MUTUAL APPROXIMATIONS BETWEEN THE GALILEAN MOONS

Bruno Eduardo Morgado

R. Vieira-Martins, M. Assafin, J.I.B. Camargo, A. Dias-Oliveira, A. R. Gomes-Júnior

SUMMARY

- Motivation
- Our goal
- The Mutual Approximation Technique
- Observations and Results
- Comparison between Phemus and Approximations
- Future Work

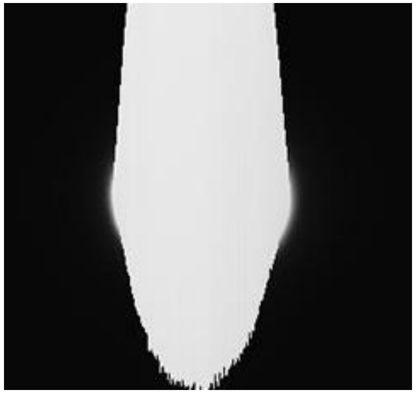
MOTIVATION

Astrometric observations of the Galilean Moons can give us hints about their formations process and evolution.

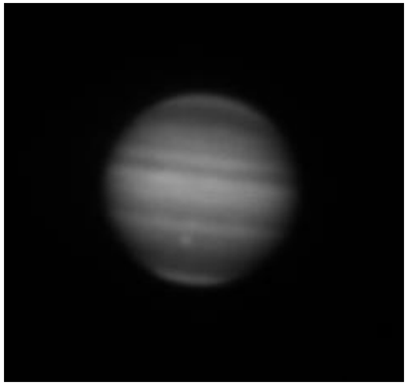
- The study of tidal forces can provide informations about the interiors of these moons:
  - (i) Volcanoes in Io (J1) (✓) Lainey et al., 2009
  - (ii) Oceans in Europa (J2) (?) Hussmann et al., 2002
  - (iii) Oceans in Ganymede(J3) (?) NASA release 2015

MOTIVATION

However this CCD astrometry is not an easy task.



(i)



(ii)

60 cm telescope in OPD (Itajuba)

- Images with exposition of 1 second,

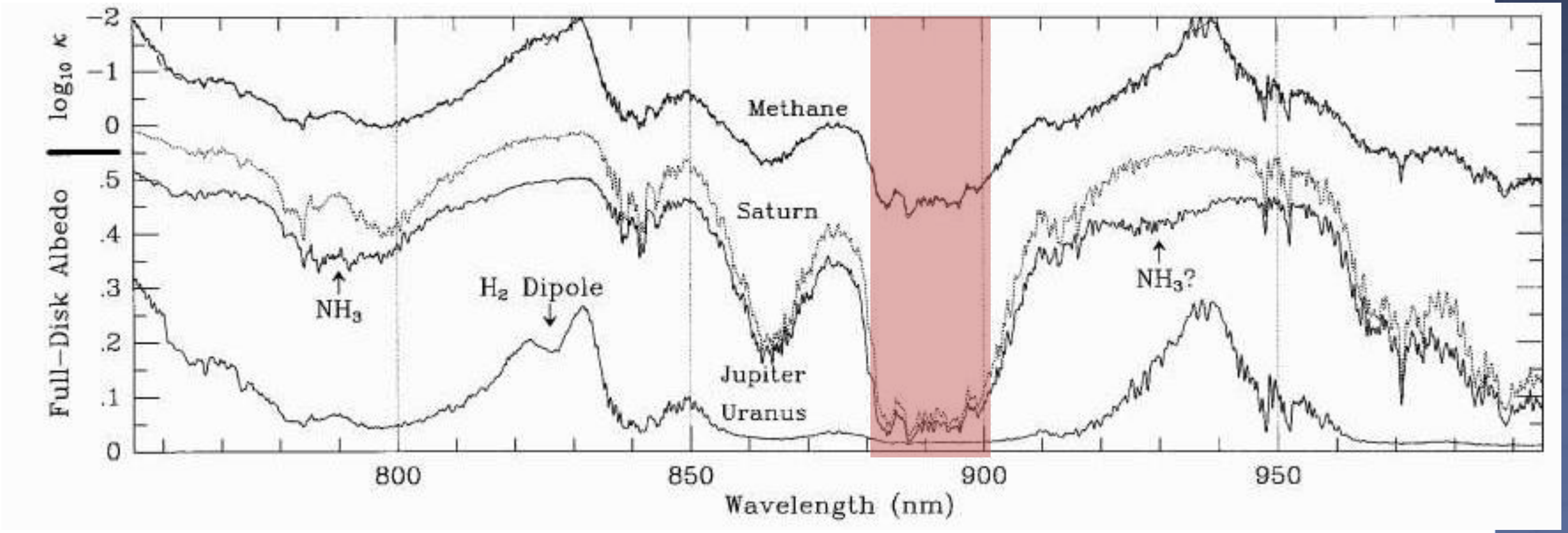
(i) I filter (Johnson)

(ii) Narrow-band Methane filter (Karkoschka, 1998)

MOTIVATION

Narrow-band Methane filter

Centred at *889 nm* with an width of *15 nm*.

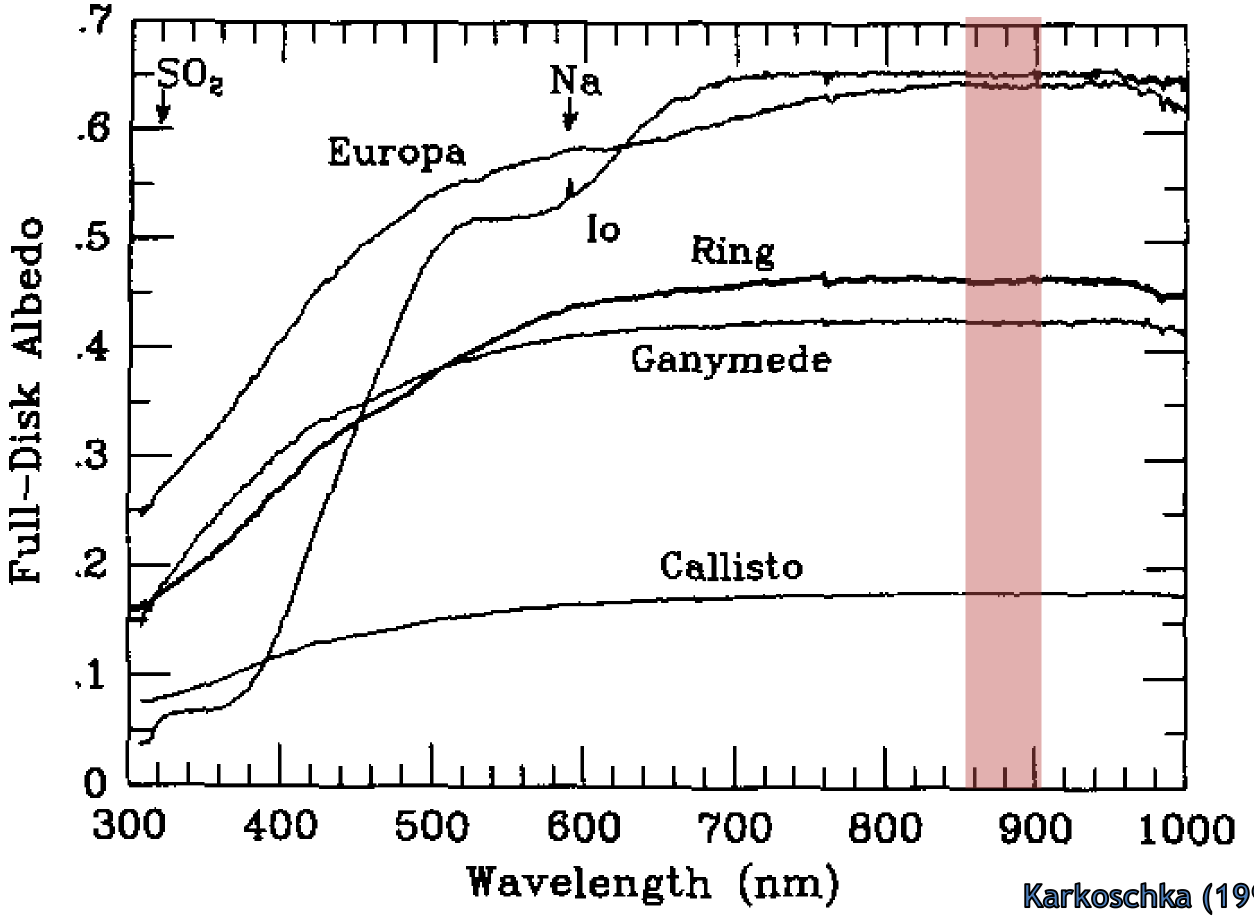


Karkoschka (1994, 1998)

MOTIVATION

Narrow-band Methane filter

Centred at *889 nm* with an width of *15 nm*.



Karkoschka (1994, 1998)

MOTIVATION

- However even taking out the scattered light of Jupiter, there is no catalogued stars in the FoV.

  UCAC 4 - (Mean Mag. V between 15 and 16).

MOTIVATION

- **Classical CCD astrometry**

  Stone et al., 2001 - 107 mas

  Kiseleva et al., 2008 - 125 mas

  Always when Jupiter is in the night sky

  Not precise enough

- **Relative Position (+ Precision Premium)**

  Peng et al., 2012 - 30 mas

  Always when two satellites are close to each other (sky plane)

  Need the ephemeris to compute the plate scale and CCD orientation

- **Mutual Phenomena**

  Dias-Oliveira et al., 2013 - 03 mas

  Arlot et al., 2014 - 05 mas

  Very precise observations

  We can only observe for a few months every 6 years

MOTIVATION

- Classical CCD astrometry

  Stone et al., 2001 - 107 mas

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  Need the ephemeris to compute the plate scale and CCD orientation

- Mutual Phenomena

  Dias-Oliveira et al., 2013 - 03 mas

  Arlot et al., 2014 - 05 mas

  Very precise observations

  We can only observe for a few months every 6 years

OUR GOAL

Determine the central instant in the close approach between two satellites.

For that we need:

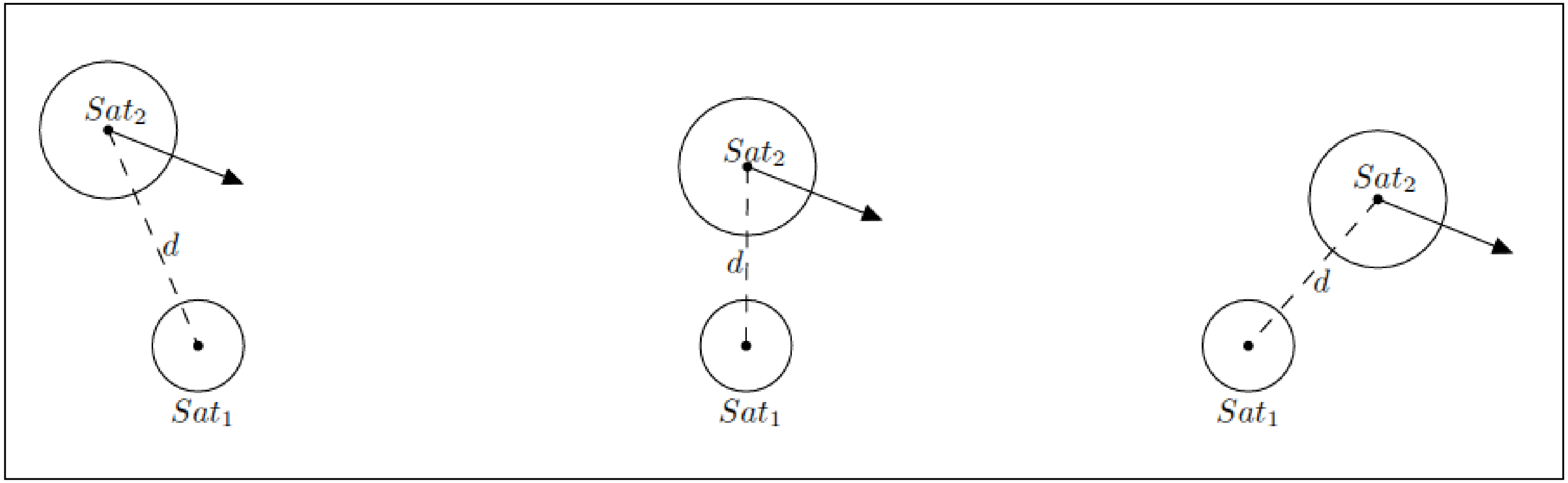
(i) Precise time insertion in the images (GPS)

