Interior properties of the inner Saturnian moons from space astrometry data

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in collaboration with:

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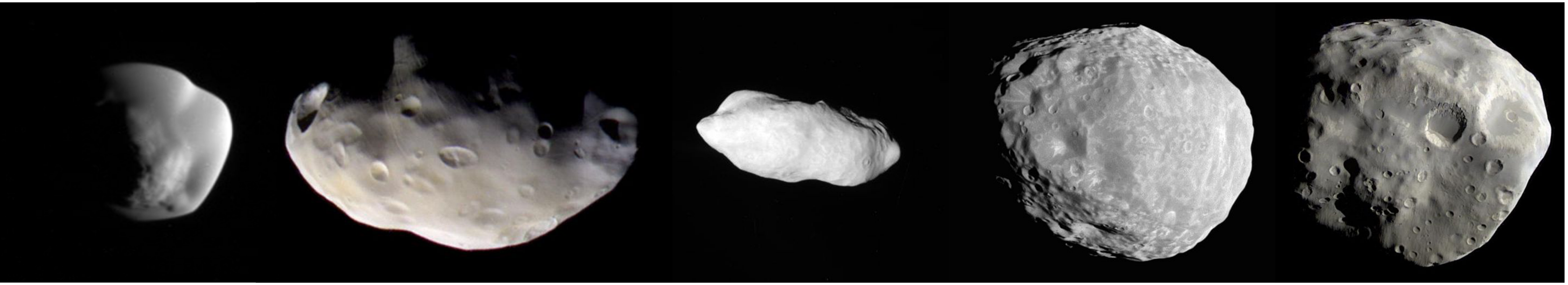

DDA meeting - 19th April 2018

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To improve their orbits

To infer their interior properties

To stud their interaction with the rings

To help understand the dynamical signature
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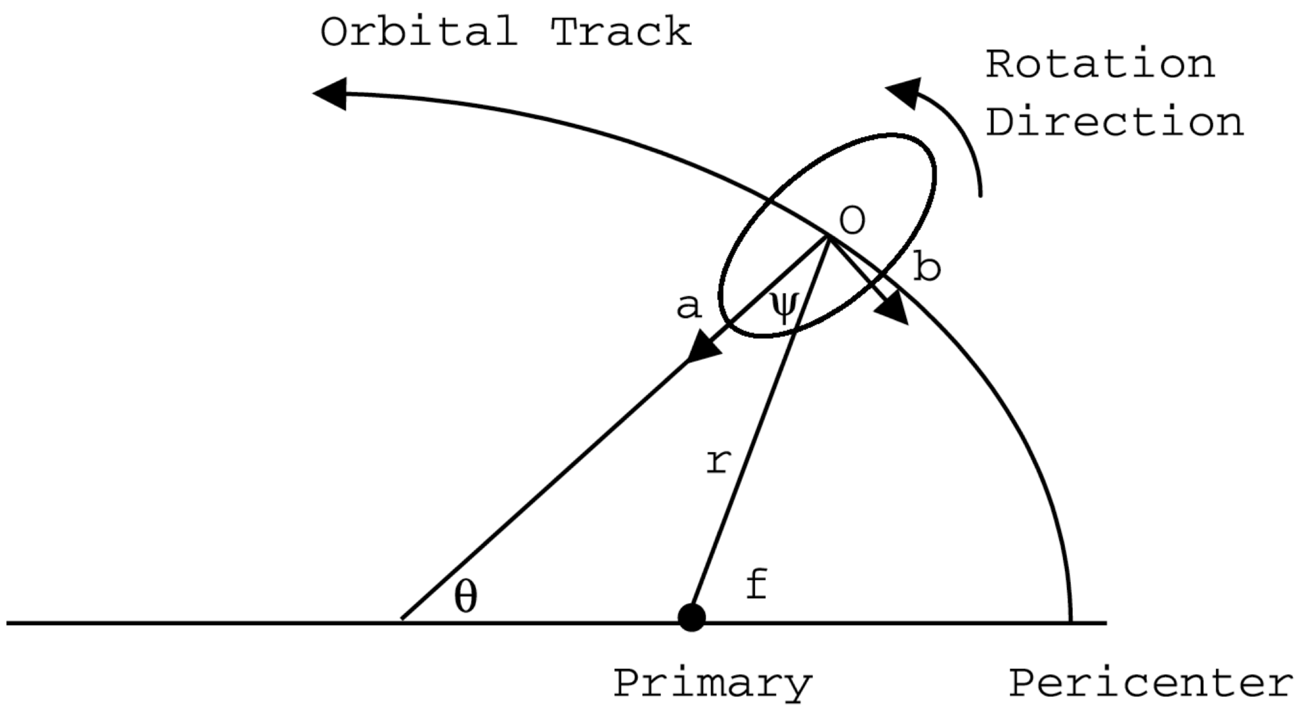
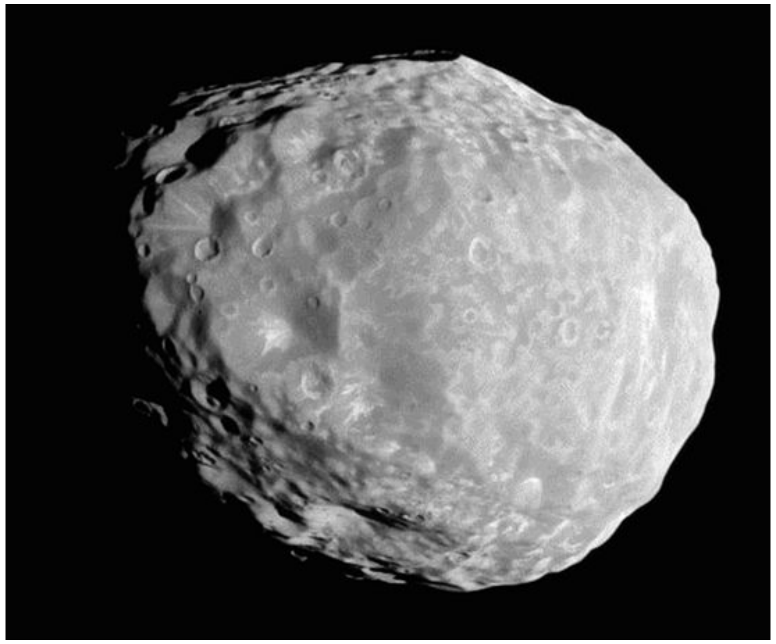
Interior properties: more than just the mass?





The amplitude $\boldsymbol{\varphi}$ of the physical libration of a spin-orbit moon can be related to the moments of inertia by:

$\boldsymbol{\varphi}$ = 2e/(1-1/3$\boldsymbol{\gamma}$) with $\boldsymbol{\gamma}$=(B-A)/C (Comstock & Bills 2003)

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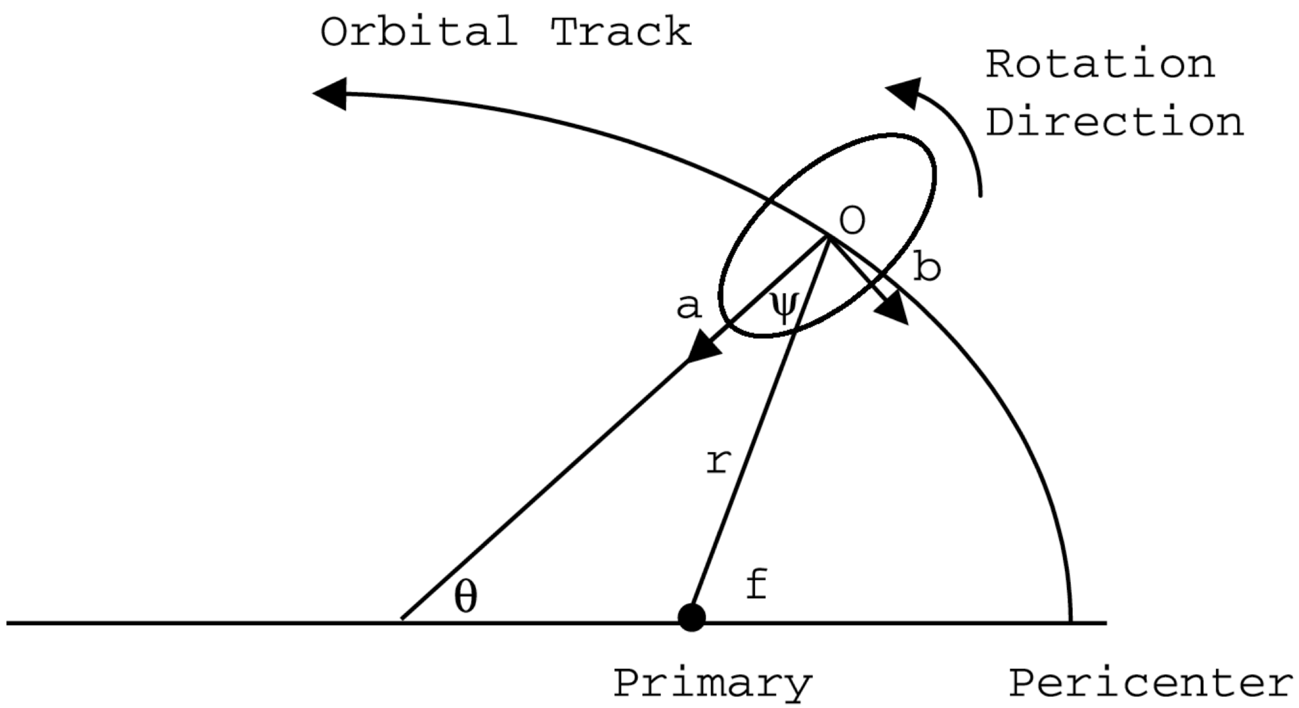

