure to the observations. For a complete description of the equations solved, we refer to Lainey et al. (2012) and references therein.

1. Ephemerides of the Martian satellites

In the context of the Mars Express flyby of Phobos in December 2013, new ephemerides of the two Mars moons, Phobos and Deimos, have been developped.

The modeling introduces:

The Mars gravity field up to order 10 (use of JPL Mars gravity field MRO110C, 2012)

The Solar and planetary perturbations (use of DE430)

The Mars rotation, precession and nutation (Kuchynka et al. 2014)

The tidal effects in the primay (Phobos/Deimos)

The Phobos' J_2 and c_{22} terms (Borderies & Yoder 1990)

The Relativistic effects (PPN, Mars and Solar terms)

The observations:

Besides the already available S/C observations, the observations considered here where those provided by WP6. This includes space observations from Mars Express as well as all the astrometric data obtained from DAMIAN digitized plates.

Postfit residuals for these latter data have been found extremely accurate (see Robert et al. 2014). We provide below O-Cs of these data (remind 0.1 arcsecond corresponds to about 30 km at the Mars opposition).

FP7-ESPaCE-Absolu-intersat	-0.0098	0.0567	-0.0075	0.0778	249, 249
	-0.0041	0.0511	-0.0060	0.0671	249, 249
FP7-ESPaCE-Absolu	-0.0090	0.0575	0.0002	0.0841	68, 68
	0.0050	0.0576	0.0166	0.0698	152, 152
FP7-ESPaCE-Tangentiel-intersat	-0.0409	0.0959	-0.0304	0.0956	52, 52
	-0.0219	0.0841	-0.0291	0.0738	52, 52
FP7-ESPaCE-Tangentiel	-0.0512	0.0826	-0.0416	0.0733	50, 50
	-0.0111	0.0938	-0.0331	0.0901	47, 47

Table 1.1 : Astrometric residuals for the ESPaCE-DAMIAN data. Columns are in the following order : mean in RA, sigma in RA, mean in DEC, sigma in DEC. Units are in second of arc.

Mariner9	-7.3597	7.4904	-5.9690	7.3091	48, 47
	3.5419	4.6247	-1.5478	4.2449	14, 14
Viking1	-0.5467	9.1206	-0.3138	7.1175	130, 130
	1.0270	3.7973	-2.8882	4.2298	19, 19
Viking2	2.3291	7.5501	-5.1547	8.2284	32, 32
	-1.4705	5.1470	2.3782	5.7030	80, 78
Phobos2	-0.1649	0.8843	-0.0537	0.5192	37, 37
	0.2952	9.3370	10.1791	9.0968	7, 7
MEX-Konrad-et-al	-0.1609	0.5140	0.1609	0.7888	278, 278
	0.0000	0.0000	0.0000	0.0000	0, 0
MEX-Andreas	0.0000	0.0000	0.0000	0.0000	0, 0
	1.6991	1.2600	-0.2543	1.0986	136, 136
MRO-ONsingle	0.0000	0.0000	0.0000	0.0000	0, 0
	-0.0093	0.0378	0.0095	0.0433	376, 376
MRO-ON	0.0051	0.0930	-0.0241	0.1153	103, 103
	-0.0127	0.0409	0.0056	0.0615	103, 103
MEX-flyby-pointing-outlier	-0.3544	0.0537	0.3718	0.0411	3, 3
	0.0000	0.0000	0.0000	0.0000	0, 0
MEX-flyby-regular	0.0747	0.2666	-0.1165	0.2002	39, 39
	0.0000	0.0000	0.0000	0.0000	0, 0
MEX-flyby-non-linear	0.2548	0.3339	-0.0780	0.2258	22, 22
	0.0000	0.0000	0.0000	0.0000	0, 0
MEX-flyby-non-linear+outlier	-0.1612	0.3183	0.1122	0.1909	8, 8
	0.0000	0.0000	0.0000	0.0000	0, 0
MEX-flyby-continuous+shortlimb	-0.1817	0.0000	-0.0079	0.0000	1, 1
	0.0000	0.0000	0.0000	0.0000	0, 0
MEX-flyby-continuous	-0.1628	0.1176	-0.0188	0.1306	187, 187
	0.0000	0.0000	0.0000	0.0000	0, 0
MEX-flyby-non-linear+shortlimb	-0.1452	0.2972	0.0604	0.2465	2, 2
	0.0000	0.0000	0.0000	0.0000	0, 0
MEX-flyby-continuousEM	-0.0032	0.0504	-0.1344	0.1339	54, 54
	0.0000	0.0000	0.0000	0.0000	0, 0
MEX-flyby-shortlimb	-0.5745	0.3313	0.1019	0.2634	3, 3
	0.0000	0.0000	0.0000	0.0000	0, 0
MEX-flyby-outlier	-0.7416	0.0745	-0.5044	0.1335	3, 3
	0.0000	0.0000	0.0000	0.0000	0, 0

Table 2.1 : Astrometric residuals for the S/C data. For all data except MRO, columns are in the following order : mean in RA, sigma in RA, mean in DEC, sigma in DEC. Units are in km. For MRO, columns are in the following order : mean in s, sigma in s, mean in l, sigma in l. Units are in pixel.