(ii) Means to reduce Jupiter brightness (Methane Filter)

(iii) A model to fit the distances curves and obtain the central instant

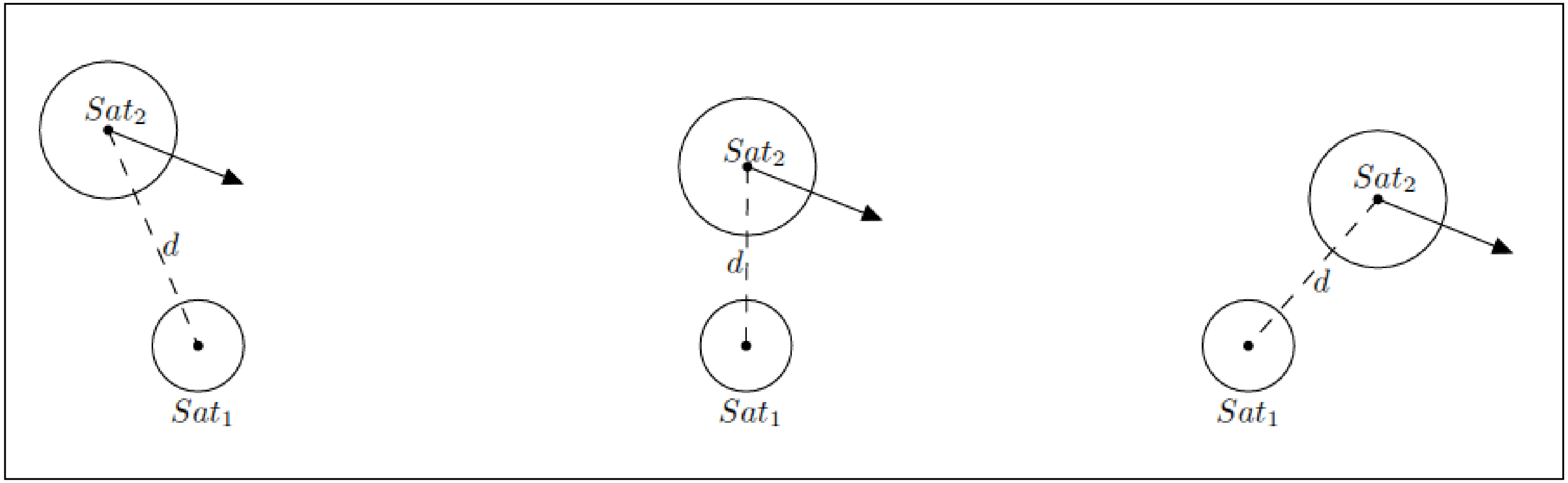
MUTUAL APPROXIMATIONS

The main idea is that: during the equinox of the host planet the satellites cross each other in the sky plane, causing an occultation. But for any other epoch they only will approach each other.



MUTUAL APPROXIMATIONS

So, we can use these approximations to determine the same parameters of an occultation: the central instant and the impact parameter (but in pixel units).



MUTUAL APPROXIMATIONS

In fact, this was already done before:

(i) Arlot et al., 1982 was the first to try a similar technique, during the mutual phenomena campaign in 1979.

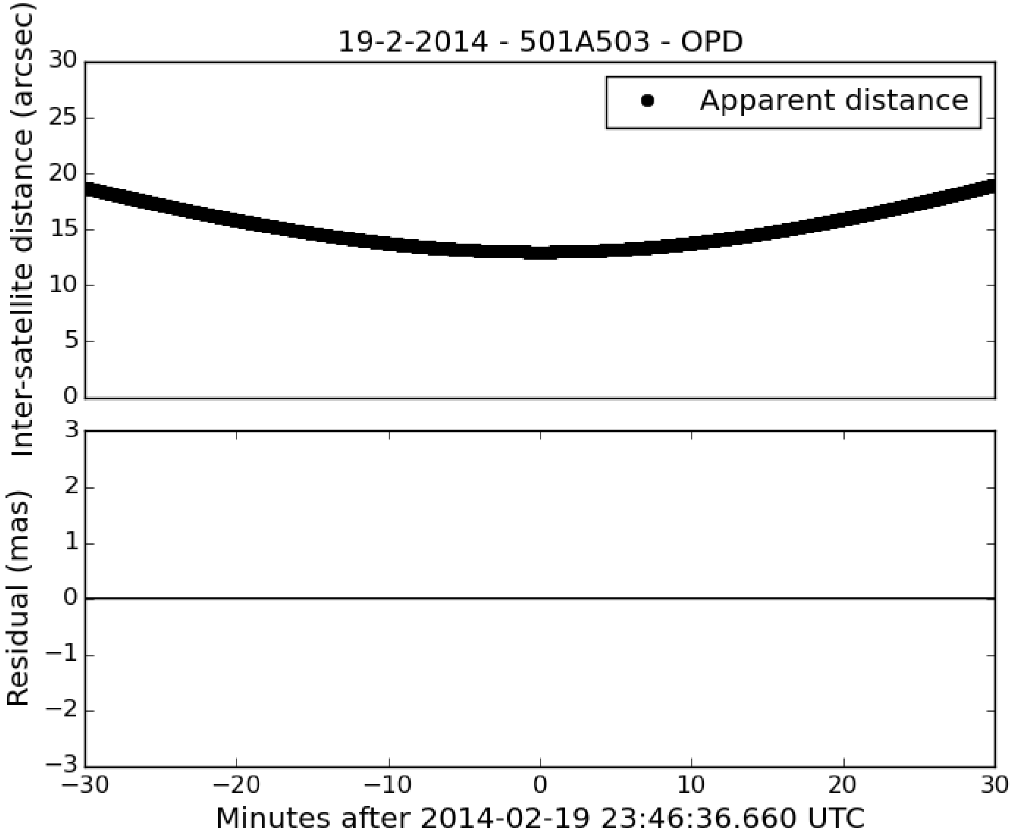
(ii) Mason et al., 1999 also observe this kind of events in the Naval Observatory (USNO).

But no further publications were made….

MUTUAL APPROXIMATIONS

How we can determine the central instant?

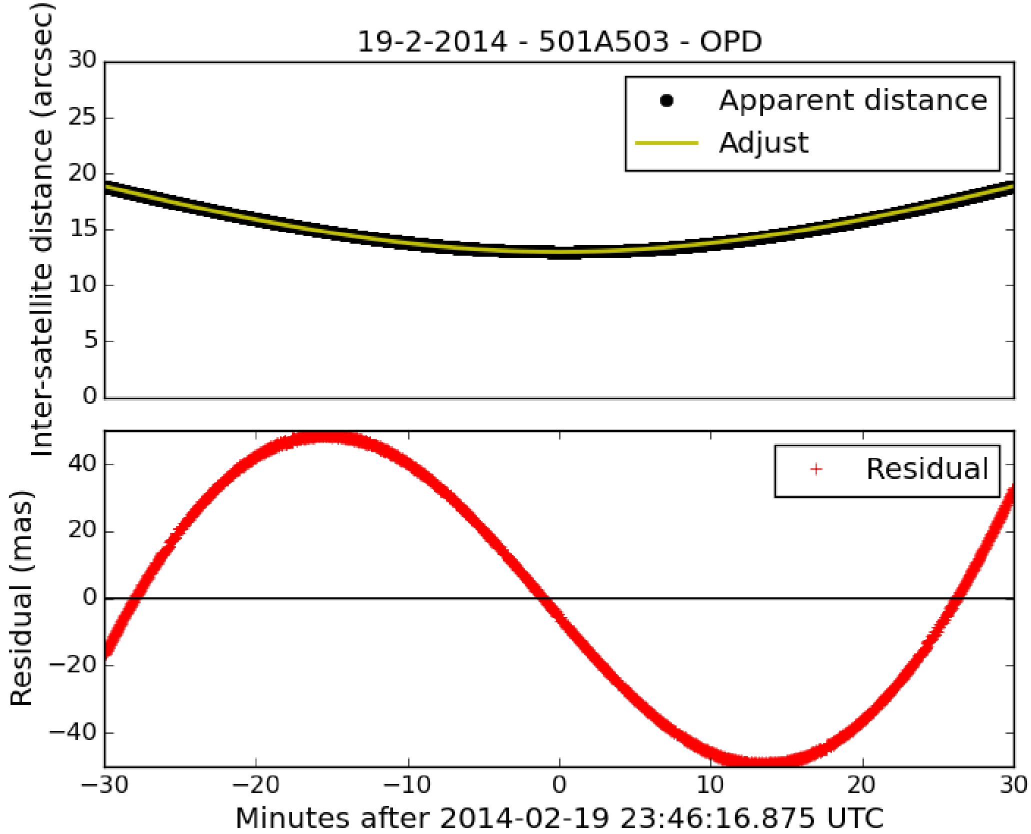
The simplest model is a polynomial, is easier to fit and to determine the minimal (The fit is made for d^2).



MUTUAL APPROXIMATIONS

How we can determine the central instant?

We chose a polynomial order n to fit the distance curve obtained with the ephemerides.

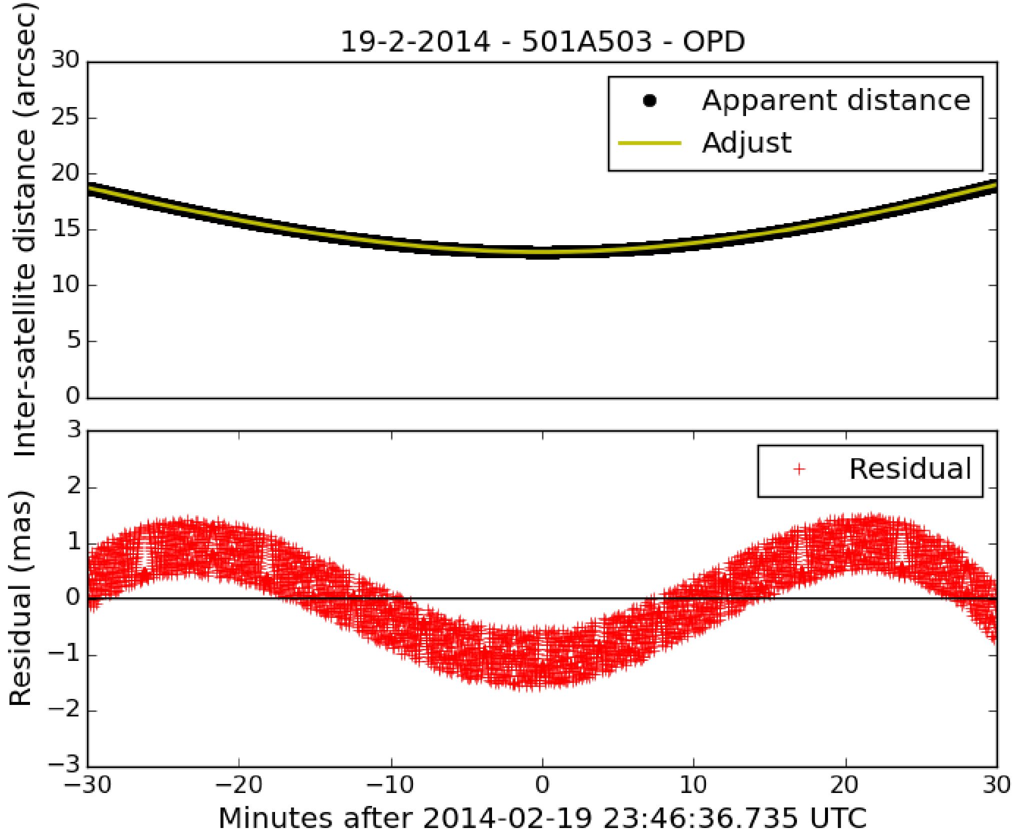


$n = 2$

MUTUAL APPROXIMATIONS

How we can determine the central instant?

We chose a polynomial order *n* to fit the distance curve obtained with the ephemerides.