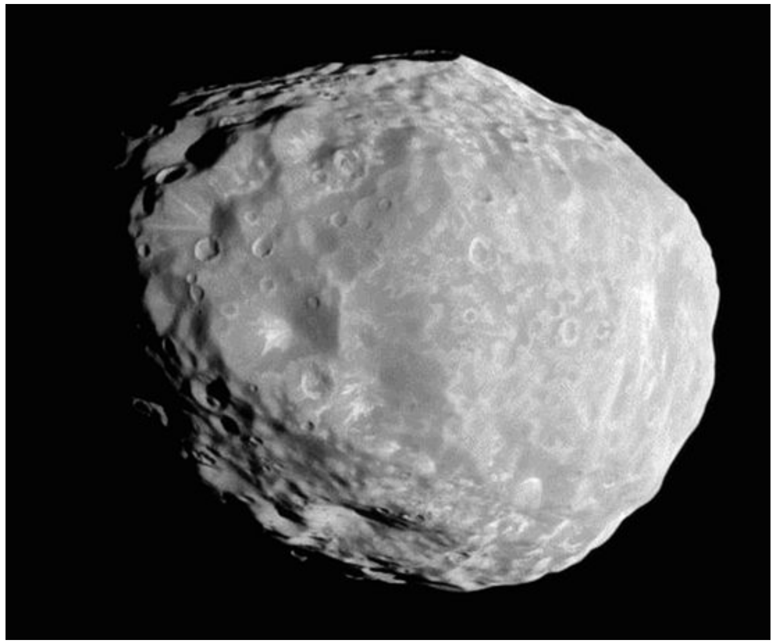

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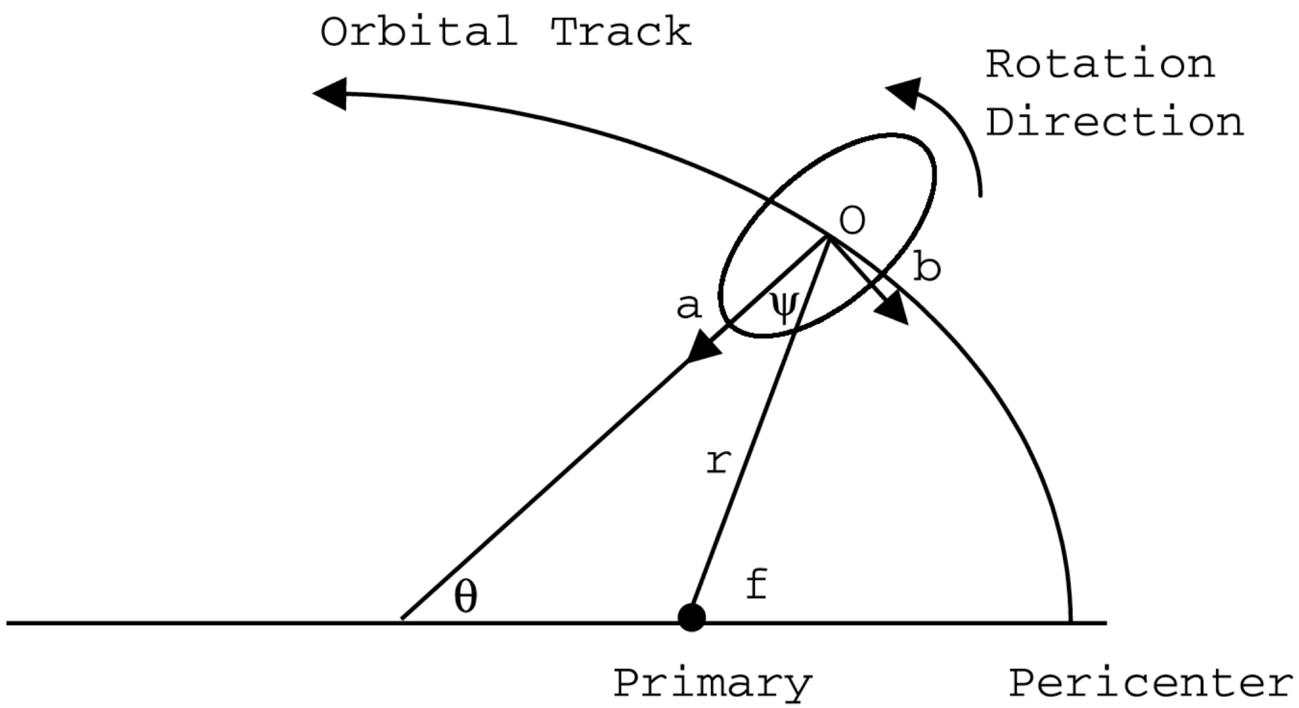
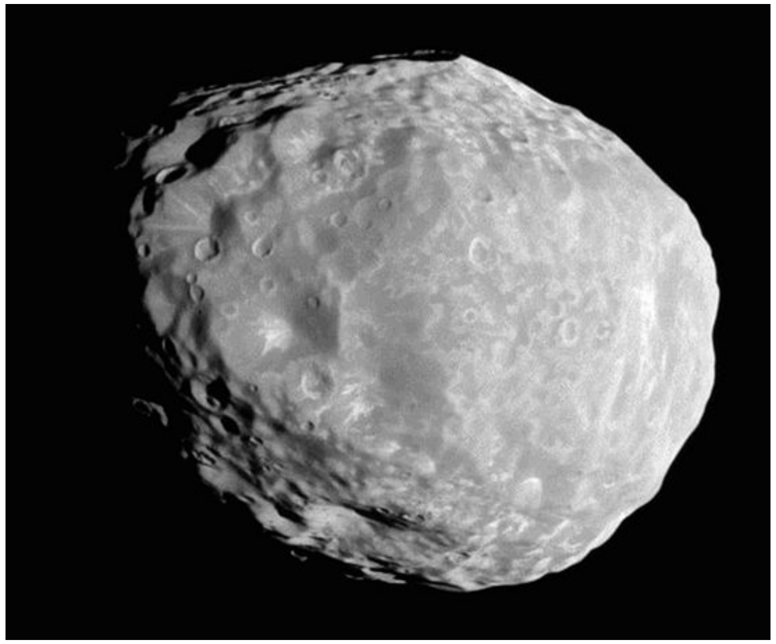
Rotation monitoring: Tiscareno et al. (2009) quantified the physical libration of Epimetheus to 5.9 ± 1.2°, but could not reach conclusive result for Janus.

Interior properties: more than just the mass?





The amplitude $\boldsymbol{\varphi}$ of the physical libration of a spin-orbit moon can be related to the moments of inertia by:

$$\boldsymbol{\varphi} = 2e/(1-1/3\boldsymbol{\gamma}) \text{ with } \boldsymbol{\gamma}=(B-A)/C \qquad \text{(Comstock \& Bills 2003)}$$

Orbit monitoring: Fitting the physical librations is challenging but feasible, as was predicted and recently done for Phobos (Borderies & Yoder 1990, Jacobson 2010)

Such perturbation has a very specific dynamical pattern barely mistaken with other perturbations (Borderies & Yoder 1990 , Jacobson 2010):

$$\Delta\varpi = \frac{3}{2}\left(\frac{R}{a}\right)^2\left[J_2 - 2c_{22}\left(5 + \frac{4\mathcal{A}}{e}\right)\right]nt + \frac{3}{2}\left(\frac{R}{a}\right)^2\frac{(J_2 + 6c_{22})}{e}\sin(M)$$

Interior properties: more than just the mass?

Borderies and Yoder (1990):

” *This term could provide a more accurate estimate of the* [Phobos’] *libration than direct observation of the figure oscillation from ranging to a lander if all effects acting on apse and node are accounted for and if the lander survives longer than about a year*.”

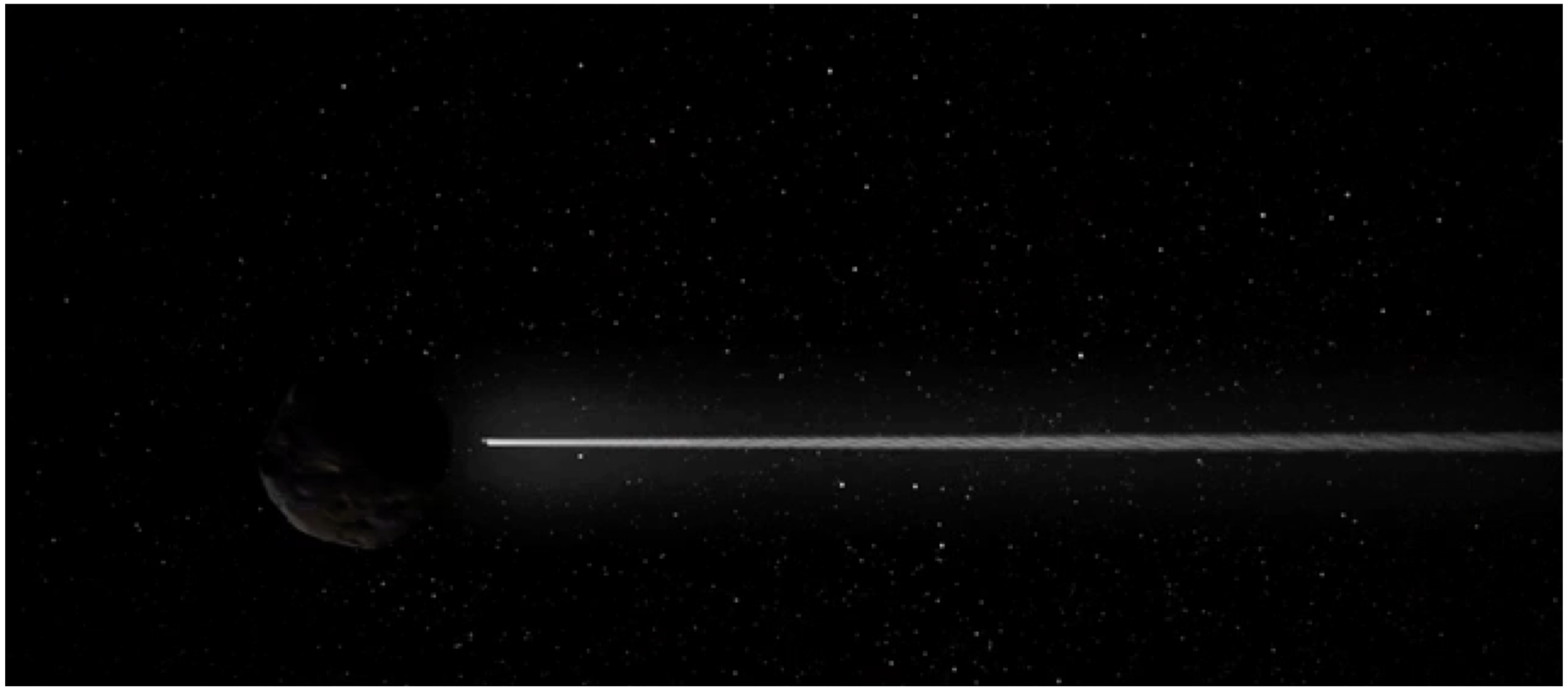
How?