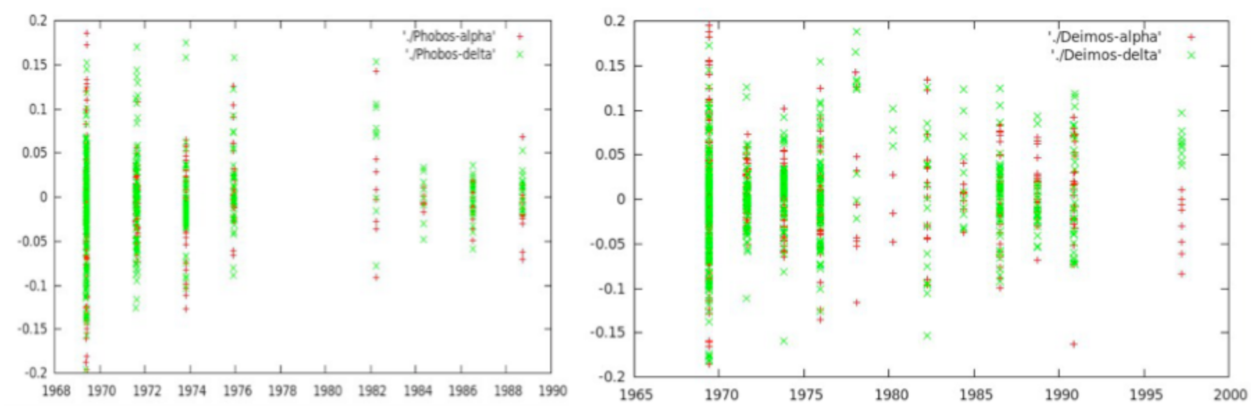

Figure 1.1 : Astrometric residuals for the DAMIAN digitized data

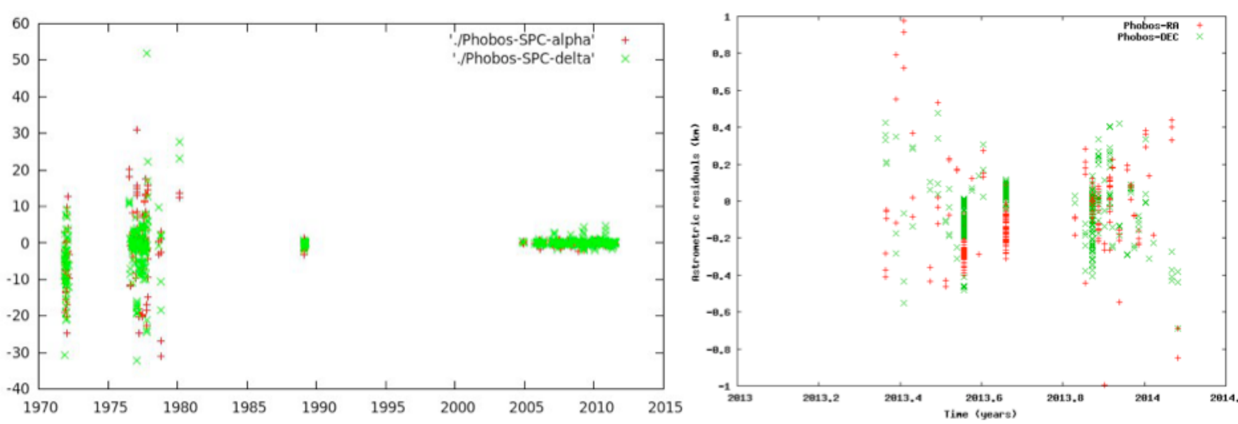

Figure 1.2 : Astrometric residuals for the pre-ESPaCE published S/C astrometric data (left) and new Mars Express data (right).

Comparison with other ephemerides :

At the present time, the most up-to-date ephemerides available are the one from JPL. We provide below a comparison between our new ephemerides on the JPL's.

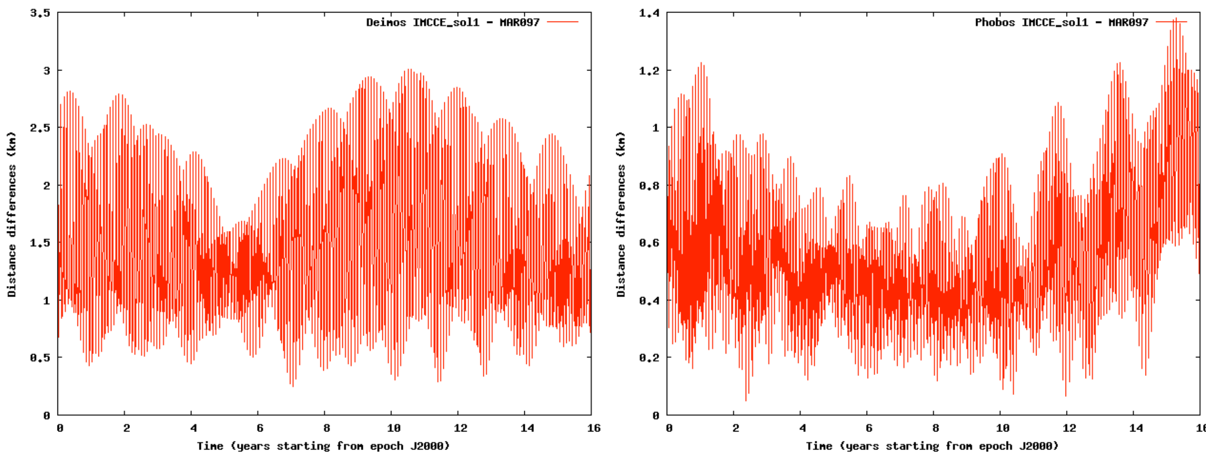

Figure 1.3 : Comparison between our new ESPaCE ephemerides and the JPL's MAR097.

Our ephemerides are available under a SPICE kernel (see D9.2). More informations are available on request (lainey@imcce.fr).

<u>References :</u>

Borderies, N.; Yoder, C. F., Phobos' gravity field and its influence on its orbit and physical librations, *Astronomy and Astrophysics* (ISSN 0004-6361), vol. 233, no. 1, July 1990, p. 235-251 (1990).