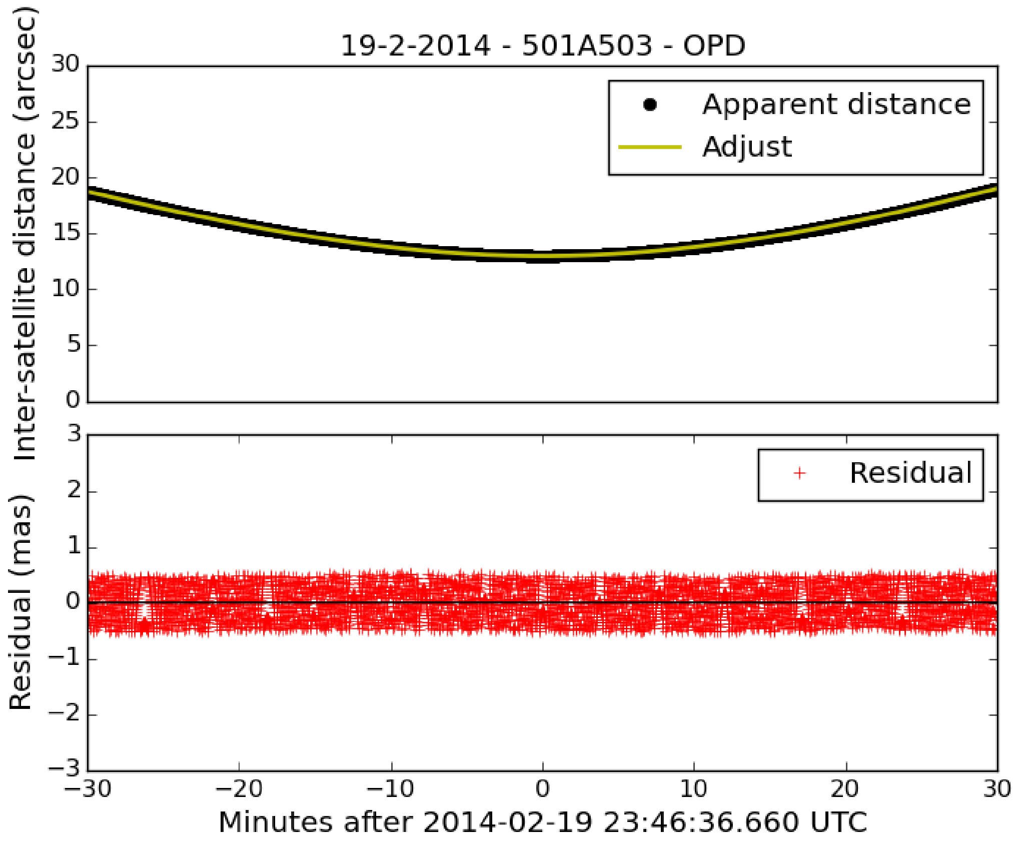


***n* = 3**

MUTUAL APPROXIMATIONS

How we can determine the central instant?

We chose a polynomial order *n* to fit the distance curve obtained with the ephemerides.

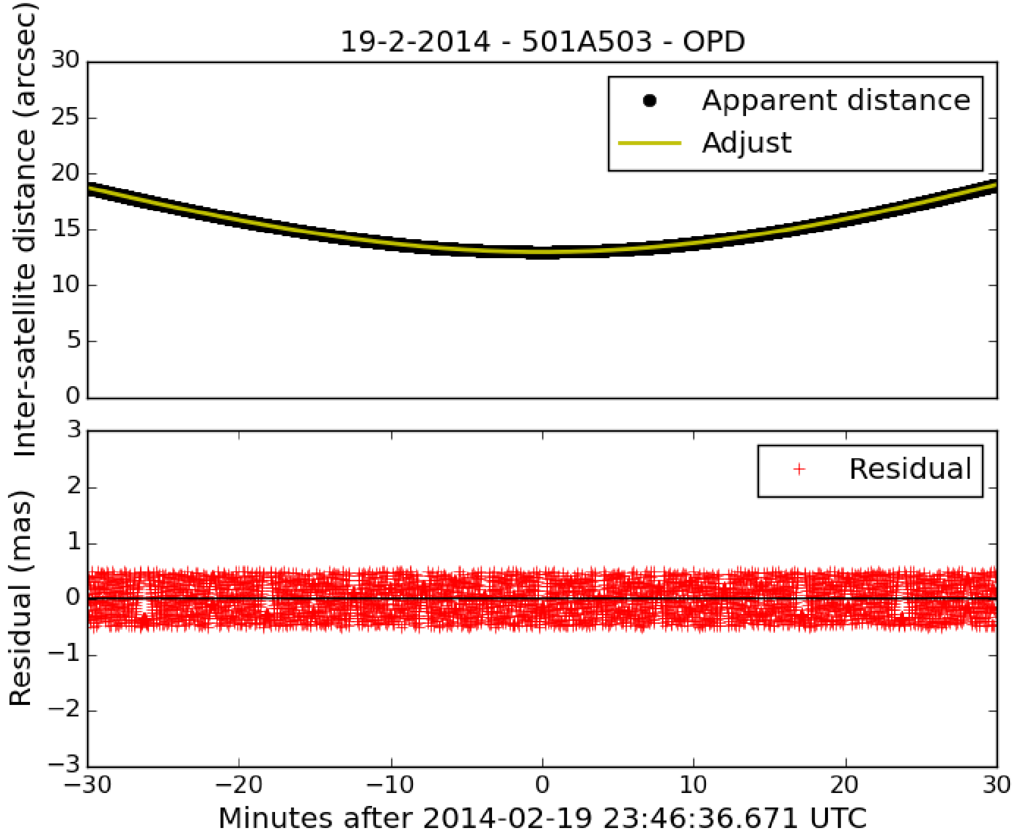


***n* = 4**

MUTUAL APPROXIMATIONS

How we can determine the central instant?

We chose a polynomial order *n* to fit the distance curve obtained with the ephemerides.

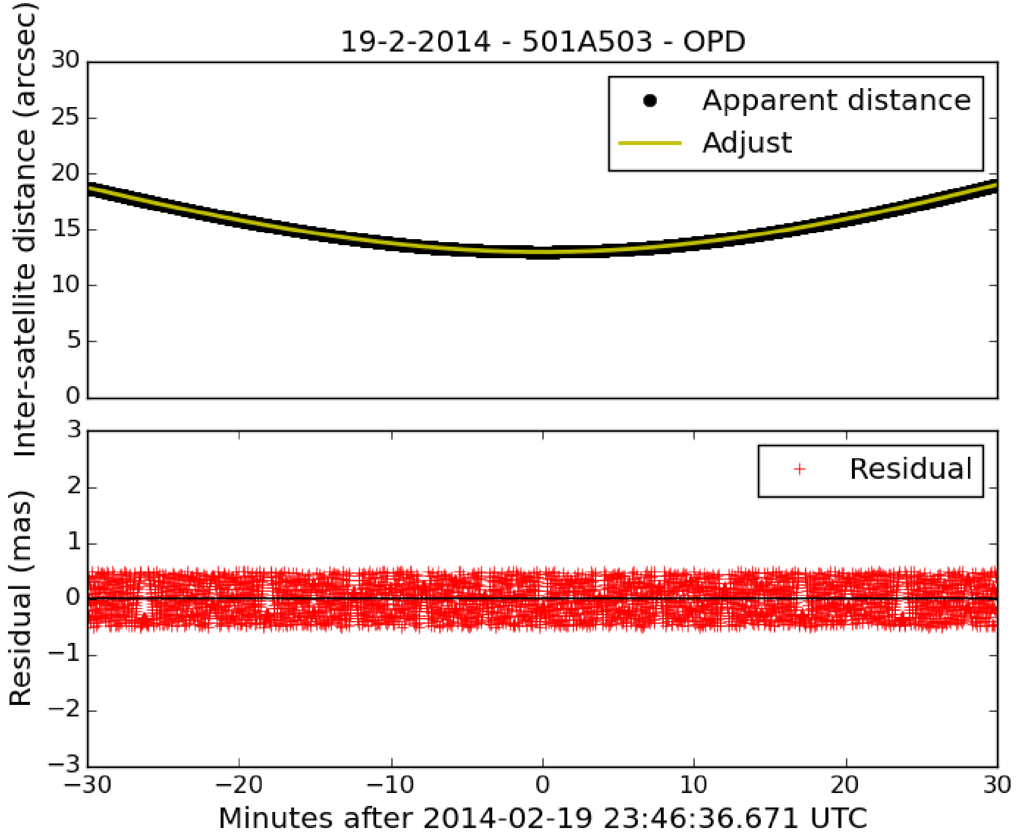


***n* = 5**

MUTUAL APPROXIMATIONS

How we can determine the central instant?

We chose a polynomial order n to fit the distance curve obtained with the ephemerides.

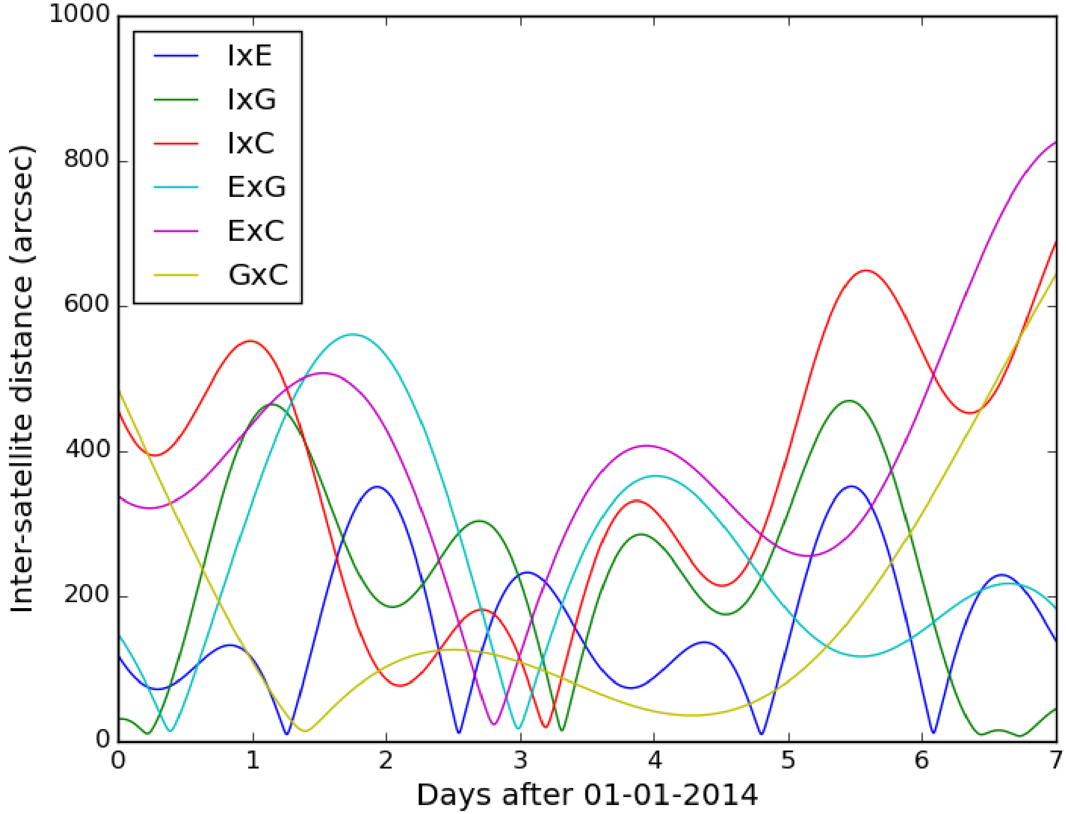


$n = 6$

MUTUAL APPROXIMATIONS

Is the mutual approximation method feasible?