1- dynamical model (Peters 1981, Jacobson 1998, Lainey et al. 2004, Cooper et al. 2015…)

2- astrometric data (basically: HST, ISS-Cassini)

3- fitting the model to the observations (sophisticated weight procedure)

In this work, we focused on the motion of Atlas, Pandora, Prometheus, Janus and Epimetheus, only.



How?

Equations of motion:

$$
\begin{aligned}
\ddot{\mathbf{r}}_i \quad = \quad & -G(m_0 + m_i)\left(\frac{\mathbf{r}_i}{r_i^3} - \nabla_i U_{\tilde{i}\hat{0}} + \nabla_0 U_{\bar{0}\hat{i}}\right) + \sum_{j=1, j\neq i}^{N} G m_j \left(\frac{\mathbf{r}_j - \mathbf{r}_i}{r_{ij}^3} - \frac{\mathbf{r}_j}{r_j^3} + \nabla_j U_{\tilde{j}\hat{0}} - \nabla_0 U_{\bar{0}\hat{j}} - \nabla_j U_{\tilde{j}\hat{i}} + \nabla_i U_{\bar{i}\hat{j}}\right) \\
& + \frac{(m_0 + m_i)}{m_i m_0}\mathbf{F}^T_{\tilde{i}\hat{0}} - \frac{1}{m_0}\sum_{j=1, j\neq i}^{N} \mathbf{F}^T_{\tilde{j}\hat{0}} + \sum_{j=1, j\neq i}^{N} \frac{\mathbf{F}^T_{ij}}{m_i} + GR \qquad (2)
\end{aligned}
$$

Variational equations:

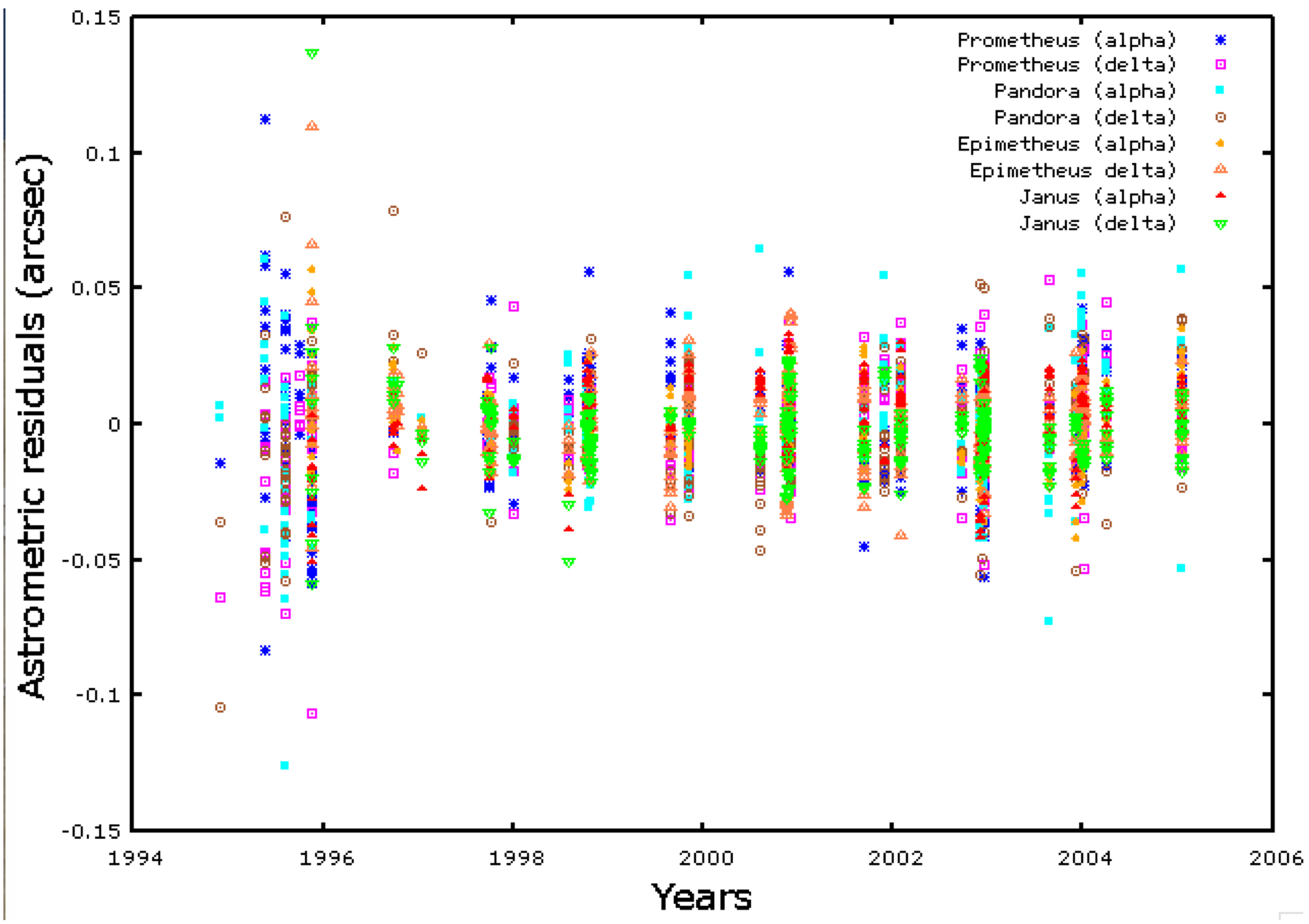
$$
\frac{\partial}{\partial c_l}\left(\frac{d^2\mathbf{r}_i}{dt^2}\right) = \frac{1}{m_i}\left[\sum_j \left(\frac{\partial \mathbf{F}_i}{\partial \mathbf{r}_j}\frac{\partial \mathbf{r}_j}{\partial c_l} + \frac{\partial \mathbf{F}_i}{\partial \dot{\mathbf{r}}_j}\frac{\partial \dot{\mathbf{r}}_j}{\partial c_l}\right) + \frac{\partial \mathbf{F}_i}{\partial c_l}\right]
$$

Modeling:

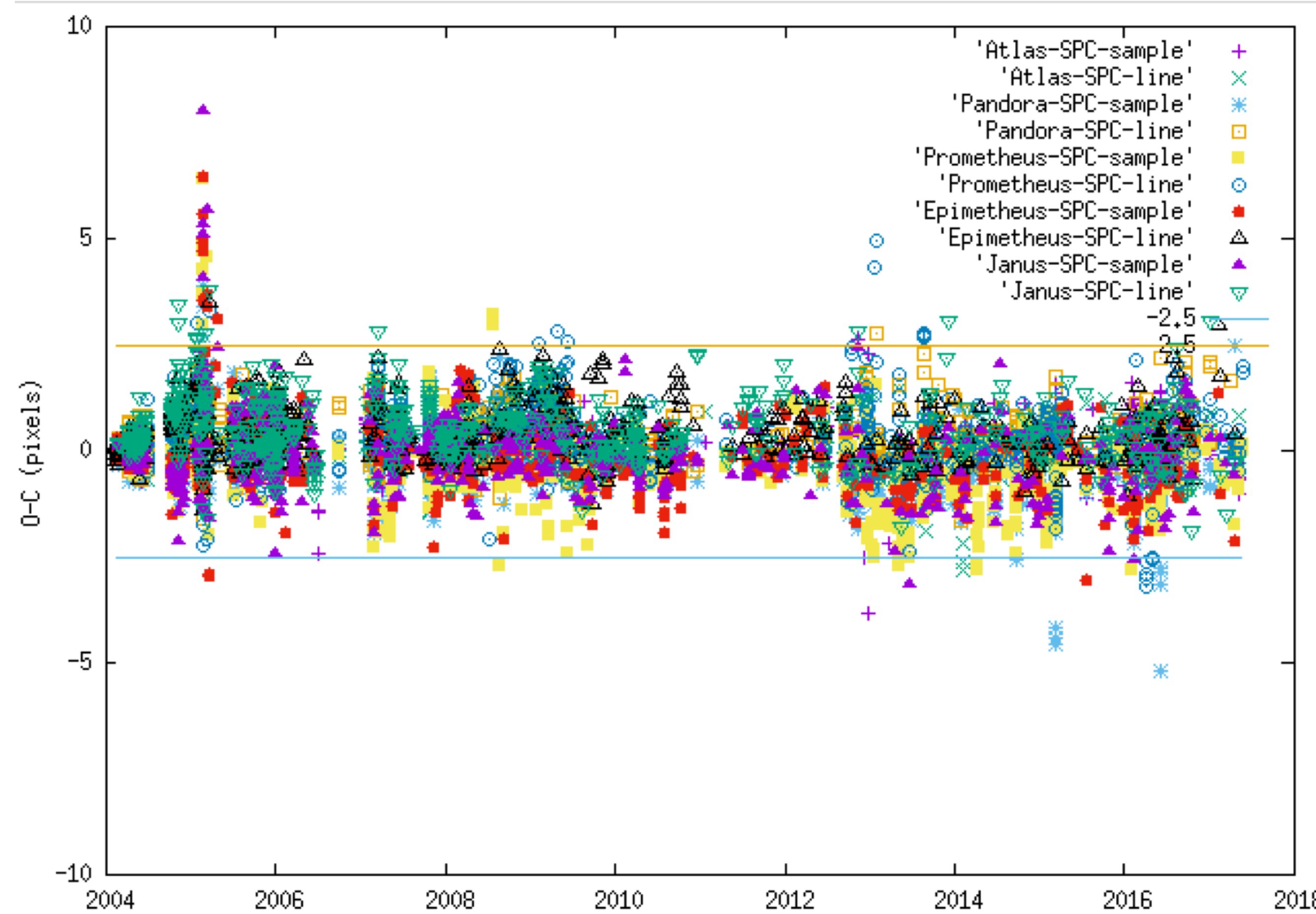
- 5 inner moons
- 8 main moons (NOE/JPL)
- Sun and Jupiter (DE430)
- Saturn's J_2, J_4, J_6, precession, nutations (SPICE kernel sat382)
- Tides (k_2 only)

Post-fit residuals

Fitting the initial conditions, the masses of the five inner moons the mass, polar orientation, precession and J_2, J_4, J_6 of Saturn:



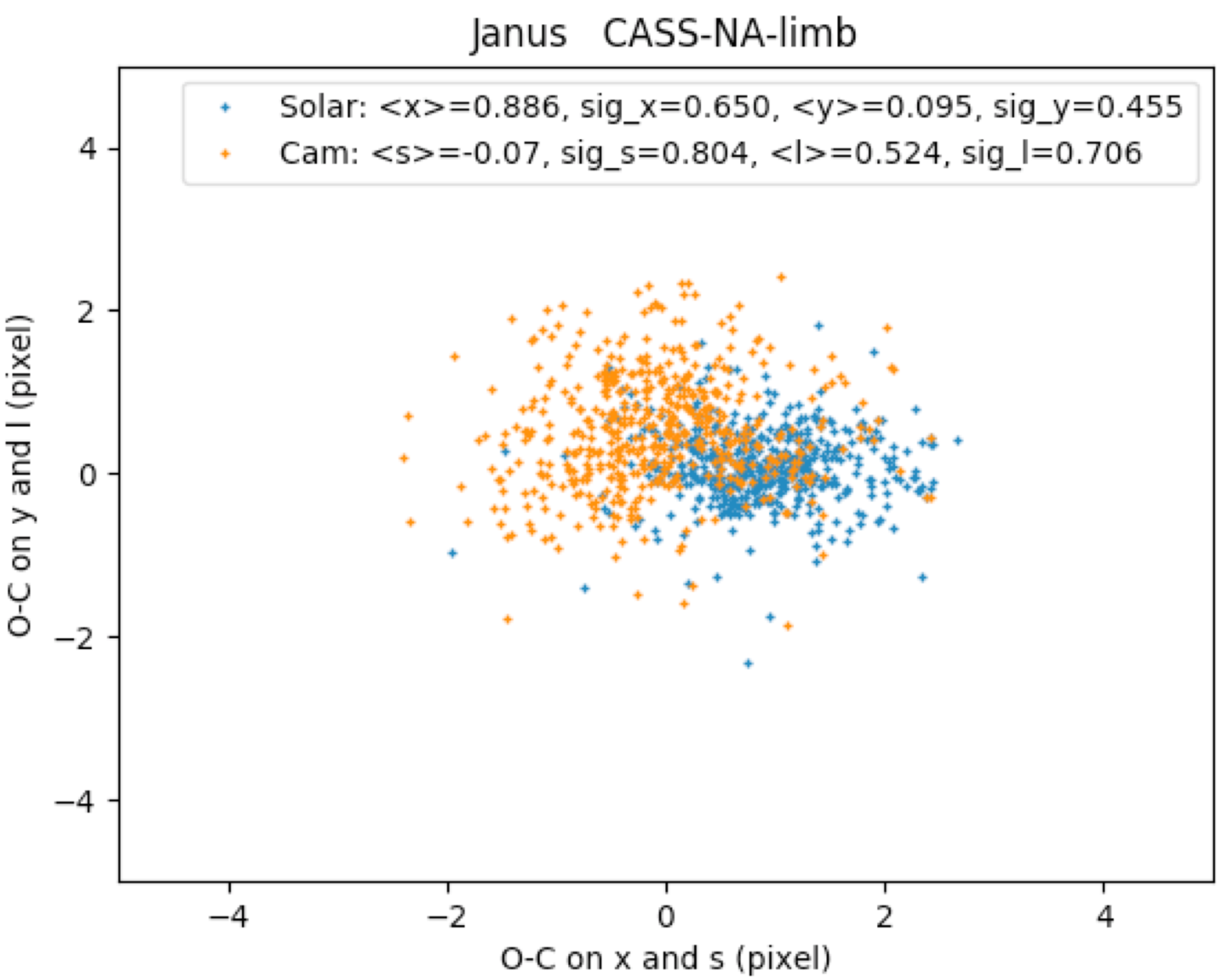
HST

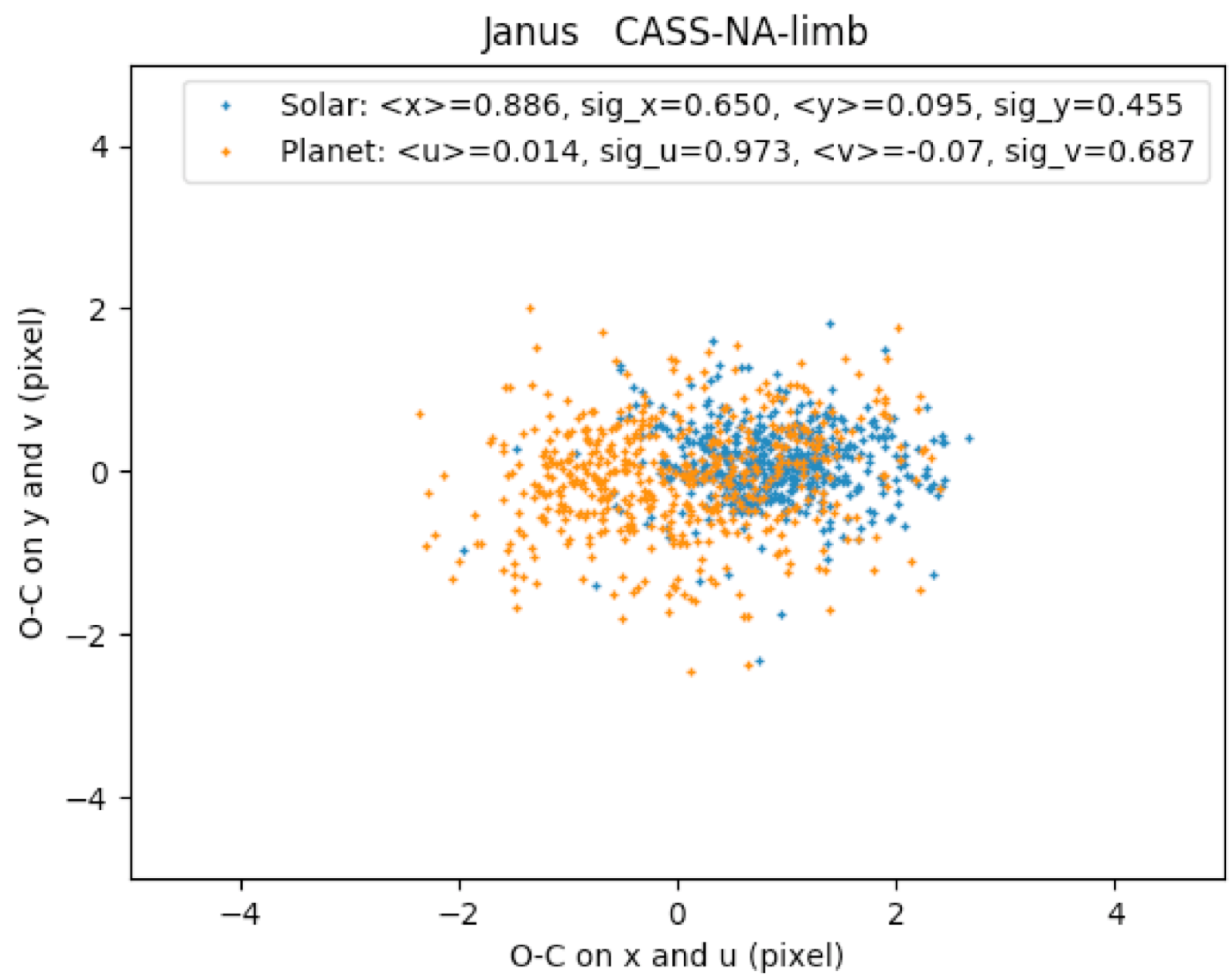


Cassini

But Cassini data are known for a possibly significant bias along Solar direction…