Kuchynka, Petr, Folkner, William M., Konopliv, Alex S., Parker, Timothy J., Park, Ryan S., Le Maistre, Sebastien, Dehant, Veronique, New constraints on Mars rotation determined from radiometric tracking of the Opportunity Mars Exploration Rover, *Icarus*, Volume 229, p. 340-347 (2014)

Robert, V.; Lainey, V.; Pascu, D.; Arlot, J.-E.; De Cuyper, J.-P.; Dehant, V.; Thuillot, W., Astrometric observations of Phobos and Deimos during the 1971 opposition of Mars, *Astronomy & Astrophysics*, Volume 572, id.A104, 4 pp. (2014)

2. Ephemerides of the Saturnian satellites

Here, fourteen moons of Saturn are considered all together that implies the eight main moons and six coorbital moons (Epimetheus, Janus, Calypso, Telesto, Helene and Polydeuces). All the astrometric observations already considered in Lainey et al. (2012) are used, with the addition of a large set of ISS-Cassini data (Cooper et al. 2014, Tajeddine et al. 2014). We also include the new reduction of old photographic plates, initially used at USNO between the years 1974 and 1998 and reprocessed in the ESPaCE WPs 5 and 6. We use a weighted least squares inversion procedure and minimize the differences between the observed and computed positions of the satellites in order to determine the parameters of the model. For each fit, the following parameters are released simultaneously and without constrains: the initial state vectors and the mass of each moon, the mass, the gravitational harmonic J_2, the orientation and the precession of the pole of Saturn as well as its tidal parameters k_2 and Q. No da/dt terms is released on Mimas. In particular, it appears that the large signal obtained in Lainey et al. (2012) can be removed after fitting the gravity field of the Saturn's system.

Satellite	μ_s	σ_s	μ_l	σ_l	N_s	N_l
Epimetheus	-0.0094	4.3180	0.1805	4.5340	350	350
Janus	0.0096	0.9780	0.5378	1.1566	322	322
Mimas	0.4190	0.2813	-0.0460	0.6600	20	20
Enceladus	-0.0014	0.3547	-0.1116	0.2783	108	108
Tethys	-0.1232	0.5284	0.0814	0.2600	25	25
Dione	-0.0278	0.4808	0.0748	0.4730	84	84
Rhea	-0.2925	0.4644	-0.0035	0.2055	58	58
Titan	0.0000	0.0000	0.0000	0.0000	0	0
Hyperion	0.0000	0.0000	0.0000	0.0000	0	0
Iapetus	0.0000	0.0000	0.0000	0.0000	0	0
Calypso	-0.0348	0.2508	-0.1742	0.2546	230	230
Telesto	-0.0190	0.2220	-0.0366	0.2960	279	279
Helene	-0.0164	0.2731	-0.0456	0.2492	262	262
Polydeuces	-0.0554	0.2508	-0.0584	0.2422	139	139

Table 2.1 (one single moon per image): Statistics of the ISS-NAC astrometric residuals computed from IMCCE model (no tidal dissipation within Enceladus scenario) in pixel. μ and σ denote respectively the mean and standard deviation of the residuals computed on sample and line. N_s and N_l are the number of observations considered for the respective coordinate.

Satellite	μ_s	σ_s	μ_l	σ_l	N_s	N_l
Epimetheus	0.0203	0.2778	0.0449	0.2912	28	28
Janus	-0.0203	0.2778	-0.0449	0.2912	28	28
Mimas	0.0255	0.1784	-0.0064	0.2745	134	134
Enceladus	-0.0307	0.1784	0.0084	0.1248	327	327
Tethys	0.0211	0.1088	0.0186	0.1359	424	424
Dione	-0.0204	0.1061	0.0054	0.1070	592	592
Rhea	0.0175	0.1370	-0.0234	0.1208	556	556
Titan	0.0000	0.0000	0.0000	0.0000	0	0
Hyperion	0.0000	0.0000	0.0000	0.0000	0	0
Iapetus	0.0000	0.0000	0.0000	0.0000	0	0
Calypso	0.1470	0.0000	-0.5137	0.0000	1	1
Telesto	-0.0997	0.0702	0.2454	0.1691	3	3
Helene	-0.1308	0.0508	0.2090	0.0096	2	2
Polydeuces	0.1379	0.0731	-0.2135	0.1657	3	3

Table 2.2 (multiple moon per image): Statistics of the ISS-NAC astrometric residuals computed from IMCCE model (no tidal dissipation within Enceladus scenario) in pixel. μ and σ denote respectively the mean and standard deviation of the residuals computed on sample and line. N_s and N_l are the number of observations considered for the respective coordinate.

Satellite	μ_{RA}	σ_{RA}	μ_{DEC}	σ_{DEC}	N_{RA}	N_{DEC}
Mimas	-1.1001	3.9151	-1.1401	2.8370	826	826
Enceladus	-0.1979	2.8234	0.2713	2.6588	732	732
Tethys	0.0532	4.5654	-0.0123	3.5007	924	924
Dione	-0.2068	4.1726	-0.5264	3.4948	948	949
Rhea	-0.3170	3.3581	-0.1138	2.4739	1021	1021
Titan	0.0000	0.0000	0.0000	0.0000	0	0
Hyperion	-0.1292	15.4526	-5.9373	12.7287	92	90
Iapetus	1.4754	5.1951	-1.1544	5.4322	1534	1534

Table 2.3 (one moon per image): Statistics of the ISS-NAC astrometric residuals computed from IMCCE model (no tidal dissipation within Enceladus scenario) in km. μ and σ denote respectively the mean and standard deviation of the residuals computed on RA and DEC. N_{RA} and N_{DEC} are the number of observations considered for the respective coordinate.

To save space, we do not provide here statistics of ground based and HST data, since they are pretty similar to the ones published in Lainey et al. (2012). We provide below the plots of the O-Cs, only. Full statistics are available on request.