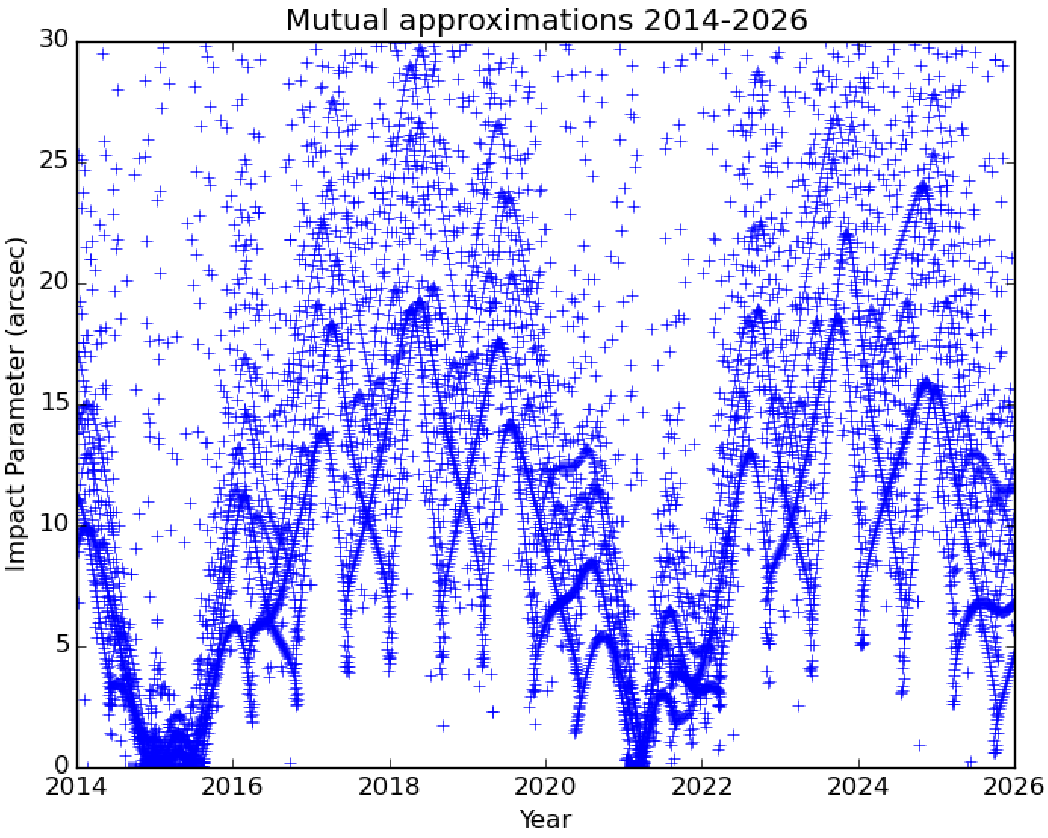
How many approximations there are?



MUTUAL APPROXIMATIONS

Is the mutual approximation method feasible?

How these approximations changes during one orbit of Jupiter?



OBSERVATIONS AND RESULTS

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Io and Europa – 03/02/2014

60 cm telescope in OPD (Itajubá)

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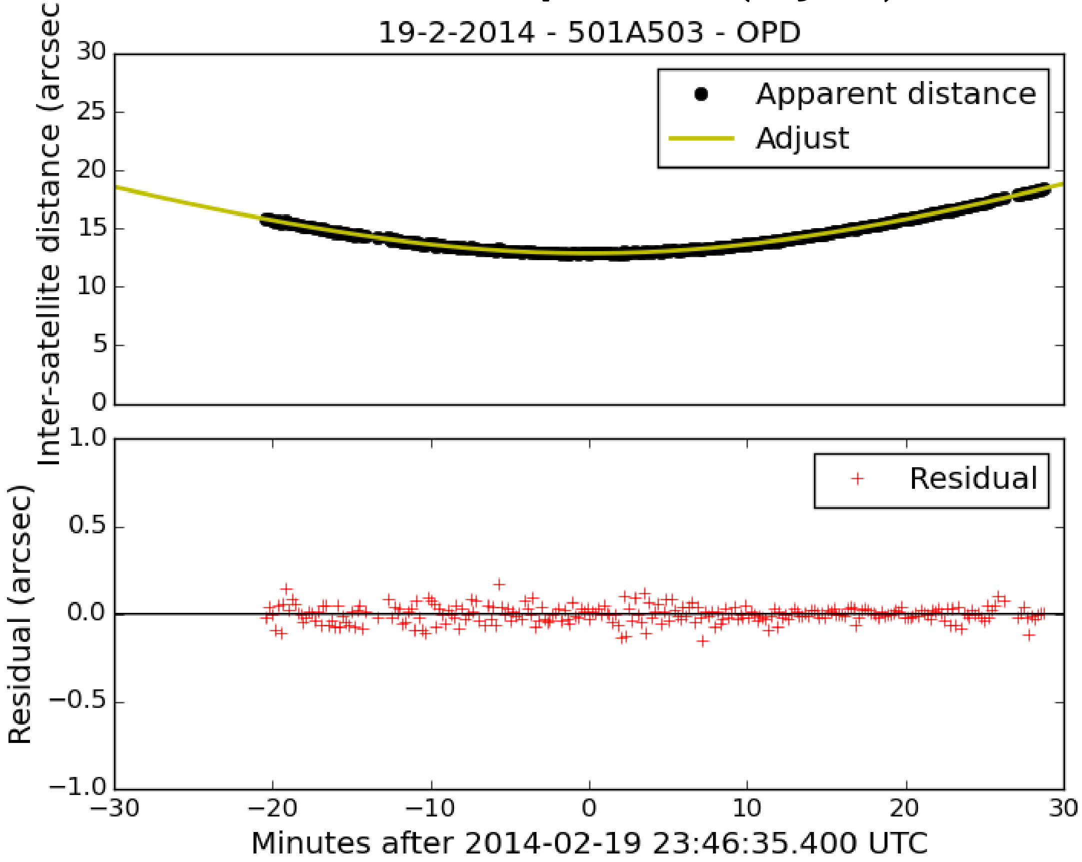
Io and Europa – 03/02/2014

60 cm telescope in OPD (Itajubá)

OBSERVATIONS AND RESULTS

Date (d-m-y)	Event	t_0 (hh:mm:ss)	E_{t0} (mas)	Δt_0 (s)	(mas)
19-02-14	IaG	23:46:35.40 (0.76)	5.78	+2.31	+17.59

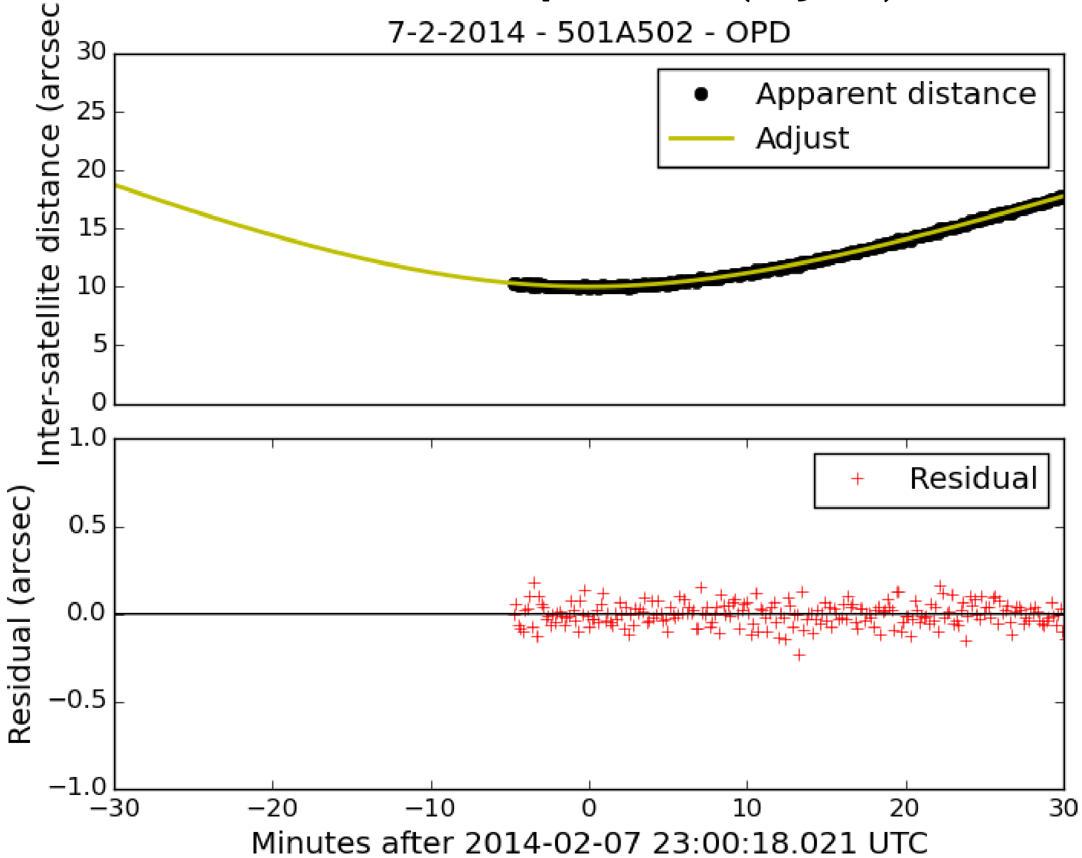
60 cm telescope in OPD (Itajubá)



OBSERVATIONS AND RESULTS

Date (d-m-y)	Event	t_0 (hh:mm:ss)	E_{t0} (mas)	Δt_0 (s)	(mas)
07-02-14	IaE	23:00:17.29 (4.94)	40.97	–1.38	–11.46

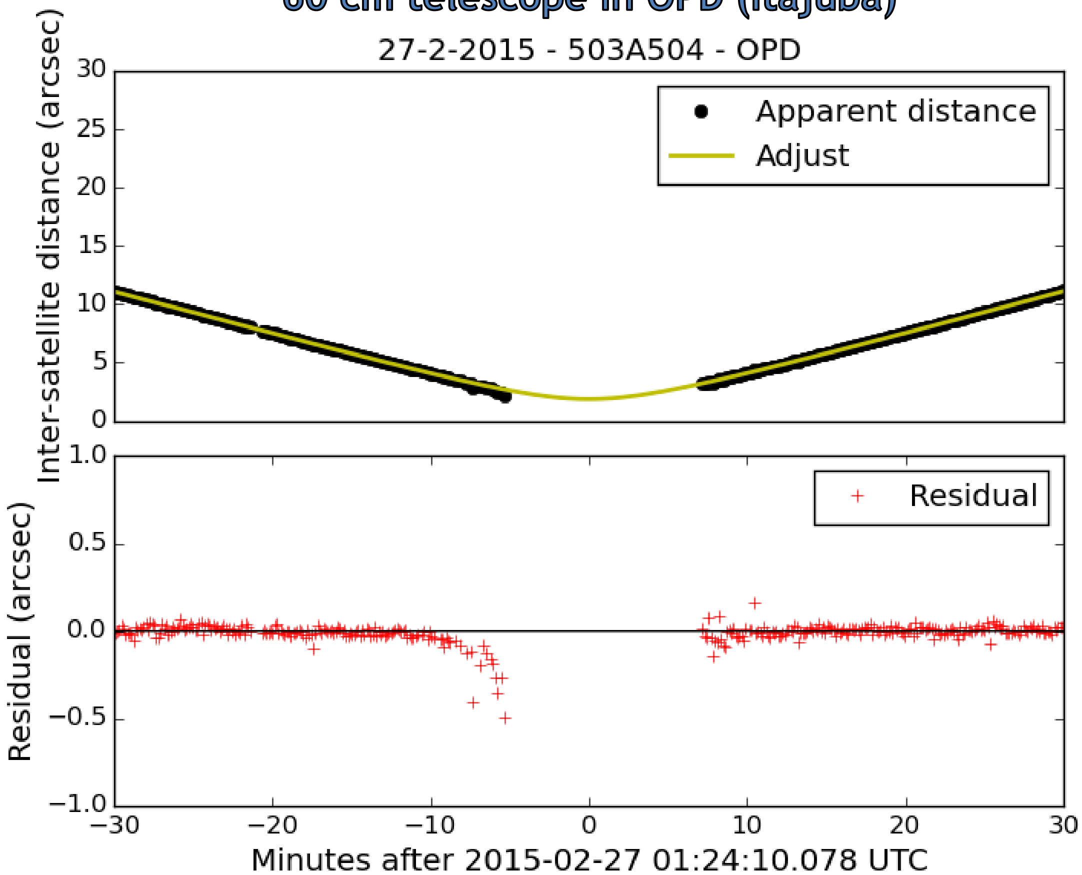
60 cm telescope in OPD (Itajubá)



