Mitigation of Non-conservative Force Model Error

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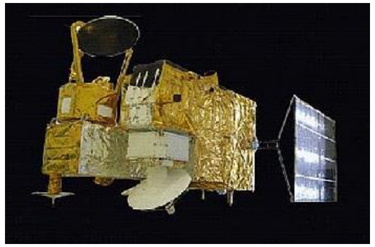
Outline

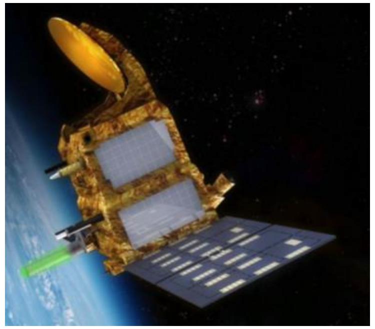
I	**Nonconservative Force Model Accelerations on DORIS Satellites.** A. Overview. B. SRP, Albedo/IR, Drag Acceleration Magnitudes, by satellite. C. OPR Residual Comparison with DORIS ACs D. “Other” accelerations: Thermal, more detailed Albedo/IR.
II	**Impact of Using new Total Solar Irradiance (TSI).**
III	**Improving a macromodel.** A. Example with Jason-2 or Jason-3. B. Adjusting Cr/arc for Jason-2/Jason-3. C. Cr/arc history for other satellites.
IV	**Jason-2/3 Orbit comparison among ACs.**
V	**Survey of modelling for IDS ACs.**
VI	**Conclusions and Recommendations**

Satellite Sensitivity to Nonconservative Forces

Cryosat-2

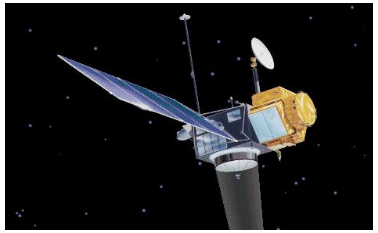


HY-2A



Saral

Satellite	Solar Array Area (m^2)	Mass (kg)	A/m (10^{-4} m^2/kg)	Articulating Solar Array
TOPEX (EOL)	25.50	2405.4	106.0	Y
Envisat (EOL)	71.19	7828	90.9	Y
SPOT-4 (EOL)	24.80	2678.7	92.6	Y
SPOT-5 (EOL)	24.70	3018	81.8	Y
Jason-2 (080704)	**9.80**	**501.8**	**195.3**	**Y**
Jason-2 (181002)	**9.80**	**481.8**	**203.4**	**Y**
Cryosat-2 (190729)	11.69	718.3	162.7	No
HY-2A	15.80 (+Y face)	1543	101.9	No
SARAL (190601)	5.49 (+Z face)	402.9	**136.2**	**No**
Jason-3 (190729)	**9.80**	**503.7**	**194.5**	**Y**
Sentinel-3A	10.50	1130	92.9	Y
Galileo	14.7	733	201	Y
LAGEOS-1	0.28274	406.965	6.95	---



TOPEX/Poseidon

SPOT-5

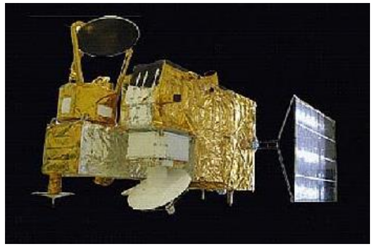
Jason-2

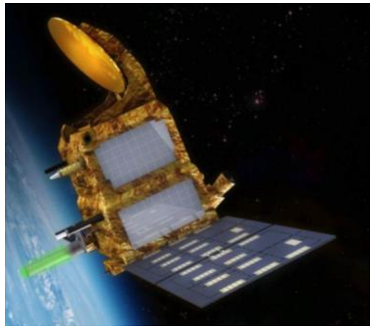
Sentinel-3A

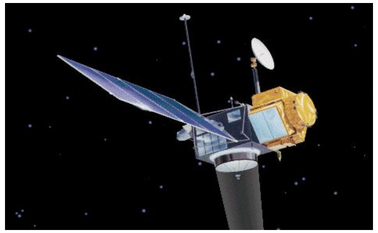
DORIS Spacecraft and Attitude Modelling

Satellite	Articulating Solar Array	Spacecraft Quaternions	Solar Array Quaternions	Quaternions Used by DORIS ACs
TOPEX	Y	Some arcs (1-2%)	No	Only GSC
Envisat	Y	?	?	-
SPOT-4	Y	No	No	-
SPOT-5	Y	No	No	-
Jason-2	Y	Yes	Yes	ESA?, GOP, GSC, GRG
Cryosat-2	No	Yes	---	GSC
HY-2A	No	Not Publically Available (?)	Not Publically Available(?)	No
SARAL	No	Yes	---	Not yet
Jason-3	Y	Yes	Yes	ESA?, GOP, GSC, GRG
Sentinel-3A	Y	Yes	Yes	-
Sentinel-3B	Y	Yes	Yes	-


Cryosat-2


HY-2A


Saral


TOPEX/Poseidon


SPOT-5


Jason-2


Sentinel-3A

Computation of Accelerations for DORIS satellites

I. NASA Precise Orbit Determination and Geodetic Parameter Estimation software (GEODYN), versions 1810, and 1906. Computed per arc during reprocessing of DORIS (& SLR) data.