Biais on Janus limb fit

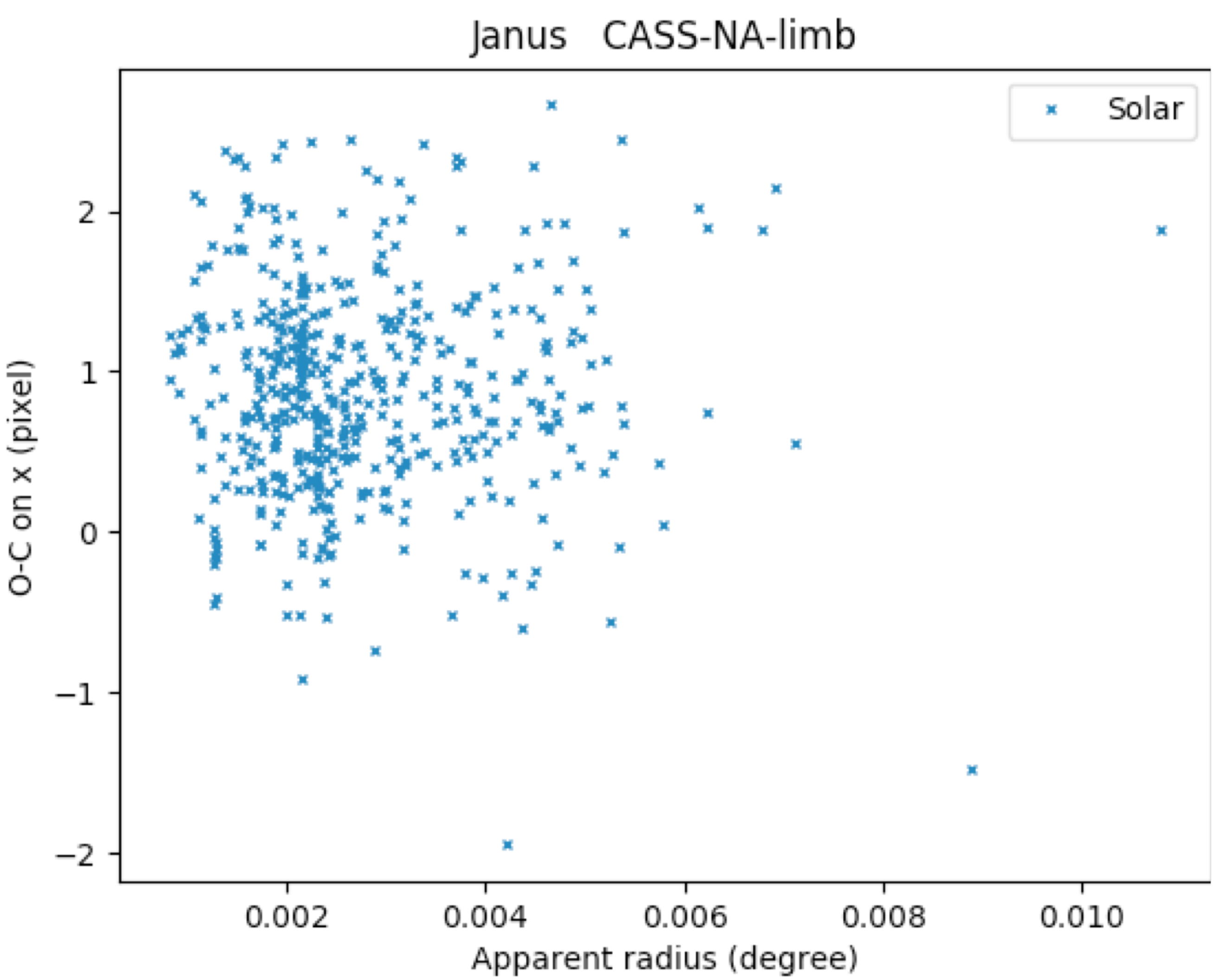


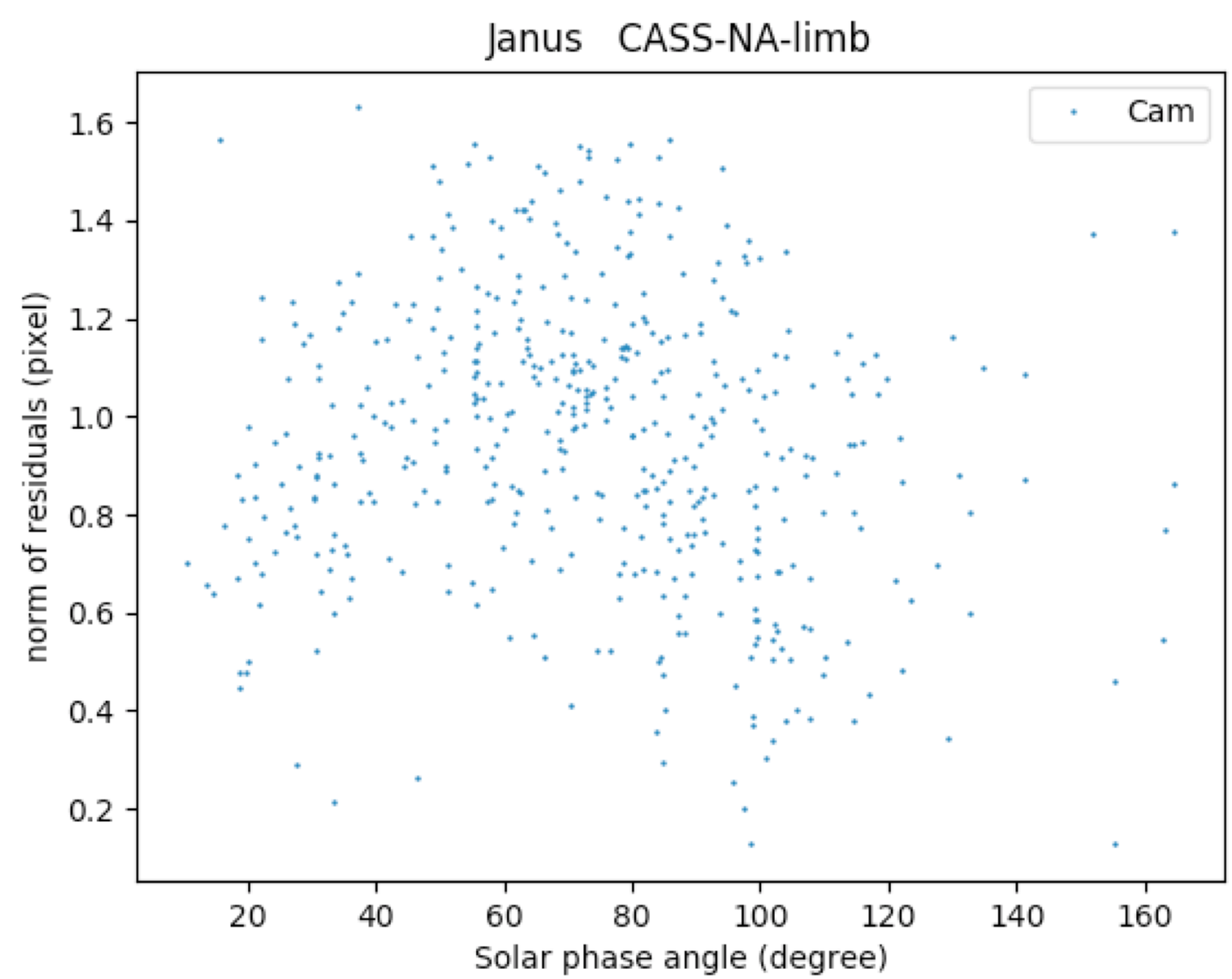


- There is a clear biais (0.9 pixel!) along the Solar direction
- The bias is NOT related to a COF/COM shift

NB: same conclusion for the other inner moons…

Biais on Janus limb fit





No obvious relation between residuals and apparent radius (left) and Solar phase (right)