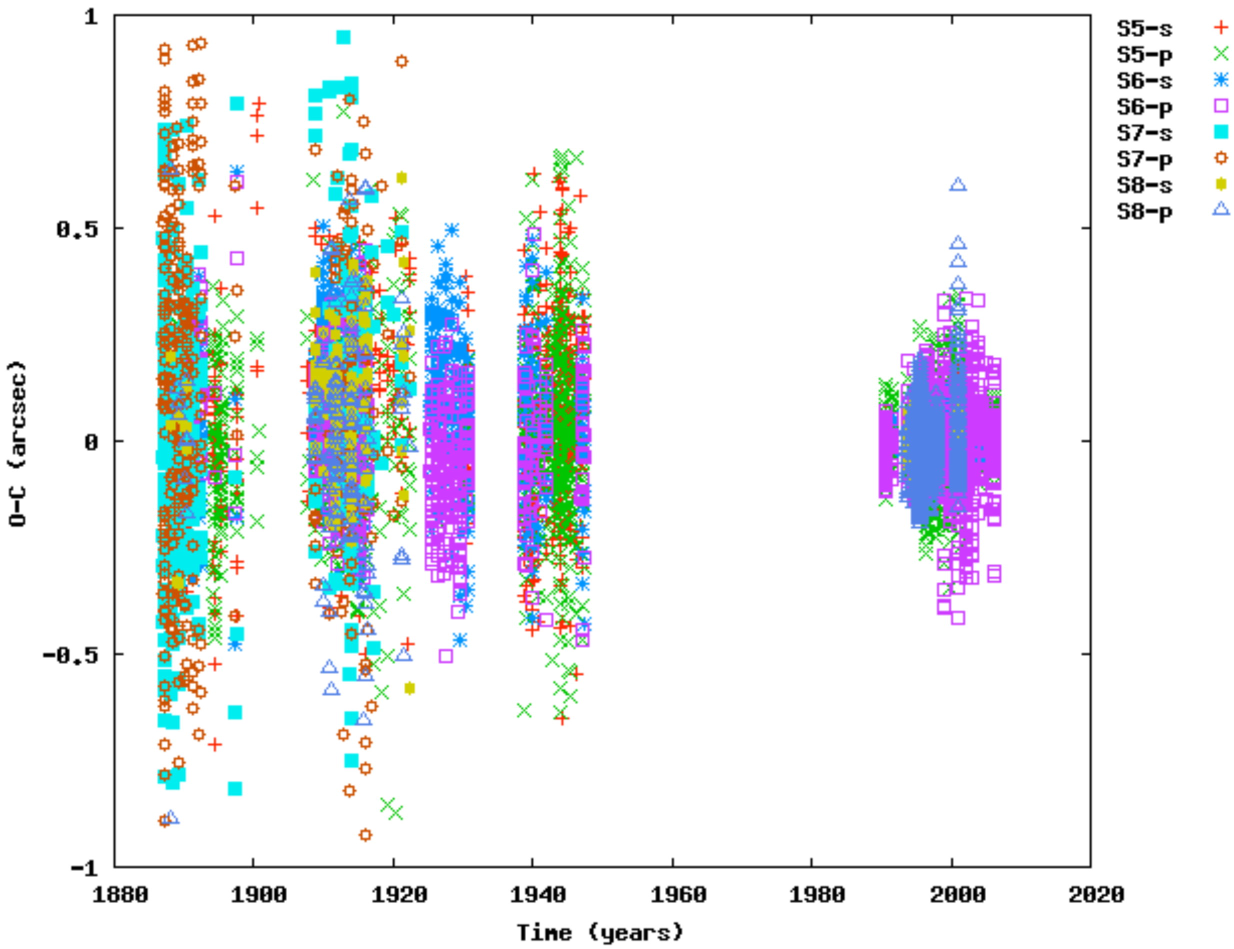

Figure 2.1: Post-fit residuals in variable s, p for Rhea (S5) to Iapetus (S8) over the full time period covered by observations. Only observations satisfying a 3-sigma criteria and in the interval [-1:1] second of arc are given. Plots are derived from the no tides within Enceladus hypothesis. We remind that 0.1 second of arc corresponds to about 600 km at the Saturn distance.