OBSERVATIONS AND RESULTS

Date (d-m-y)	Event	t_0 (hh:mm:ss)	E_{t0} (mas)	Δt_0 (s)	Δt_0 (mas)
27-02-15	GaC	01:24:10.29 (1.42)	8.14	+0.71	+4.07

60 cm telescope in OPD (Itajubá)



OBSERVATIONS AND RESULTS

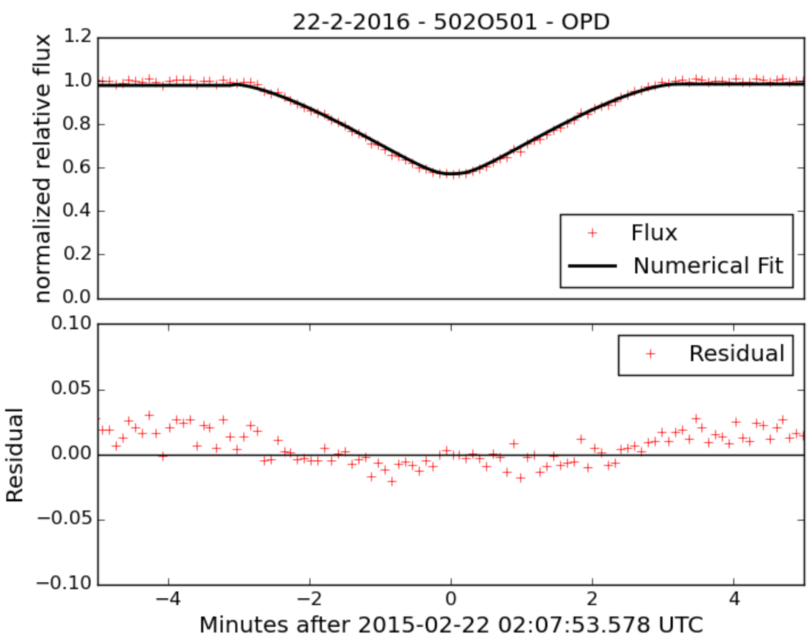
Date (d-m-y)	Event	t_0 (hh:mm:ss)	E_{t0} (mas)	Δt_0 (s)	Δt_0 (mas)
03-02-14	IaE	03:18:47.42 (0.20)	1.55	+4.37	+33.92
05-02-14	EaG	23:27:50.65 (0.66)	4.04	+2.86	+17.53
19-02-14	IaG	23:46:35.40 (0.76)	5.78	+2.31	+17.59
27-02-14	IaE	22:34:27.89 (0.10)	0.79	–1.16	–9.16
07-04-14	IaE	22:35:27.89 (0.19)	1.46	–0.35	–2.68
20-04-14	EaG	21:47:40.57 (0.52)	1.85	–9.70	–34.47
21-04-14	GaC	21:41:53.56 (1.01)	4.74	+1.71	+8.04
21-04-14	IaG	23:13:56.69 (1.01)	5.45	–2.73	–14.74
07-02-14	IaE	23:00:17.29 (4.94)	40.97	–1.38	–11.46
18-03-14	IaE	22:43:23.26 (2.52)	16.06	–7.93	–50.54
27-02-15	GaC	01:24:10.29 (1.42)	8.14	+0.71	+4.07
11-04-15	EaG	22:07:13.35 (1.13)	5.76	–2.60	–13.25
13-04-15	IaE	23:44:40.98 (1.12)	8.60	–1.78	–13.67
19-04-15	EaG	01:17:48.89 (1.00)	5.15	–4.10	–21.12

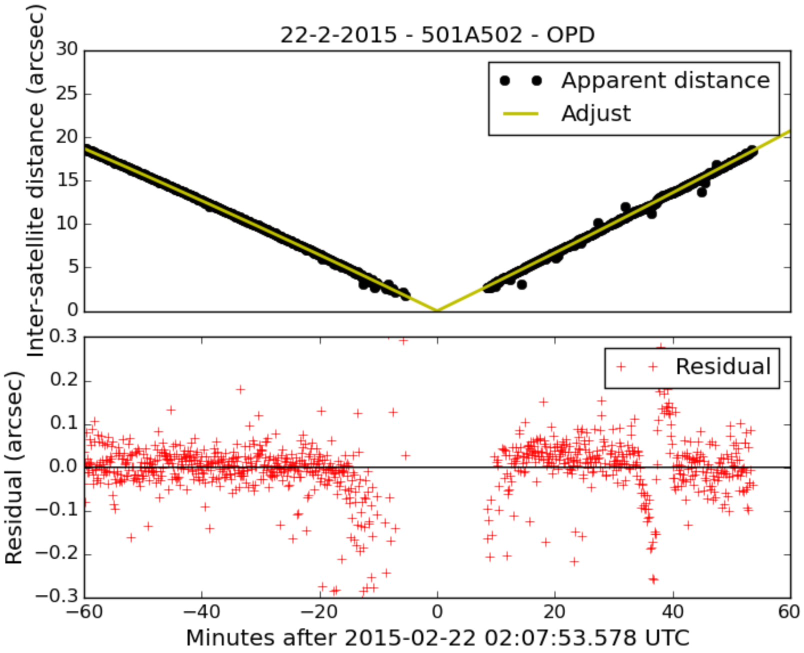
Morgado et al., 2016

OBSERVATIONS AND RESULTS

- Classical CCD astrometry
  - Stone et al., 2001 - 107 mas
  - Kiseleva et al., 2008 - 125 mas
- Relative Position (+ Precision Premium)
  - Peng et al., 2012 - 30 mas
- Mutual Approximation
  - Morgado et al., 2016 - 08 mas
- Mutual Phenomena
  - Dias-Oliveira et al., 2013 - 03 mas
  - Arlot et al., 2014 - 05 mas

PHEMUS VS APPROX





PHEMUS VS APPROX

Date	Event	[1]	[2]
09-05-2009	2o1	07 21 56,00	07 21 55,48 (3,23)
28-05-2009	1o2	07 44 18,25	07 44 20,55 (3,62)
22-06-2009	1o2	03 27 55,43	03 27 53,19 (4,72)
06-07-2009	1o2	07 48 34,94	07 48 31,95 (3,02)
07-08-2009	1o2	05 37 47,84	05 37 49,80 (3,59)
22-02-2015	2o1	02 07 52,67	02 07 53,58 (1,32)
03-03-2015	3o1	04 08 16,84	04 08 13,42 (3,85)

- [1] Mutual phenomena: using Emelyanov (2003) method
- [2] Mutual approximation: Morgado et al., 2016

[1] and [2] agrees in 1σ

*Note that the precision of the approximations is affected by the absence of positions near the central instant.

FUTURE WORK

- Observe more approximations between the Galilean moons.

  (39 more observation in early 2016, in a huge collaboration effort.)

- Test if this method also works for other satellites' systems.

  (already tested for the Uranian satellites, it works!)

- New orbit fitting using these (and more) observations.

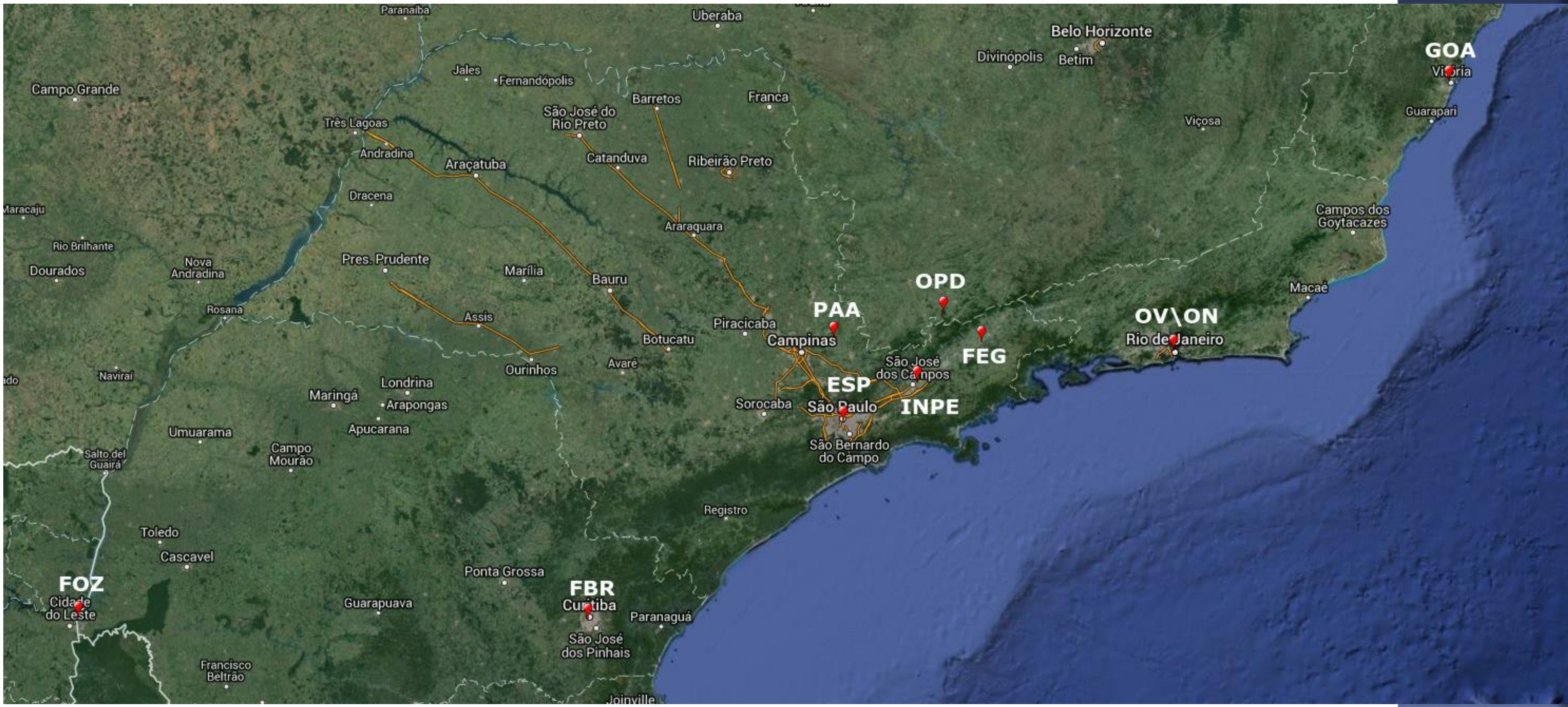
  (collaboration with the IMCCE in the near future).

FUTURE WORK

- **Mutual approximation campaign in 2016:**

FUTURE WORK

- **Mutual approximation campaign in 2016:**



FUTURE WORK

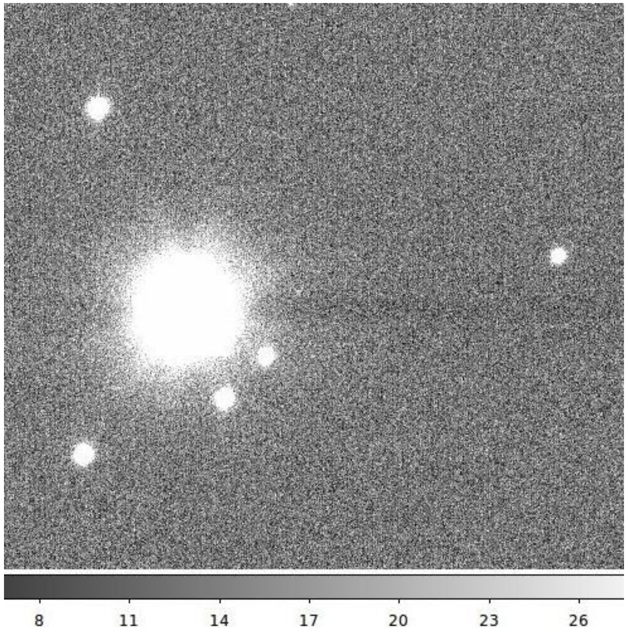
22 mutual approximations observed between February and May of 2016 (39 distances curves).