II.
- Macromodels for all satellites.
- New Tuned macromodels for TOPEX, J2, J3, HY-2A.
- UCL model for computing Solar Radiation Pressure (SRP) on Envisat.

III. Atmospheric Density Model: MSIS86 (driven by F10.7, and Kp Indices).

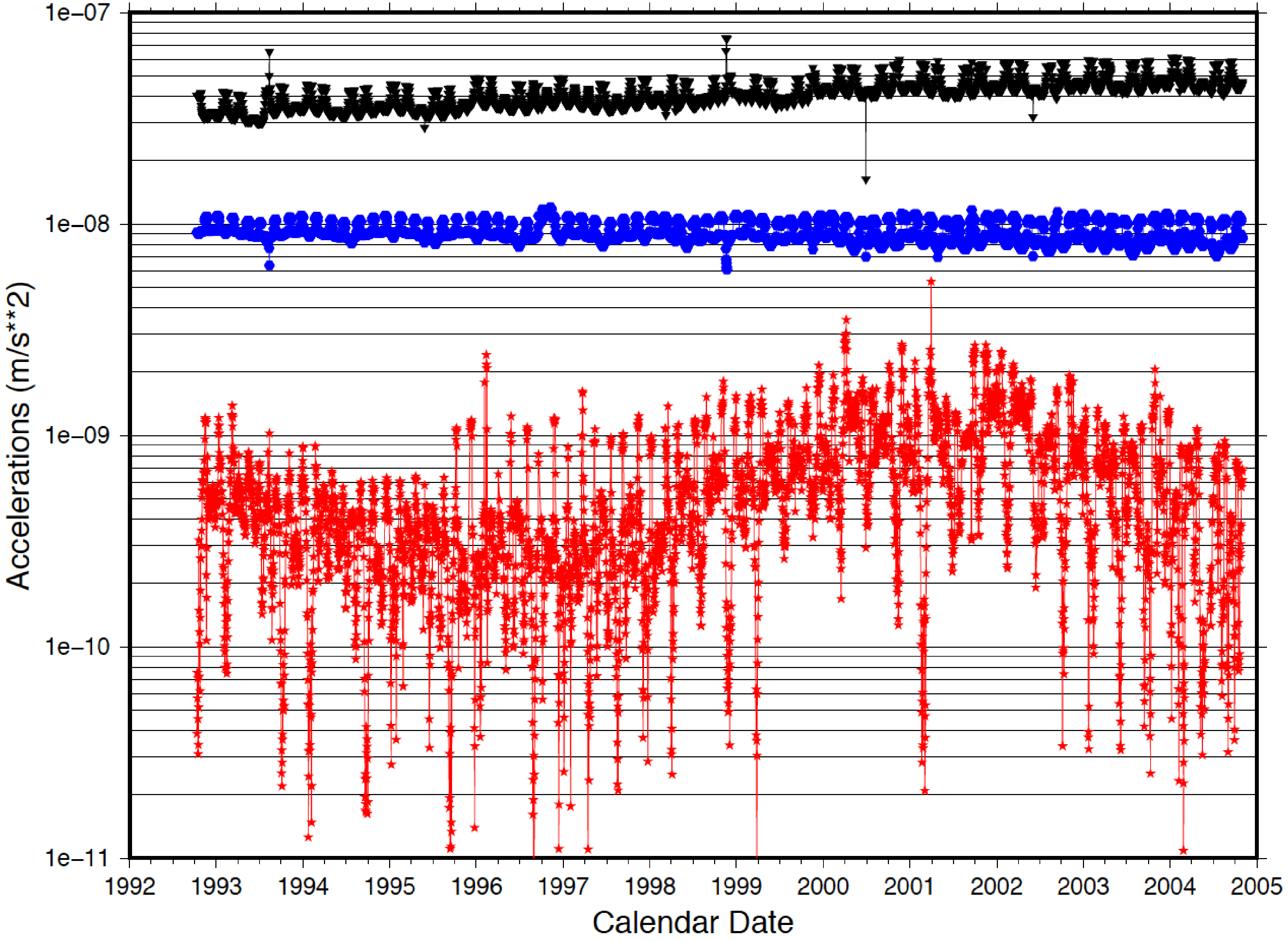
IV. Planetary Radiation Pressure (Earth Albedo Radiation and Thermal Emission)
- Knocke et al. (1988).