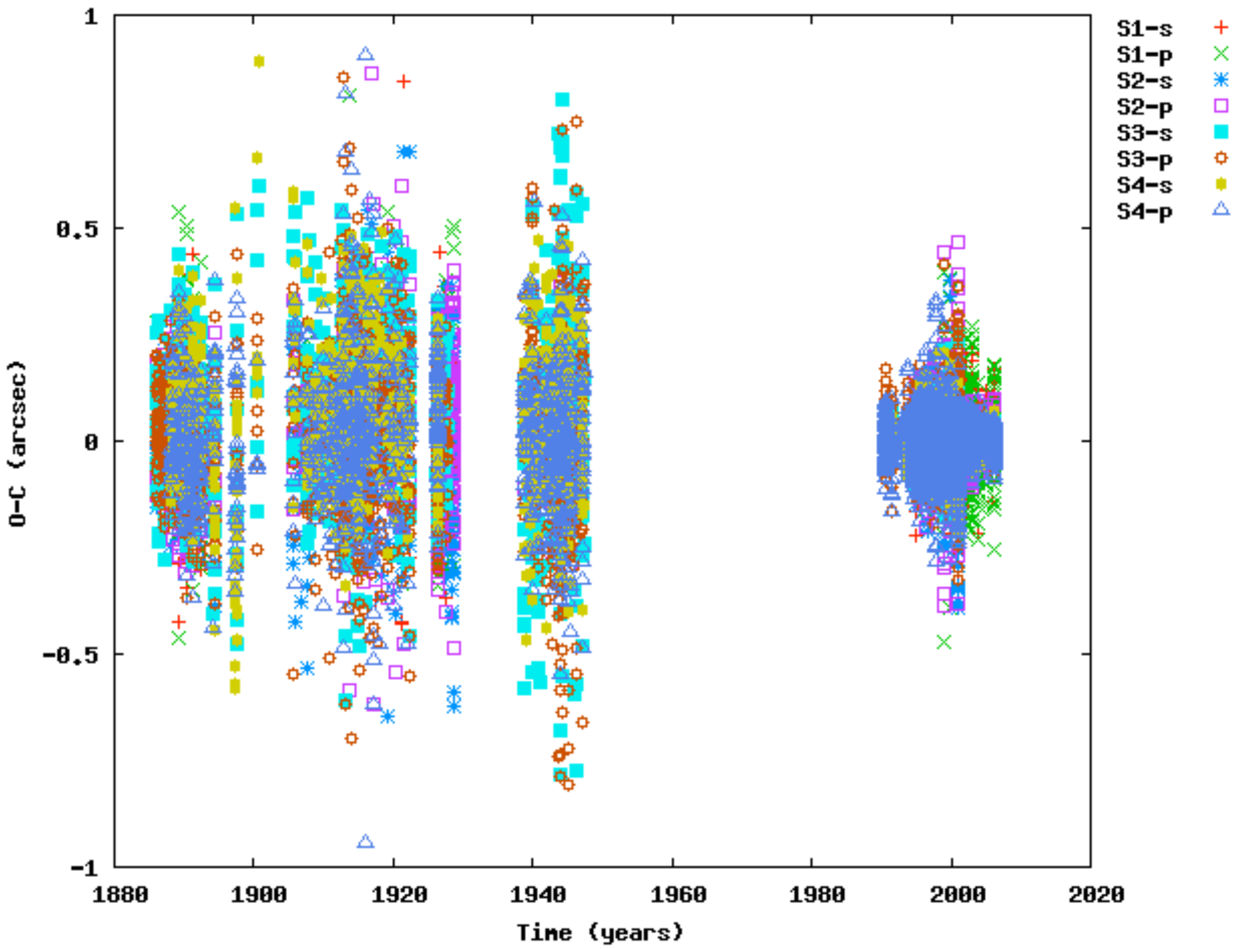

Figure 2.2: Post-fit residuals in variable s, p for Mimas (S1) to Dione (S4) over the full time period covered by observations. Only observations satisfying a 3-sigma criteria and in the interval [-1:1] second of arc are given. Plots are derived from the no tides within Enceladus hypothesis. We remind that 0.1 second of arc corresponds to about 600 km at the Saturn distance.

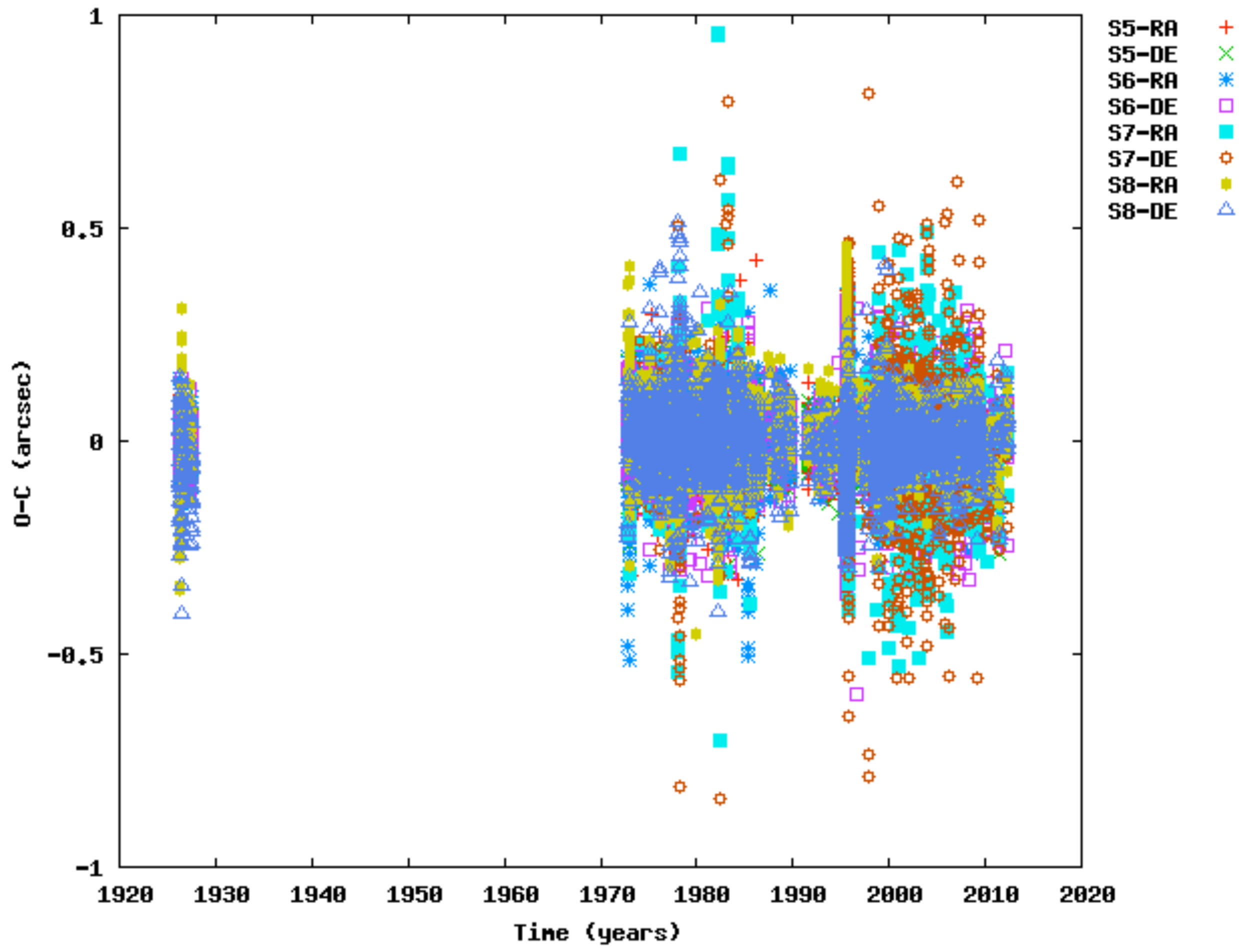

Figure 2.3: Post-fit residuals in variable α, δ for Rhea (S5) to Iapetus (S8) over the full time period covered by observations. Only observations satisfying a 3-sigma criteria and in the interval [-1:1] second of arc are given. Plots are derived from the no tides within Enceladus hypothesis. We remind that 0.1 second of arc corresponds to about 600 km at the Saturn distance.