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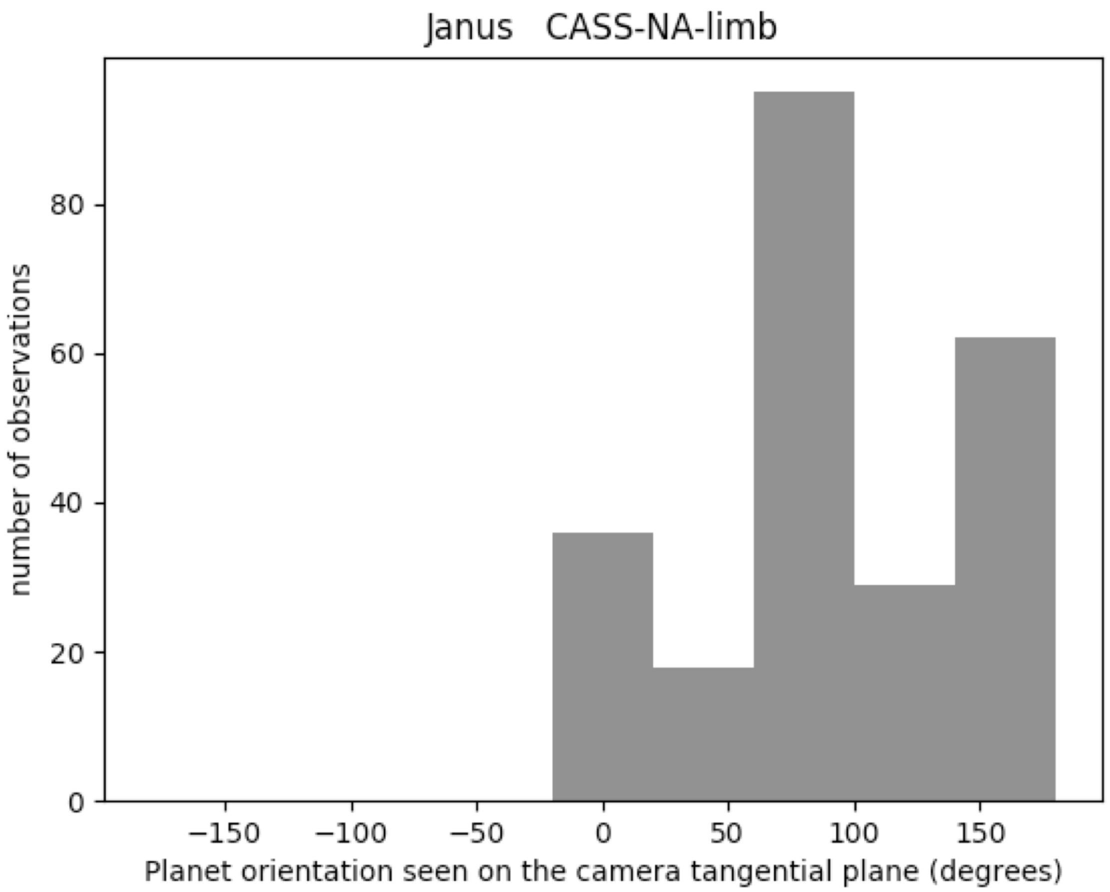
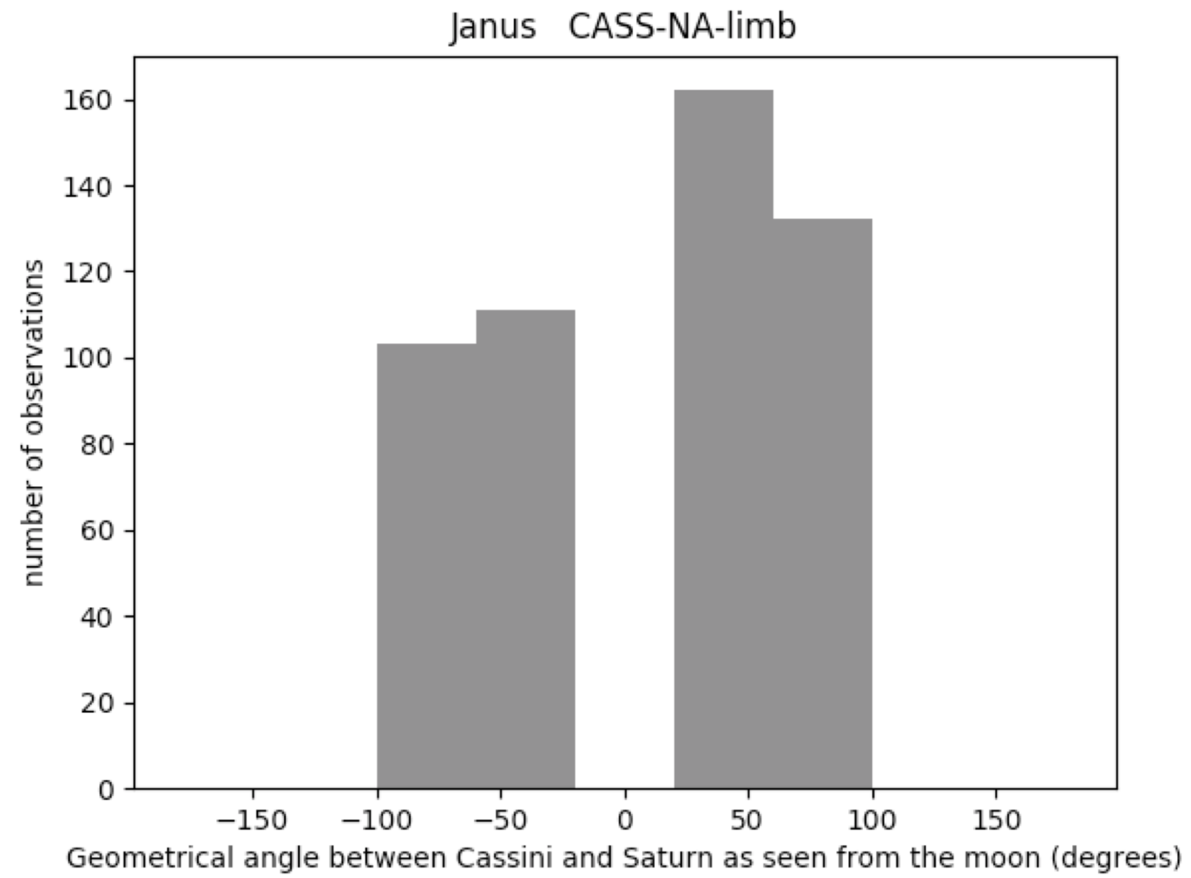
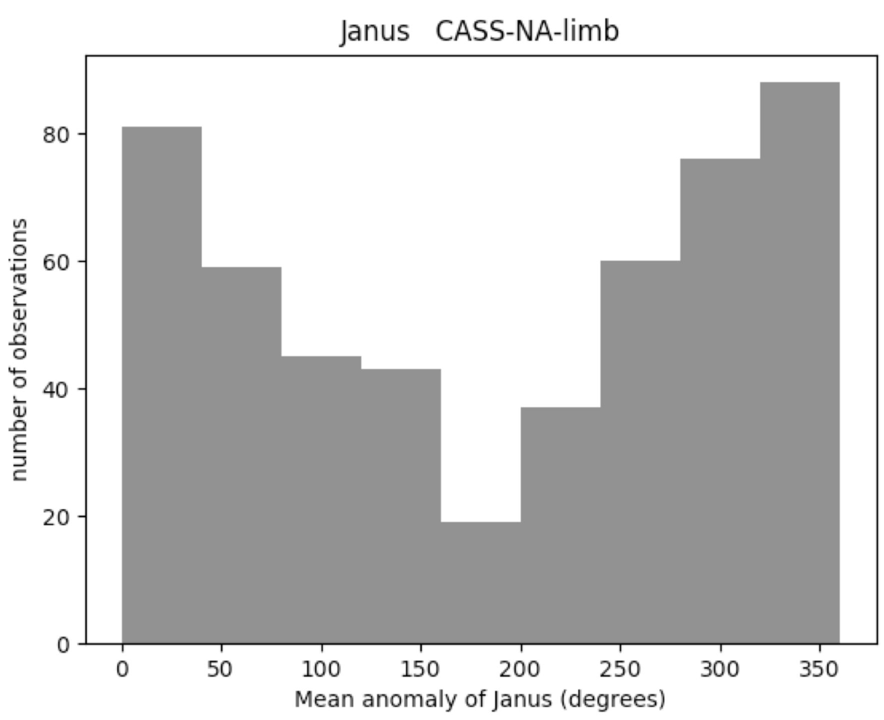
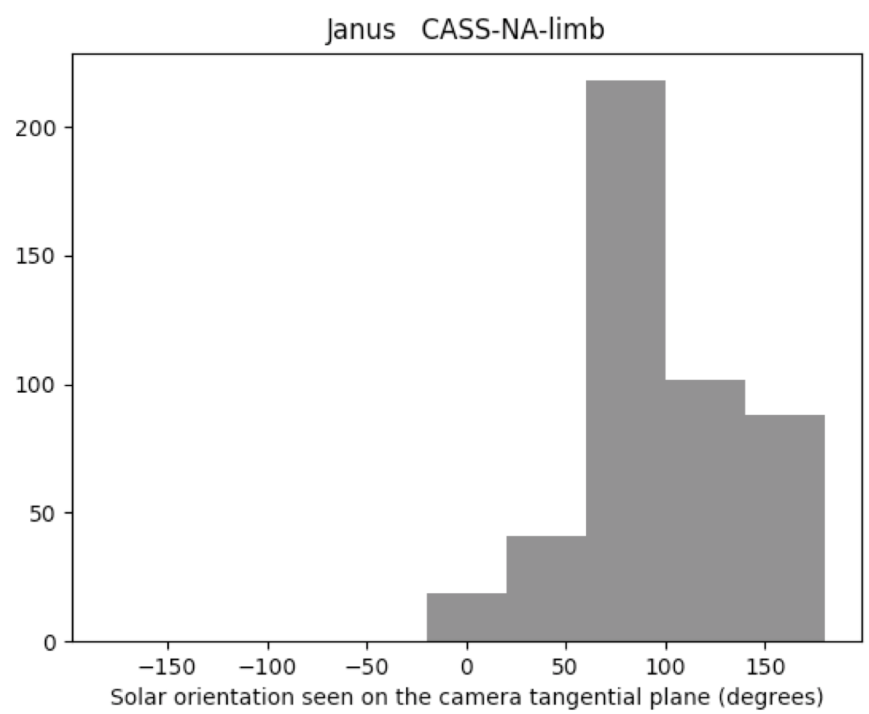
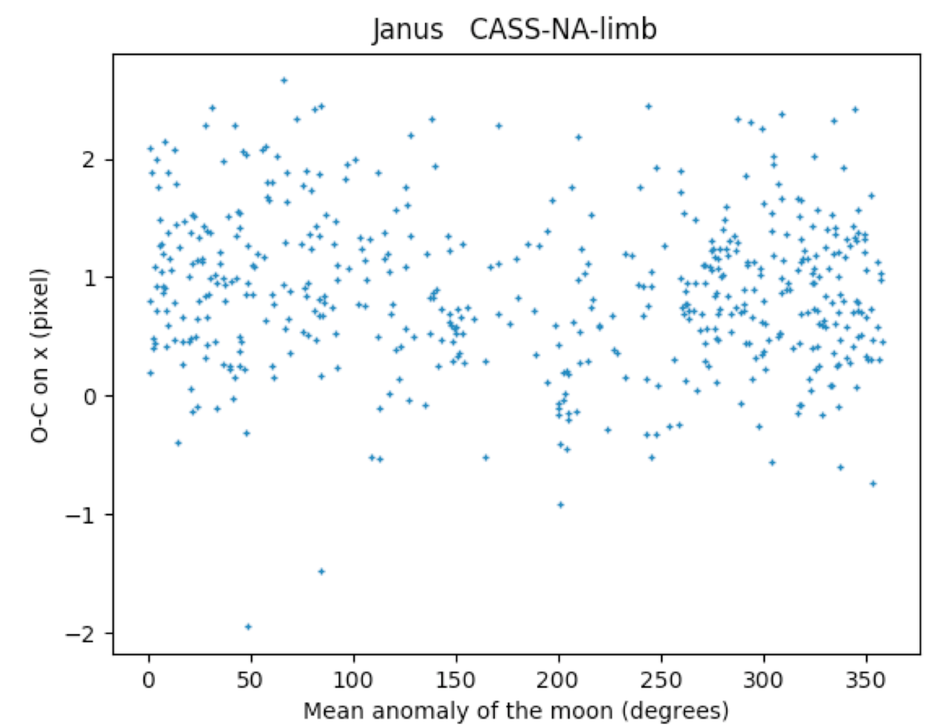