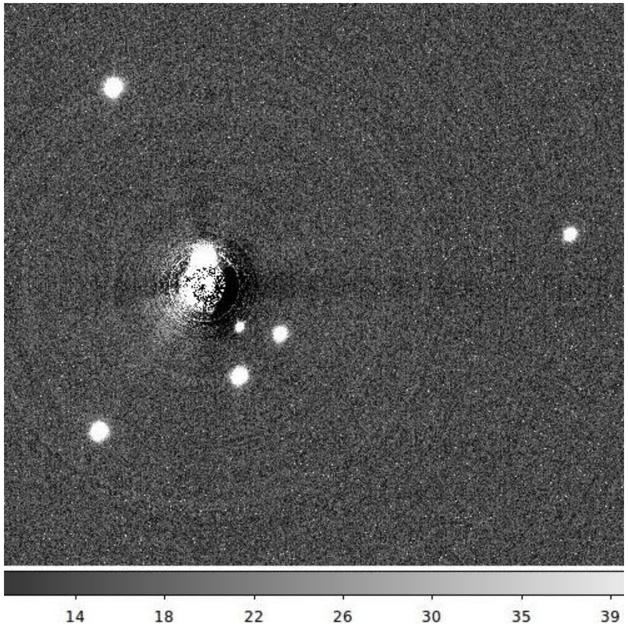
- 50% of the observations with precisions bellow 10 mas. (73% bellow 20 mas).

FUTURE WORK

- Test with the Uranian satellites

Approximation between Miranda (705) and Umbriel (702)





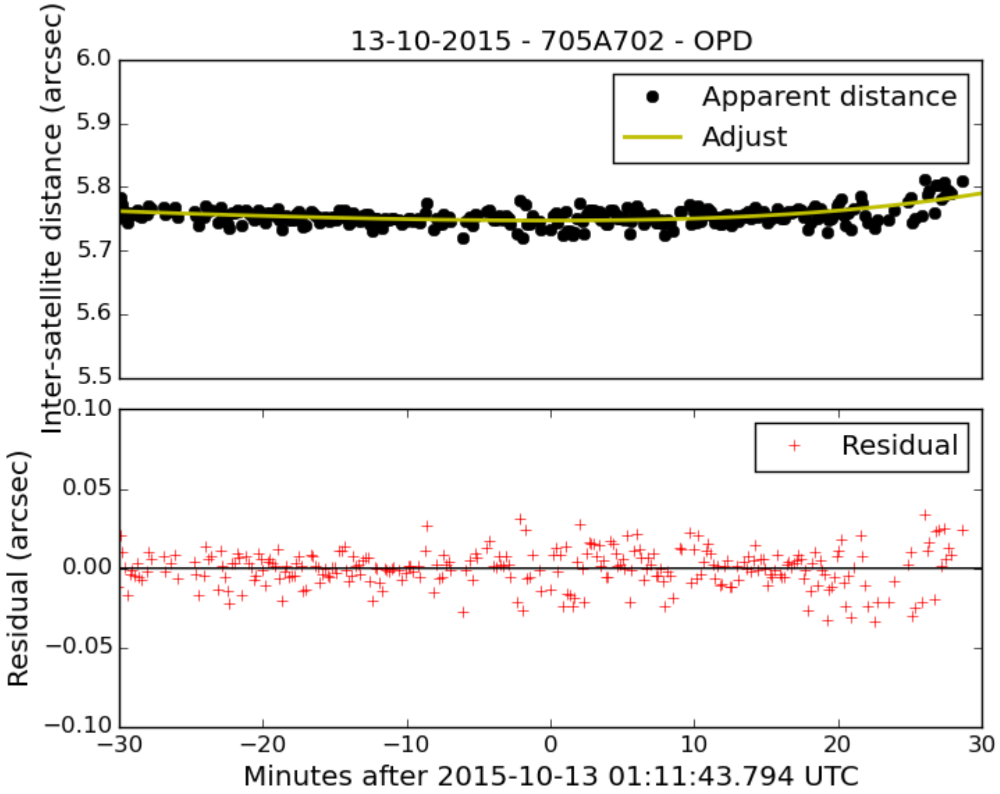
Assafin et al., 2008

FUTURE WORK

- **Test with the Uranian satellites**

Approximation between Miranda (705) and Umbriel (702)

Precision for the central instant was 54.280 s (4.88 mas)



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10.1093/mnras/stw1244 arXiv:1605.06573

Astrometry of mutual approximations between natural satellites. Application to the Galilean moons.*

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[1] *Observatório Nacional/MCTI, R. General José Cristino 77, Rio de Janeiro RJ 20.921-400, Brazil*

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THANKS!!

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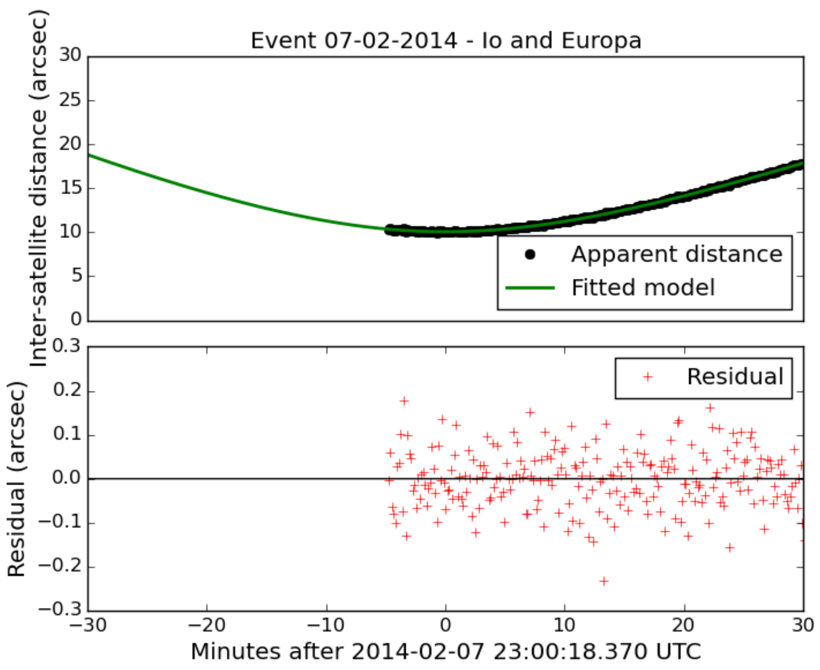
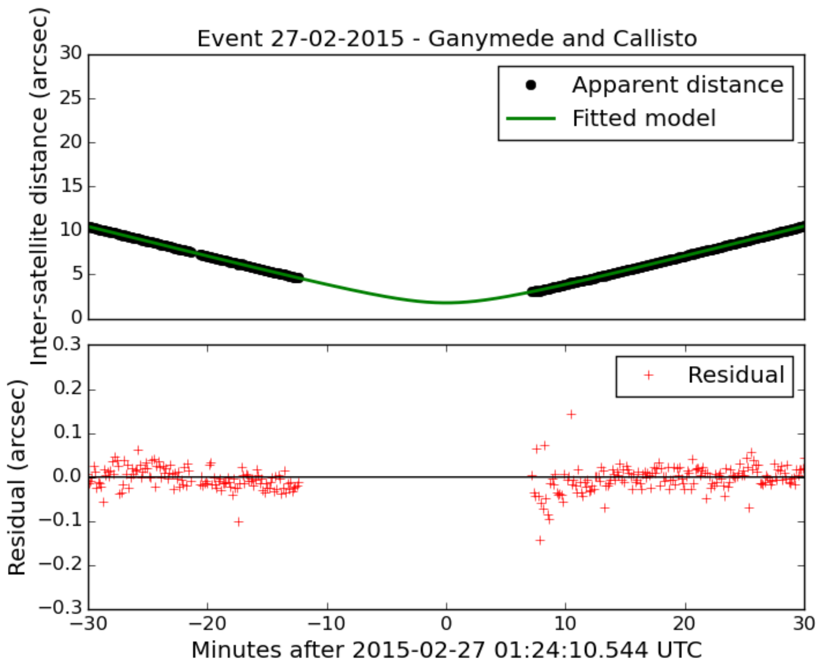
C A P E S

APPENDIX I

- "Bad" observations examples:





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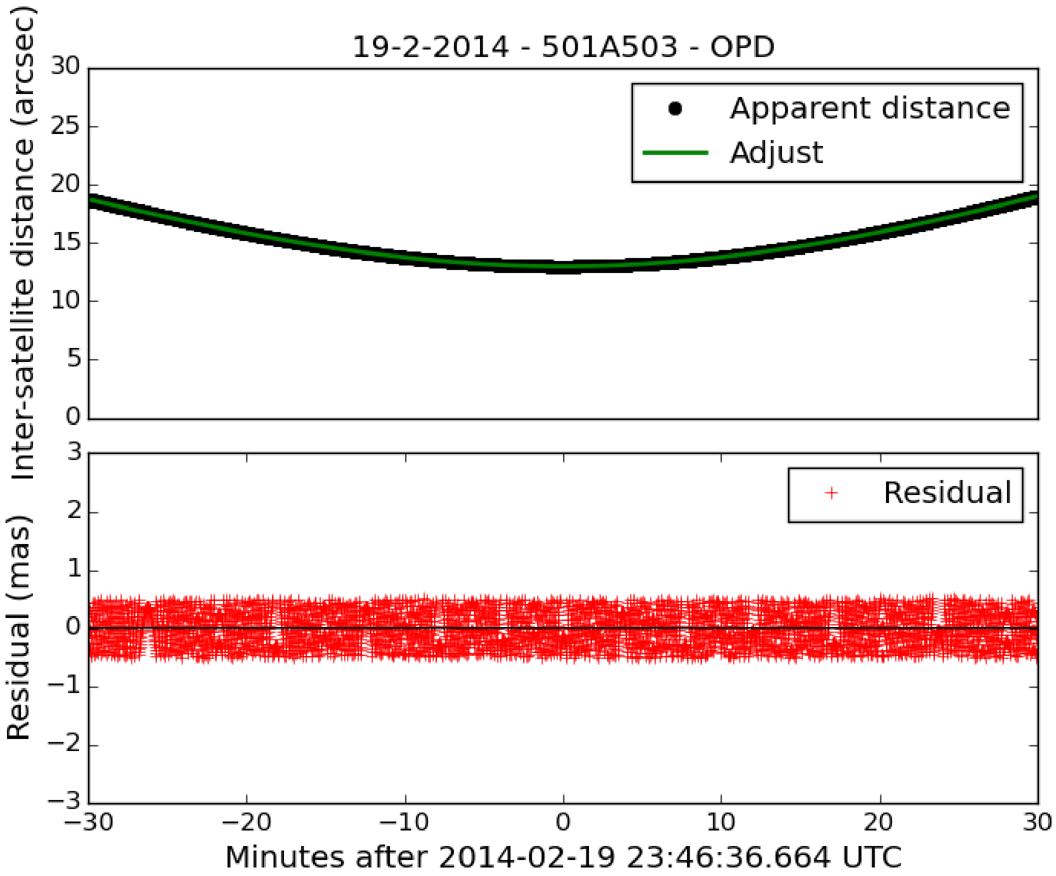