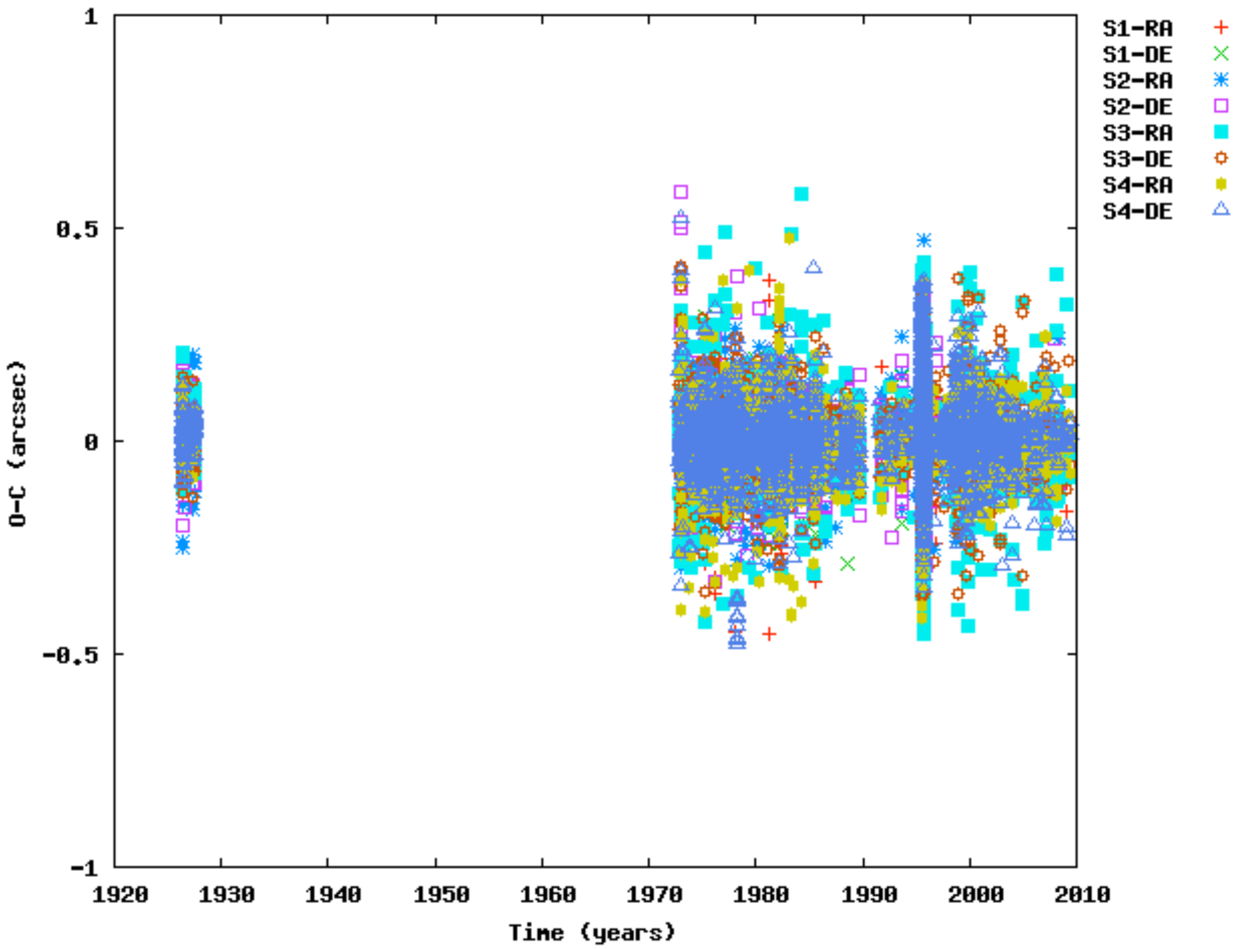

Figure 2.4: Post-fit residuals in variable α, δ for Mimas (S1) to Dione (S4) over the full time period covered by observations. Only observations satisfying a 3-sigma criteria and in the interval [-1:1] second of arc are given. Plots are derived from the no tides within Enceladus hypothesis. We remind that 0.1 second of arc corresponds to about 600 km at the Saturn distance.

References :

Cooper, N. J.; Murray, C. D.; Lainey, V.; Tajeddine, R.; Evans, M. W.; Williams, G. A., Cassini ISS mutual event astrometry of the mid-sized Saturnian satellites 2005-2012, A&A, 572, 8 (2014)

Valéry Lainey, Robert A. Jacobson, Radwan Tajeddine, Nick Cooper, Carl Murray, Vincent Robert, Gabriel Tobie, Tristan Guillot, Stéphane Mathis, Françoise Remus, Josselin Desmars, Jean-Eudes Arlot, Jean-Pierre De Cuyper, Véronique Dehant, Dan Pascu, William Thuillot, Christophe Le Poncin-Lafitte, Jean-Paul Zahn, A new constraint on the Saturn's tidal parameters from astrometry with Cassini data, to be submitted to *Nature*.

Lainey, Valéry; Karatekin, Özgür; Desmars, Josselin; Charnoz, Sébastien; Arlot, Jean-Eudes; Emelyanov, Nicolai; Le Poncin-Lafitte, Christophe; Mathis, Stéphane; Remus, Françoise; Tobie, Gabriel; Zahn, Jean-Paul Strong tidal dissipation in Saturn and Constraints on Enceladus' thermal state from astrometry. *The Astrophysical Journal* 752, 14 (2012).

Tajeddine, R.; Lainey, V.; Cooper, N. J.; Murray, C. D., Cassini ISS astrometry of the Saturnian satellites: Tethys, Dione, Rhea, Iapetus, and Phoebe 2004-2012, Astronomy & Astrophysics, Volume 575, id.A73, 6 pp. (2015)

3. Ephemerides of the Uranian satellites

New ephemerides of the five main moons of Uranus were developed. The dataset and astrometric residuals are similar to that published in Lainey 2008. The major improvement is the introduction of the observations of the PHEURA campaign reduced by WP6.