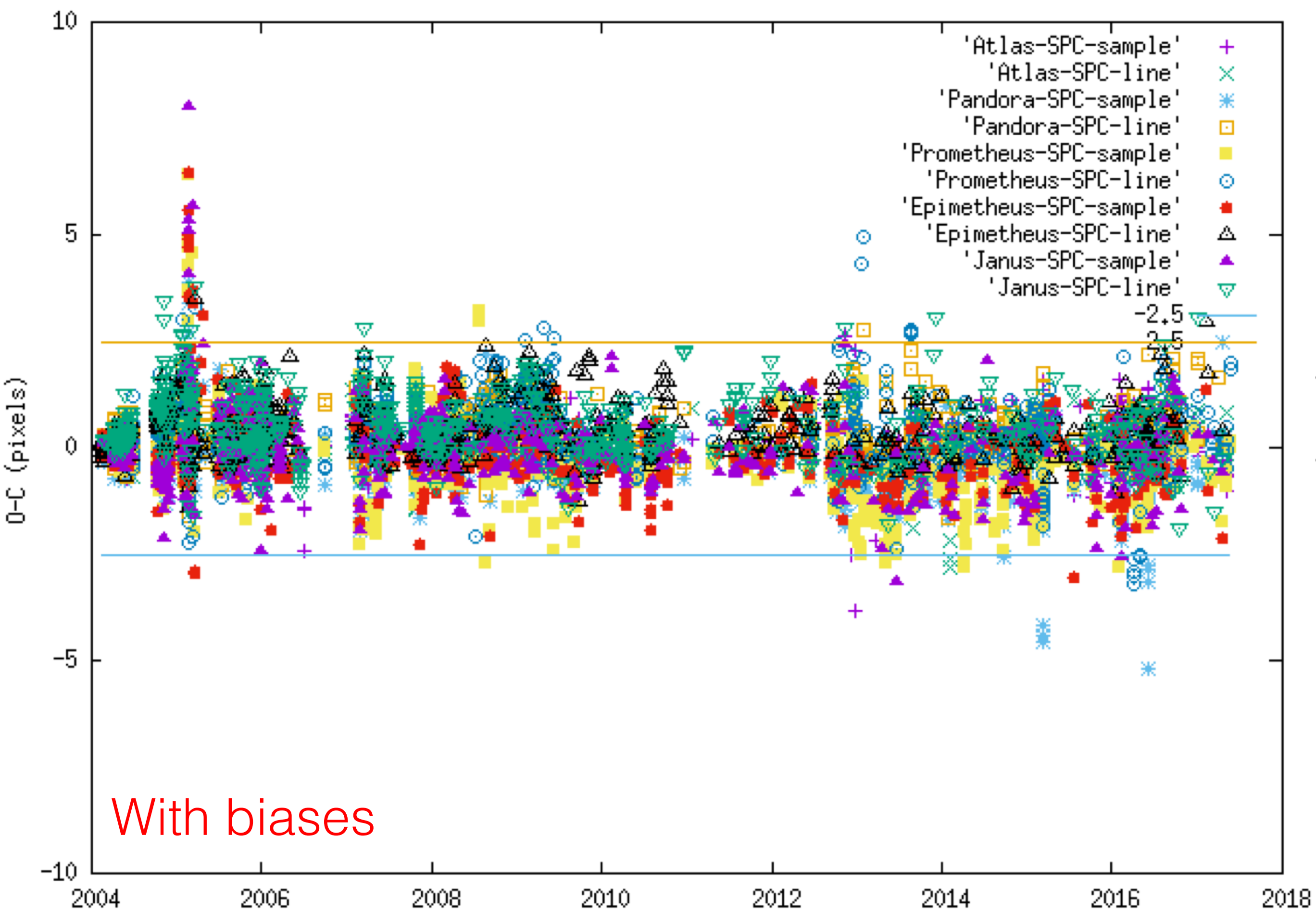


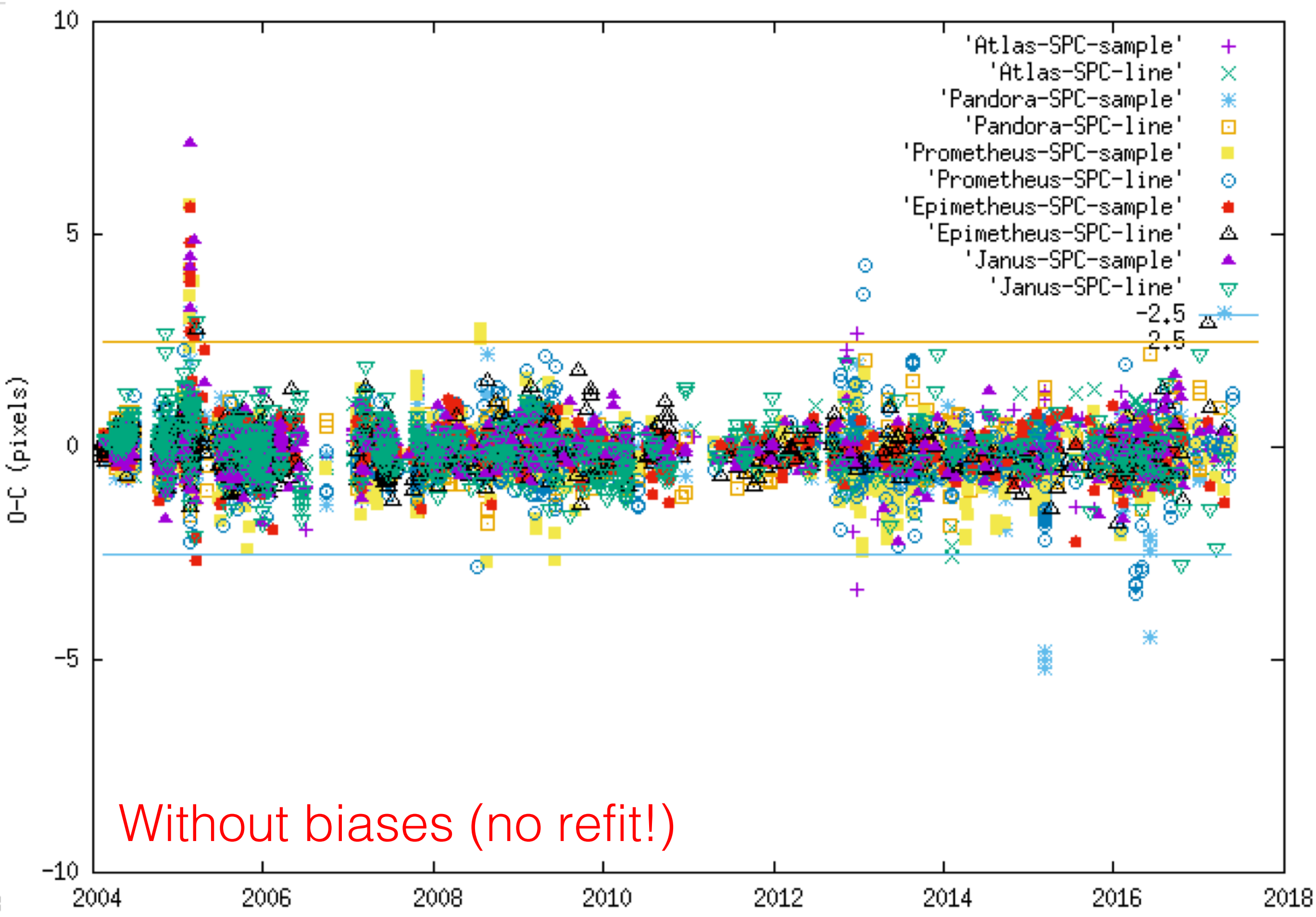




Biais on inner moons limb fit

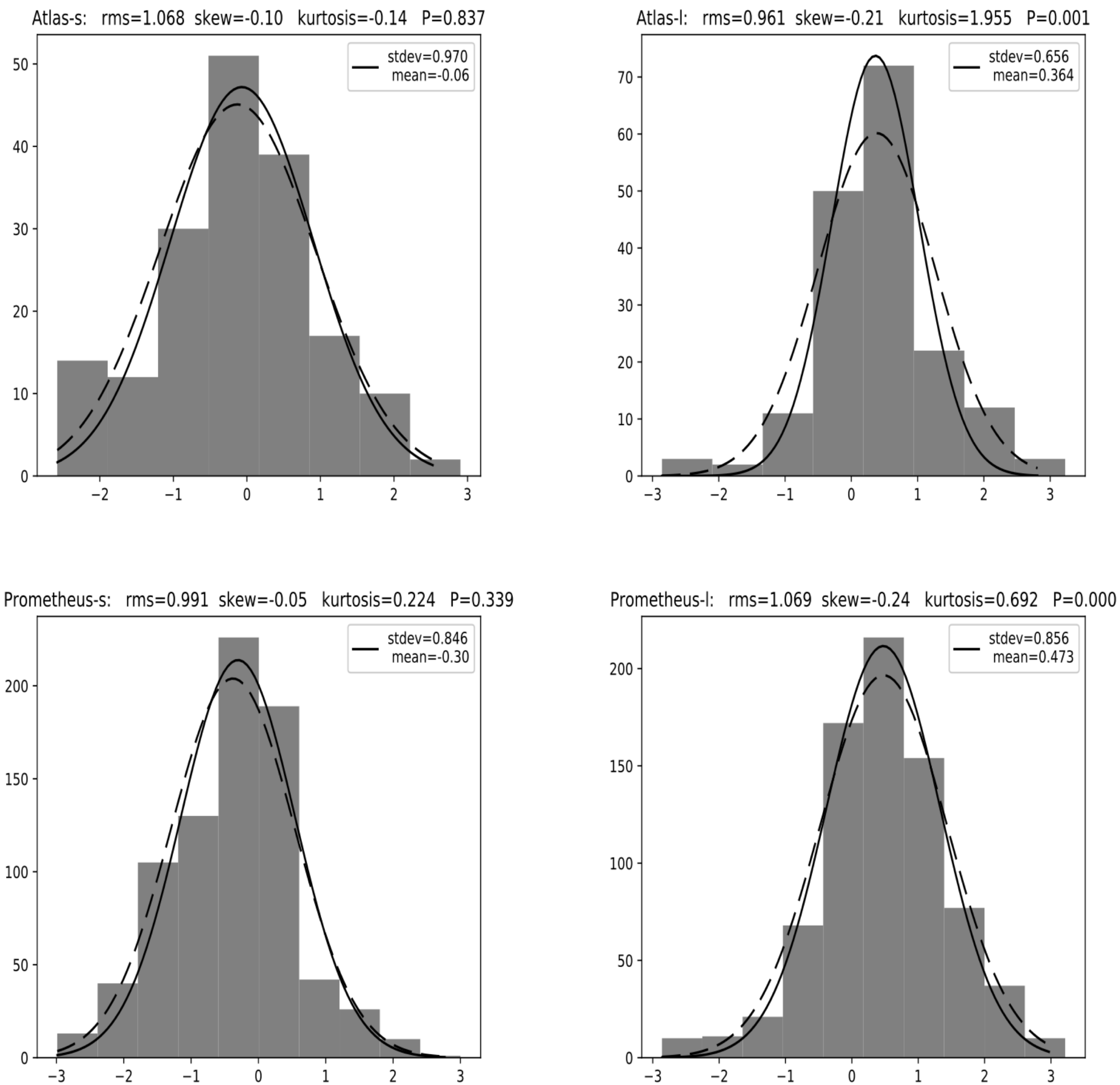
Moon	Bias X (pixel)
Janus	0.89
Epimetheus	0.81
Pandora	0.70
Prometheus	0.72
Atlas	0.49





Now how far can we be confident in the error bars?

After applying a moon/coordinate rescale on the sigma provided in the .psf files!