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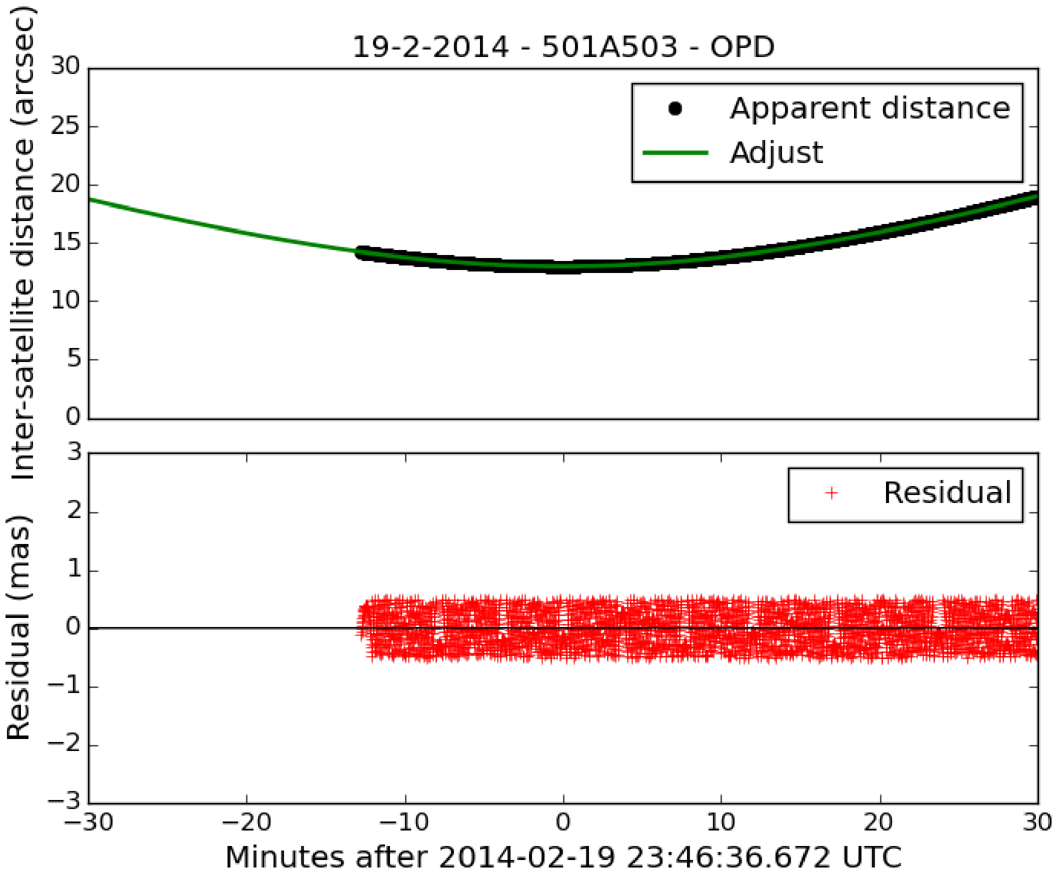

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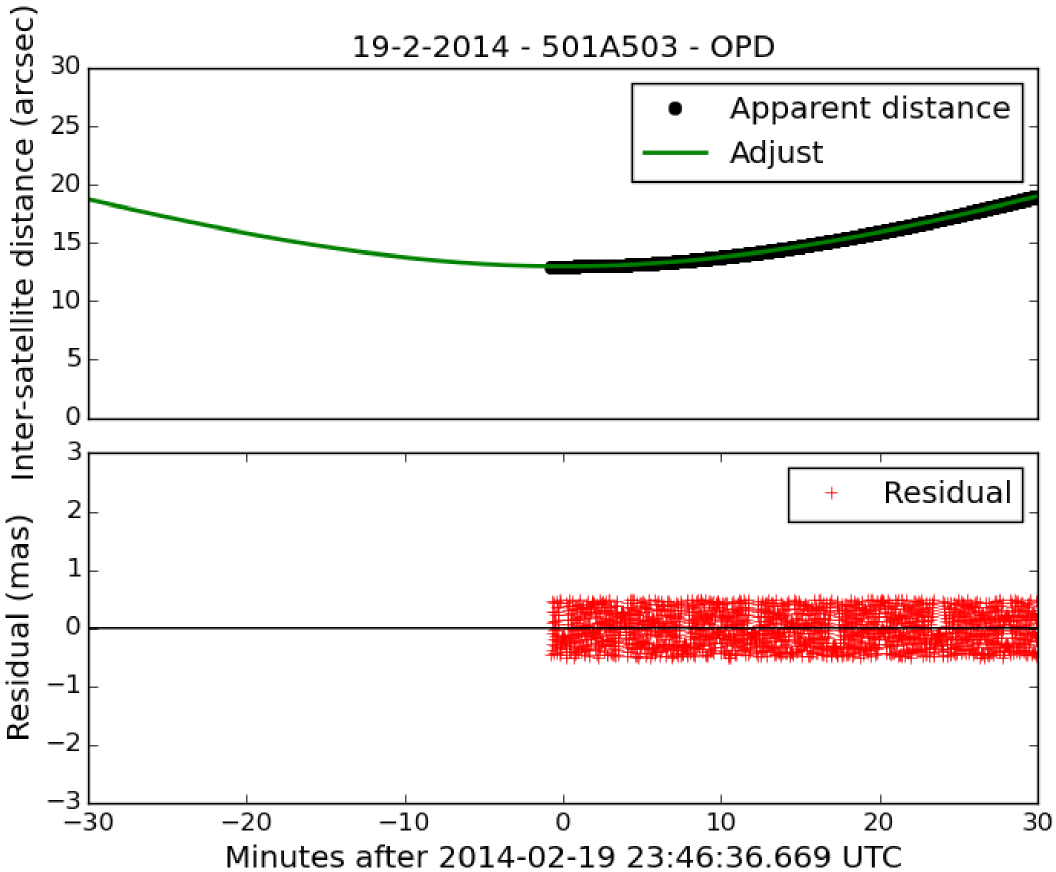

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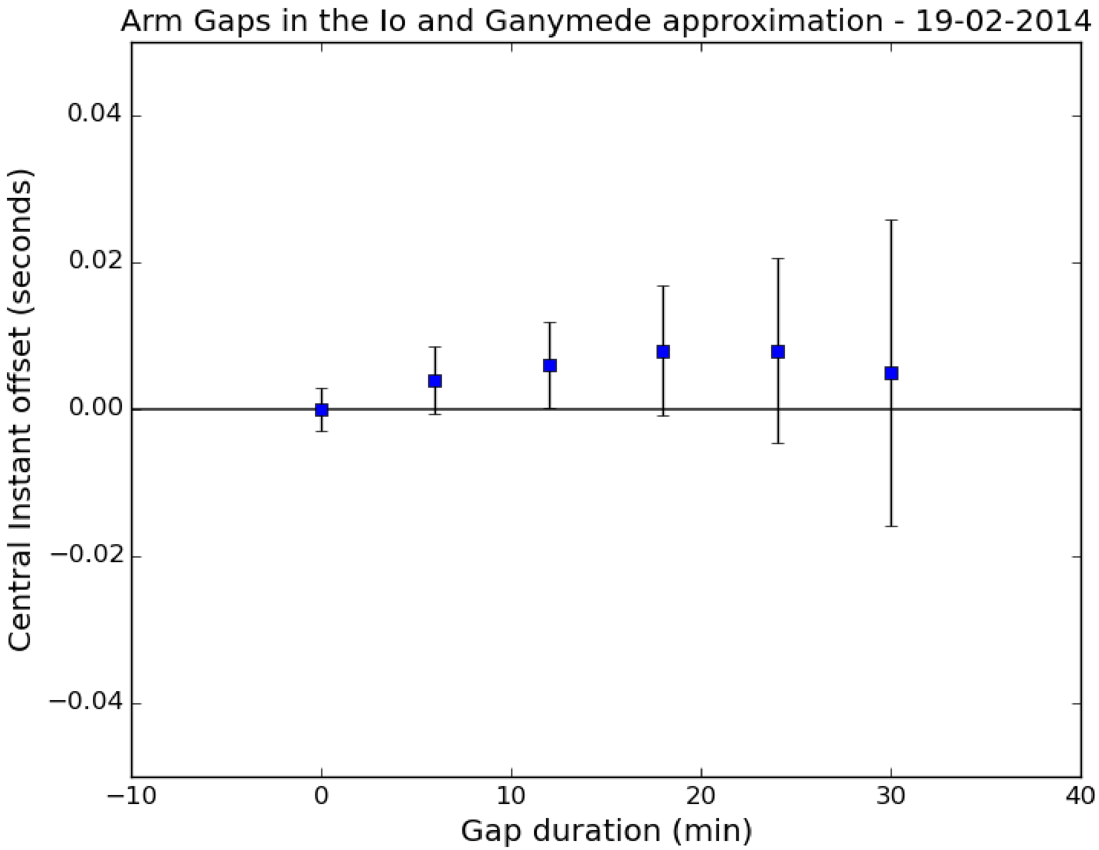

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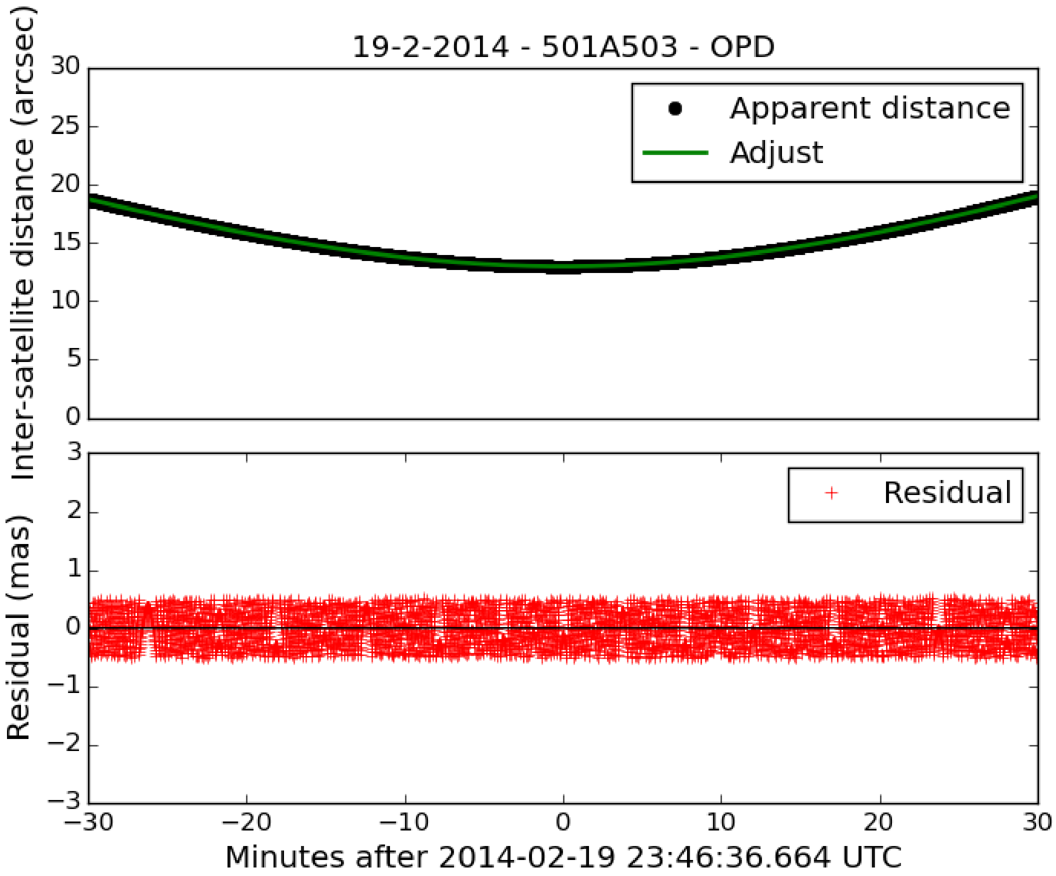