PHEURA					
Ariel	-0.0038	0.0053	-0.0044	0.0194	13, 13
Umbriel	-0.0034	0.0040	0.0072	0.0041	12, 12
Titania	0.0028	0.0118	-0.0002	0.0069	6, 6
Oberon	-0.0007	0.0029	0.0010	0.0042	5, 5
Miranda	0.0000	0.0000	0.0000	0.0000	0, 0

Table 3.1 : Astrometric residuals for the PHEURA astrometric data. Columns are in the following order: mean in RA, sigma in RA, mean in DEC, sigma in DEC. Residuals are in arc seconds.

We provide below graphical representations of the astrometric residuals. More information on the modelling is available in Lainey 2008.

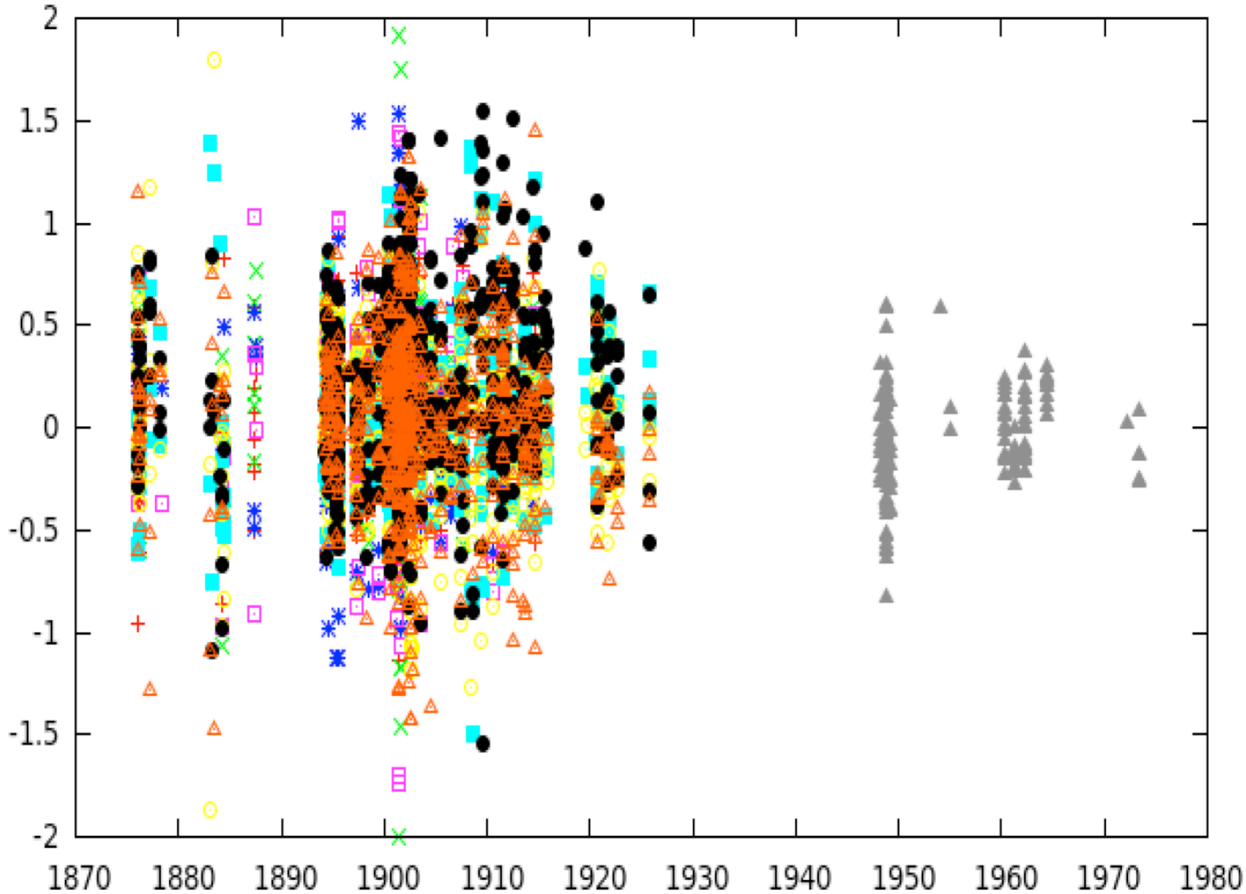

Figure 3.1 : Astrometric residuals for the pre-ESPaCE published astrometric data (micrometer and heliometer only). Residuals are in arcseconds.