Statistics analysis of the residuals

Kurtosis
Skewness
Pearsons' test

Now looks reasonably Gaussian

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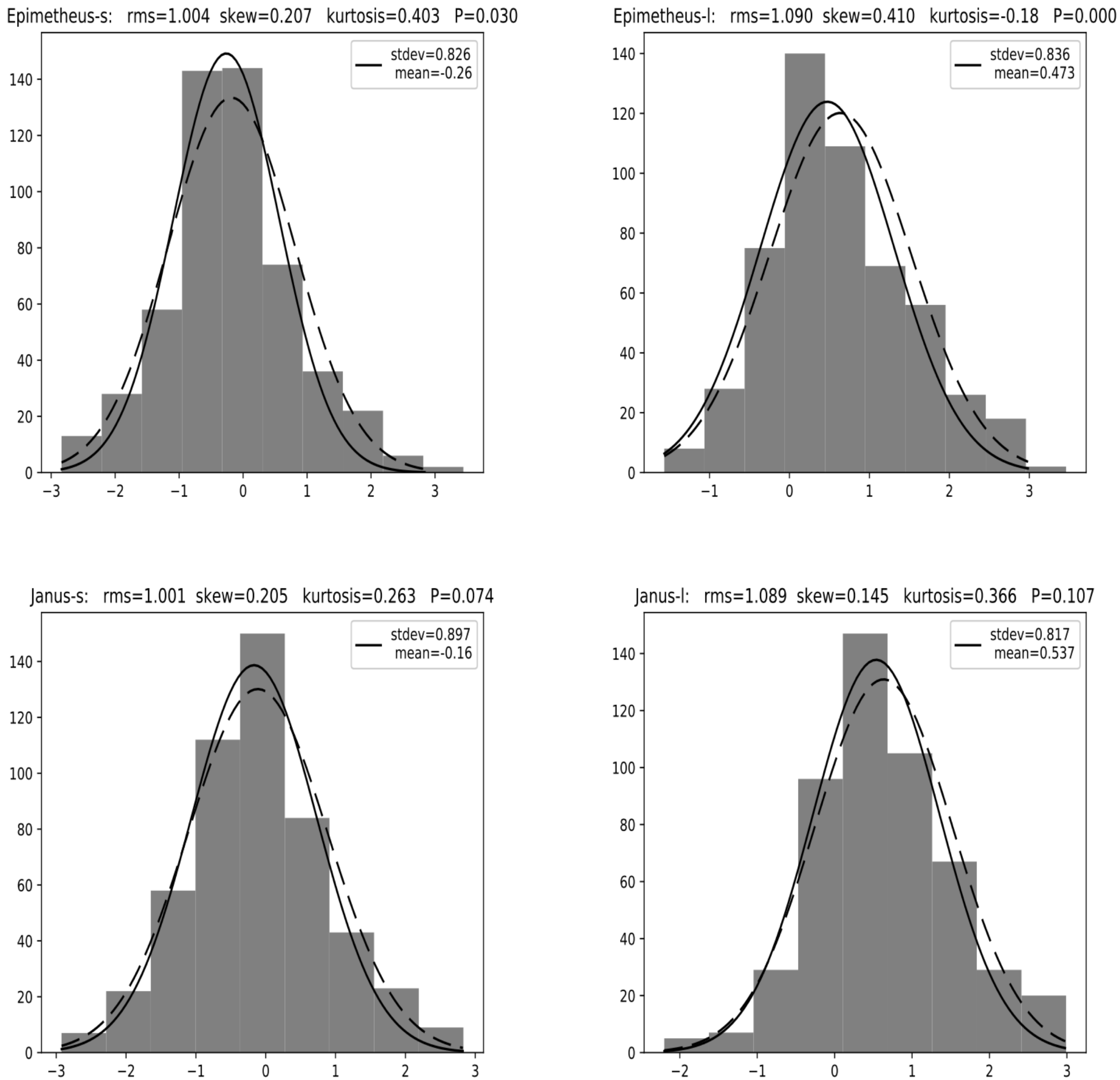

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Interior properties: mass and densities

Error bars (merging 3-sigma solution)

Simulation	Atlas	Prometheus	Pandora	Epimetheus	Janu
Cassini (J_6 not constrained)	3.7231E-4 ± 7.6E-7	1.06615E-2 ± 3.0E-6	9.0855E-3 ± 4.5E-6	3.50793E-2 ± 4.2E-6	0.126401 ± 1.6E-
Cassini [2004-2010]	3.694E-4 ± 1.4E-6	1.06625E-2 ± 7.1E-6	9.134E-3± 1.4E-5	3.50854E-2± 5.2E-6	0.126425± 1.9E-
Cassini [2011-2017]	3.769E-4± 1.7E-6	1.06454E-2 ± 9.3E-6	9.162E-3± 2.0E-5	3.50826E-2± 8.0E-6	0.12641± 3.0E-
Cassini	3.721E-4 ± 7.6E-7	1.06611E-2 ± 3.0E-6	9.0847E-3 ± 4.5E-6	3.50788E-2 ± 4.2E-6	0.126398 ± 1.6E-
Cassini (sat359l eph.)	3.7171E-4 ± 7.5E-7	1.06576E-2 ± 3.0E-6	9.0788E-3 ± 4.5E-6	3.50799E-2 ± 4.2E-6	0.126403 ± 1.6E-
Cassini (sat375 eph.)	3.7178E-4 ± 7.6E-7	1.06587E-2 ± 3.0E-6	9.0793E-3 ± 4.5E-6	3.50795E-2 ± 4.2E-6	0.126402 ± 1.6E-
Cassini + HST	3.7295E-4 ± 8.3E-7	1.06667E-2 ± 3.0E-6	9.0971E-3 ± 4.7E-6	3.50764E-2 ± 4.2E-6	0.126391 ± 1.6E-
Cassini (incl. J_3, J_5)	3.7220E-4 ± 7.6E-7	1.06606E-2 ± 3.0E-6	9.0848E-3 ± 4.5E-6	3.50796E-2 ± 4.2E-6	0.126401 ± 1.6E-
Cassini (no nutations)	3.7196E-4 ± 7.6E-7	1.06609E-2 ± 3.0E-6	9.0833E-3 ± 4.5E-6	3.50779E-2 ± 4.2E-6	0.126396 ± 1.6E-
Cassini (Pallene)	3.7199E-4 ± 7.5E-7	1.06609E-2 ± 3.0E-6	9.0849E-3 ± 4.5E-6	3.50777E-2 ± 4.2E-6	0.12639 ± 1.6E-
Global solution (km^3/s^2)	$(3.73 \pm 0.06)\times10^{-4}$	$(1.066 \pm 0.001)\times10^{-2}$	$(9.09 \pm 0.02)\times10^{-3}$	$(3.508 \pm 0.001)\times10^{-2}$	0.12640 ± 0.0000
Volume (in km^3 from Thomas et al. 2013)	14368 ± 1487	335131 ± 17780	281015 ± 18658	825589 ± 40393	3022853 ± 5505
Density (g/cm^3)	0.389 ± 0.041	0.477 ± 0.025	0.485 ± 0.032	0.637 ± 0.031	0.627 ± 0.01

- Good agreement with former studies (Thomas et al. 2013, Cooper et al. 2015)
- Thanks to our data treatment, we obtain about same uncertainties, but releasing much more physical parameters

Interior properties: more than just the mass?

Error bars (merging 5-sigma solution)

Simulation	*A*-Prometheus	*A*-Pandora	*A*-Epimetheus	*A*-Janus
HST only (masses+libr.+B+A+J2/4/6constr)	- ± 142.	- ± 326.	- ± 53.	- ± 27.
HST only (masses+libr.)	- ± 25.	- ± 38.	- ± 22.	- ± 15.
Cassini (J_6 not constrained)	0.0 ± 0.8	36.2 ± 4.2	26.6 ± 1.3	2.5 ± 0.7
Cassini [2004-2010]	1.0 ± 1.8	35.8 ± 4.6	23.5 ± 2.8	6.4± 1.6
Cassini [2011-2017]	0.6 ± 1.4	46.1 ± 3.4	22.1 ± 5.3	1.8 ± 3.2
Cassini	1.3 ± 0.3	42.9 ± 1.3	26.6 ± 1.3	2.5 ± 0.7
Cassini (sat359l eph.)	1.3 ± 0.3	42.5 ± 1.3	26.8 ± 1.3	2.4 ± 0.7
Cassini (sat375 eph.)	1.3 ± 0.3	42.7 ± 1.3	26.7 ± 1.3	2.4 ± 0.7
Cassini + HST	1.5 ± 0.3	43.5 ± 1.3	26.0 ± 1.3	3.2 ± 0.7
Cassini (incl. J_3, J_5)	1.3 ± 0.3	42.7 ± 1.3	25.8 ± 1.3	2.4 ± 0.7
Cassini (no nutations)	1.3 ± 0.3	43.2 ± 1.3	26.5 ± 1.3	2.4 ± 0.7
Cassini (Pallene)	0.9 ± 0.2	40.9 ± 0.9	27.2 ± 1.3	2.7 ± 0.7
Global solution	1.55 ± 1.45	43.2 ± 6.8	26.3 ± 7.0	2.8 ± 3.9
Physical libration (deg)	-0.12 ± 0.40	10.2 ± 1.7	13.9 ± 4.0	0.3 ± 1.6

NB: estimations above do not take into account volume uncertainty!

	theory (homogeneity)	Geometric measurement	
Prometheus:	φ = -1.15 +/- 0.56 °		
Pandora:	φ = 7.51 +/- 7.04 °		
Epimetheus:	φ = 3.1 +/- 7.3	5.9 +/- 1.2 °	Tiscareno et al. 2009
Janus:	φ = 0.33 +/- 0.15 °	0.3 +/- 0.9°	

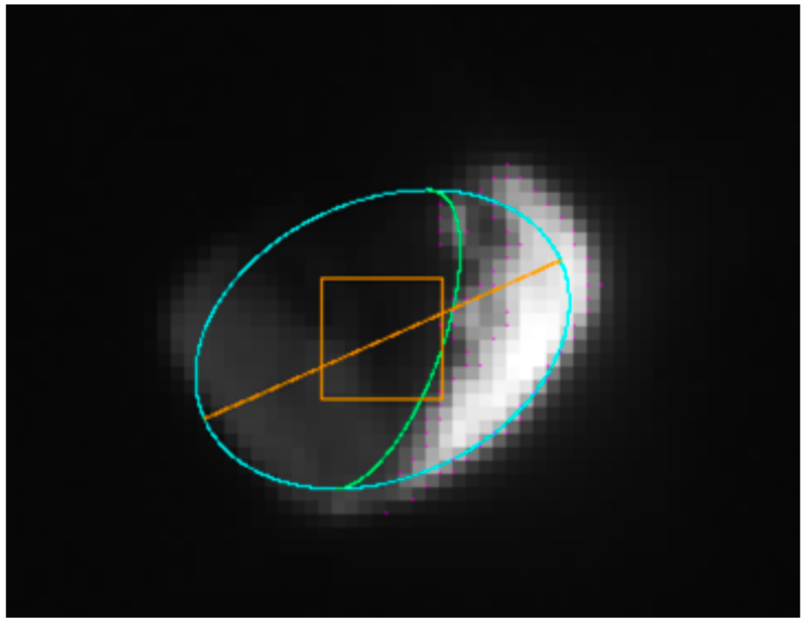
This suggests that in the knowledge of their volume, Prometheus, Pandora, Epimetheus and Janus may be close to homogeneity

Conclusion

1- Physical libration of Pandora, Prometheus, Janus and Epimetheus can be constrained from astrometry. Current estimations may be compatible with homogeneous interior.

2- The ISS-NAC data do have an important bias. But a proper treatment has been performed to correct this issue. It is still not optimal since .psf files do not contain any information on limb detection (180 deg. vs 360 deg.). Still, after correction the data show a behavior rather close to Gaussian law.

3- Post-fit residuals still have a magnitude 2-3 times larger than for main moons. This is an issue for decreasing our error bars on libration or looking at smaller dynamical effects like rings interactions. Solving this will require to reduce all data again, this time using DTM.



Acknowledgments:

This research was supported by an appointment to the NASA Postdoctoral Program at the NASA Jet Propulsion Laboratory, Caltech, administered by Universities Space Research Association under contract with NASA.