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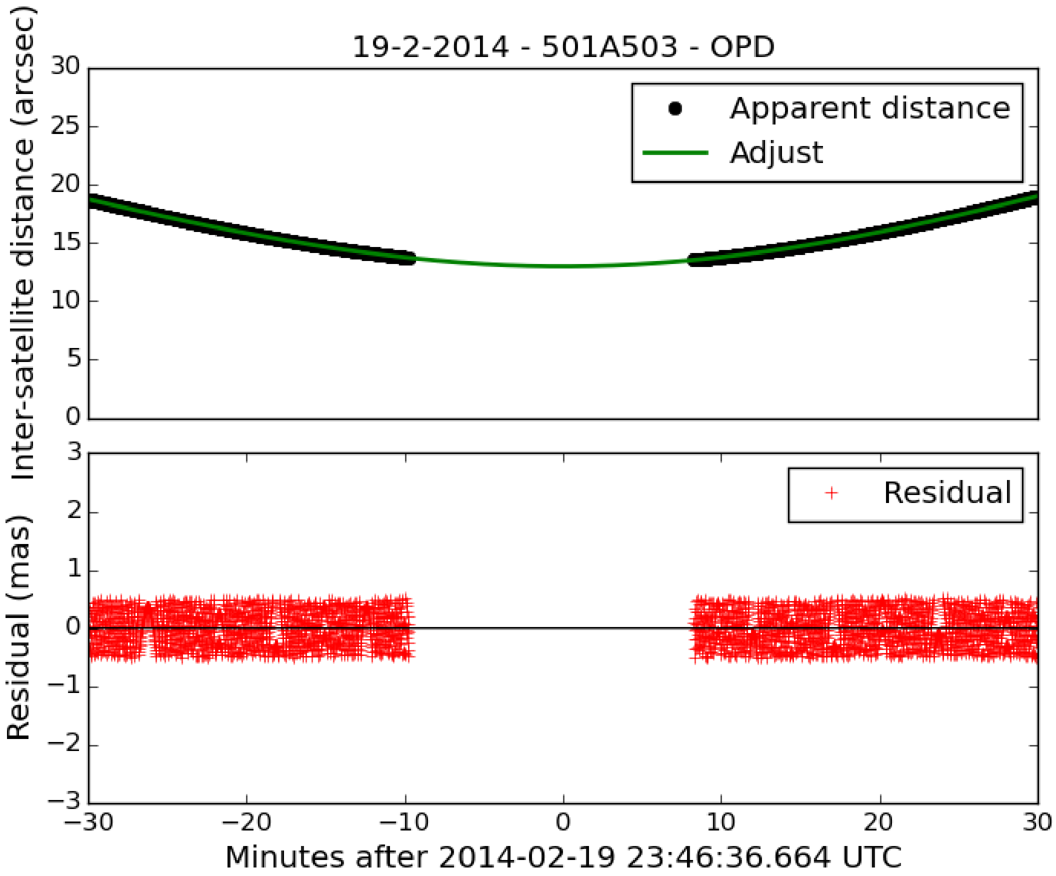

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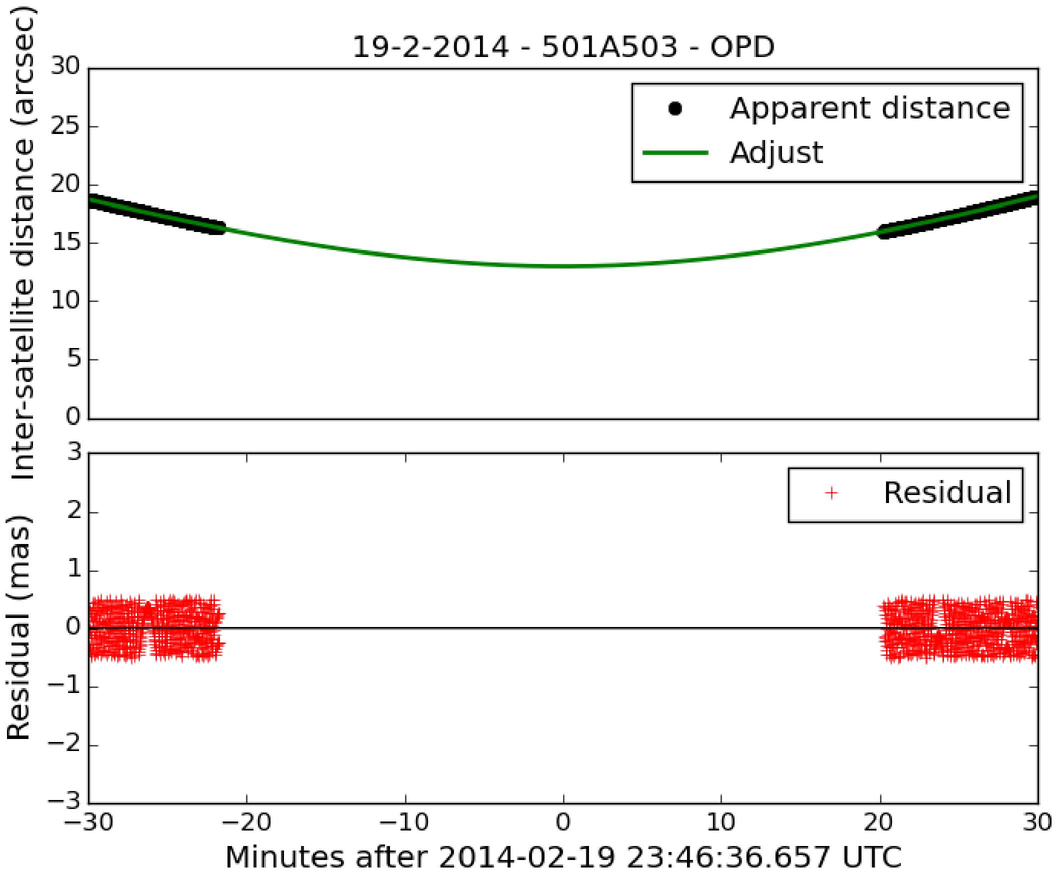

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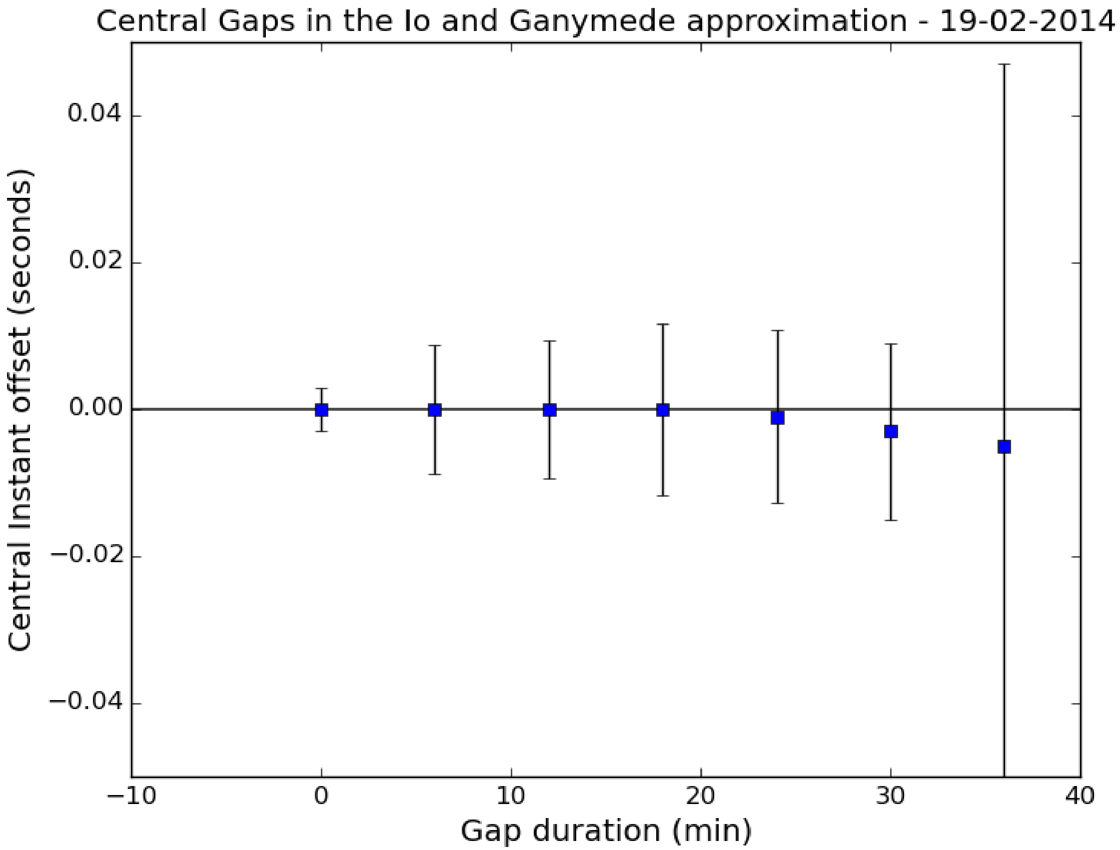

APPENDIX II

- **Mutual approximation campaign in 2016:**

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Date (dd-mm-yy)	Event	Observer	t_0 UTC (hh:mm:ss.ss)	σt_0 (s)	σt_0 (mas)	Δt_0 (s)	Δt_0 (mas)
03-2-2016	502A503	OPD	04:48:01.073	4.201	30.10	-0.151	-01.08
08-2-2016	501A502	FOZ	06:29:43.430	0.574	02.54	+5.529	+24.45
10-2-2016	502A503	OPD	07:34:30.330	2.659	20.73	-21.323	-166.19
15-2-2016	501A502	FOZ	08:39:33.477	1.148	04.80	+3.320	+13.88
24-2-2016	501A503	OPD	01:53:25.510	0.136	00.83	-1.256	-07.68
		FEG	01:53:28.292	3.964	24.68	+1.530	+09.52
		GOA	01:53:28.786	1.357	04.99	+2.046	+07.52
25-2-2016	501A502	GOA	23:55:58.161	2.395	05.31	-2.658	-05.89
18-3-2016	501A502	OPD	06:53:17.034	2.554	06.08	+8.554	+20.36
02-4-2016	501A502	OPD	05:46:03.202	0.460	01.30	-4.184	-11.90
		FOZ	05:46:02.117	1.246	03.56	-5.293	-15.14
		FEG	05:46:00.064	3.777	10.80	-7.320	-20.94
02-4-2016	501A504	OPD	23:24:20.377	0.205	01.11	-9.165	-49.83
		FOZ	23:24:27.450	1.369	07.52	-2.173	-11.94
		FEG	23:24:28.263	3.483	19.14	-1.271	-06.98

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Date (dd-mm-yy)	Event	Observer	t_0 UTC (hh:mm:ss.ss)	σt_0 (s)	σt_0 (mas)	Δt_0 (s)	Δt_0 (mas)
12-4-2016	501A504	OPD	04:35:29.676	8.862	50.83	+4.337	+24.87
		FOZ	04:35:36.105	1.099	06.40	+10.696	+62.27
		FEG	04:35:34.117	2.491	14.50	+8.782	+51.12
12-4-2016	501A502	FOZ	04:45:54.017	10.109	10.50	+23.121	+24.02
12-4-2016	502A504	FOZ	05:01:34.581	1.876	11.17	-0.915	-05.45
		FEG	05:01:41.134	4.232	25.73	+5.711	+34.01
12-4-2016	501A502	OPD	21:17:16.176	0.840	02.87	-8.253	-28.20
19-4-2016	501A502	OPD	23:35:15.347	1.013	03.84	-1.088	-04.13
		FOZ	23:35:24.192	2.154	08.18	+7.715	+29.30
		GOA	23:35:13.320	2.167	08.23	-3.092	-11.74
		FBR	23:35:13.581	3.156	11.99	-2.854	-10.84
24-4-2016	501A503	OPD	22:35:12.028	0.489	03.72	-2.573	-19.57
		FBR	22:35:13.121	2.574	19.57	-1.478	-11.24
29-4-2016	501A503	OPD	00:32:28.141	2.442	16.21	-2.411	-16.01
		FBR	00:32:28.652	4.220	28.05	-1.903	-12.65

APPENDIX II

- **Mutual approximation campaign in 2016:**

Date (dd-mm-yy)	Event	Observer	t_0 UTC (hh:mm:ss.ss)	σt_0 (s)	σt_0 (mas)	Δt_0 (s)	Δt_0 (mas)
02-5-2016	501A503	OPD	01:08:50.287	1.460	10.39	-0.578	-04.14
		FOZ	01:08:55.718	2.331	16.70	+4.797	+34.37
		FEG	01:08:52.150	1.777	12.73	+1.283	+09.19
		FBR	01:08:52.778	4.485	32.13	+1.904	+13.64
03-5-2016	502A503	OPD	01:04:55.430	1.256	04.25	+4.485	+15.16
		FBR	01:04:55.505	1.890	06.39	+4.555	+15.40
06-5-2016	502A504	OPD	00:59:06.787	6.531	31.57	+2.304	+11.14
06-5-2016	501A503	OPD	03:10:52.883	1.097	07.58	+6.695	+46.25
19-5-2016	502A503	FOZ	22:52:36.911	1.030	06.62	+2.642	+16.98

APPENDIX II

22 mutual approximations observed between February and May of 2016 (39 distances curves).

- 50% of the observations with precisions bellow 10 mas. (73% bellow 20 mas).