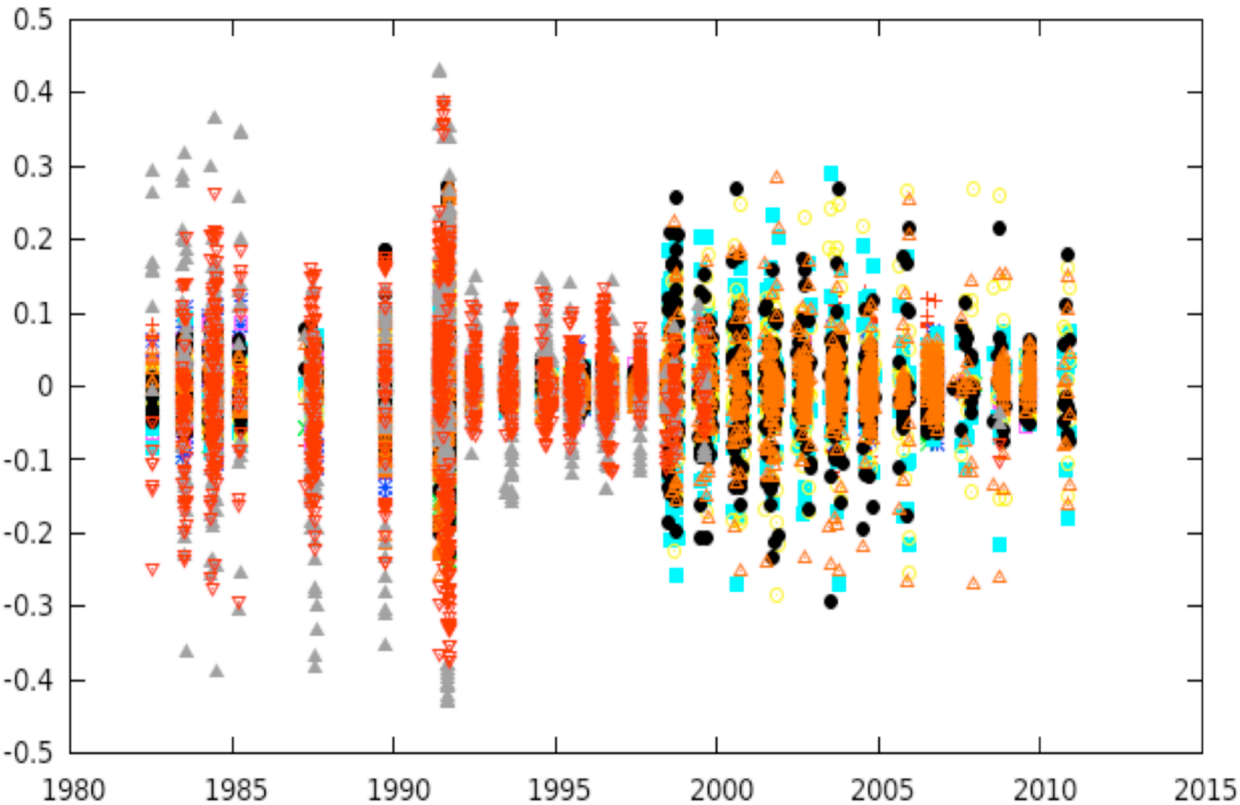

Figure 3.2 : Astrometric residuals for the pre-ESPaCE published astrometric data (RA and DEC only). Residuals are in arcseconds.

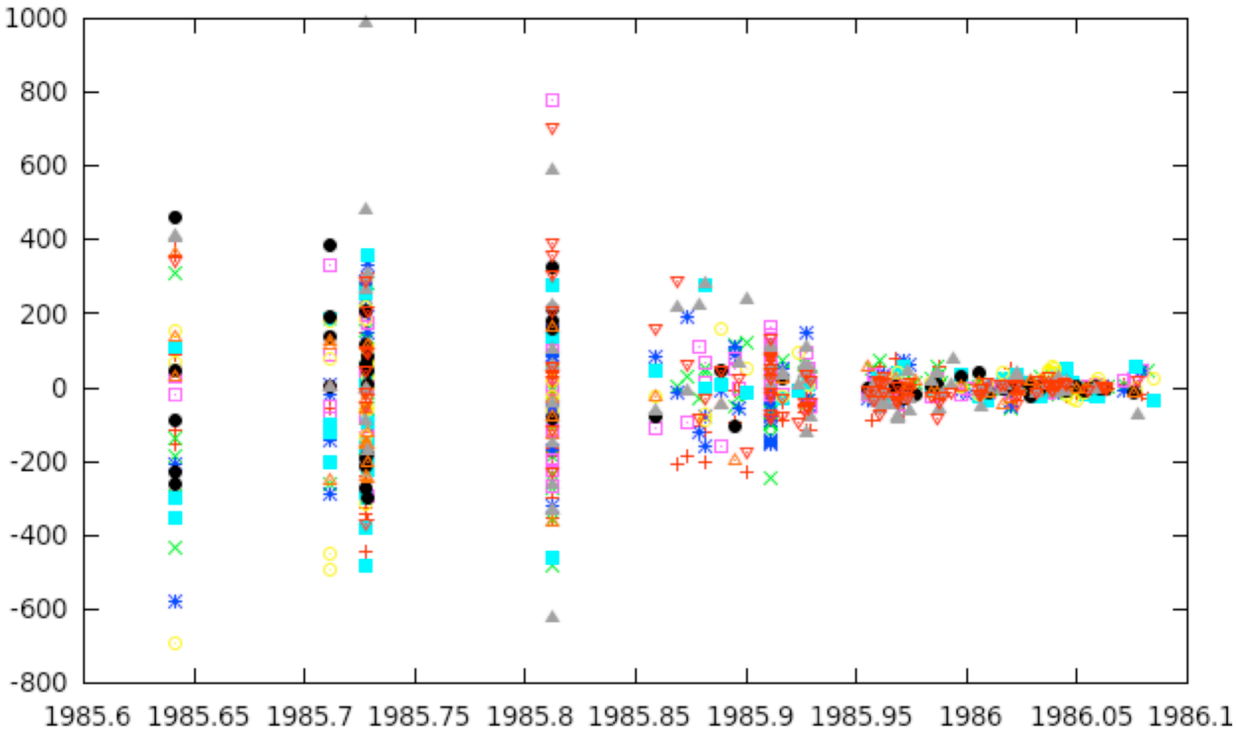

Figure 3.3 : Astrometric residuals for the Voyager 2 astrometric data (made available from JPL during ESPaCE). Residuals are in km.

References :

Arlot, J.-E.; Emelyanov, N. V.; Aslan, Z.; Assafin, M.; Bel, J.; Bhatt, B. C.; Braga-Ribas, F.; Camargo, J. I. B.; Casas, R.; Colas, F.; and 14 coauthor, Astrometric results of observations of mutual occultations and eclipses of the Uranian satellites in 2007, Astronomy & Astrophysics, Volume 557, id.A4, 6 pp. (2013)

Lainey, Valery, Possible astrometric determination of tidal dissipation within Uranus from a future space mission, American Astronomical Society, DPS meeting #46, #418.12 (2014)

Lainey, V., A new dynamical model for the Uranian satellites, Planetary and Space Science, Volume 56, Issue 14, p. 1766-1772 (2008).