V. Modelling Satellite Attitude:
- Internal model: SPOT satellites, TOPEX, Envisat, HY-2A, Saral.
- Spacecraft Body quaternions: Some TOPEX arcs; Jason-2, Jason-3, Cryosat-2
- Solar array quaternions: Jason-2, Jason-3.

Legend for Acceleration plots:

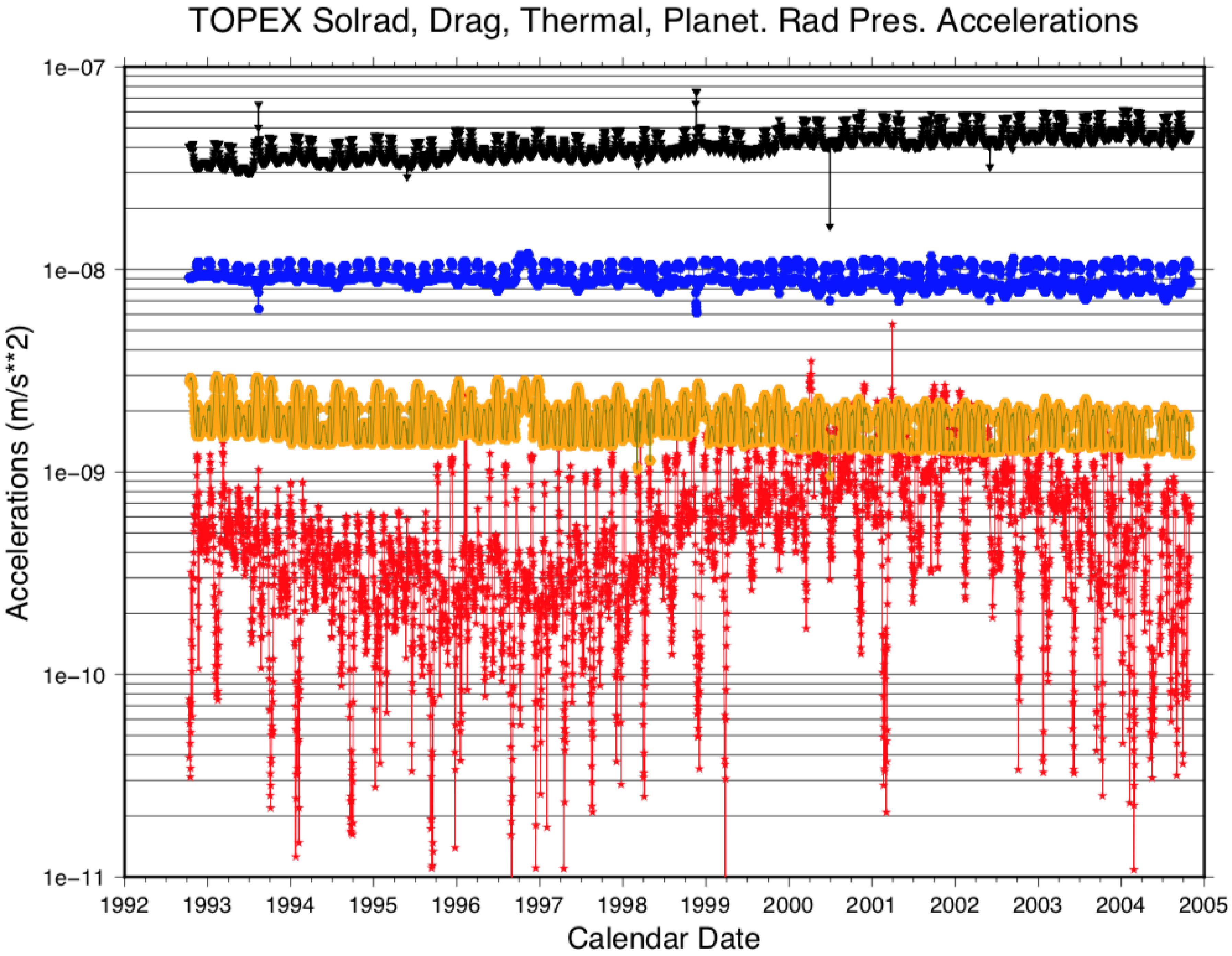
SRP (in black); Albedo/Thermal IR (Blue); Atmospheric Drag (Red); Thermal (Orange)

TOPEX Solrad, Drag, Planet. Rad Pres. Accelerations

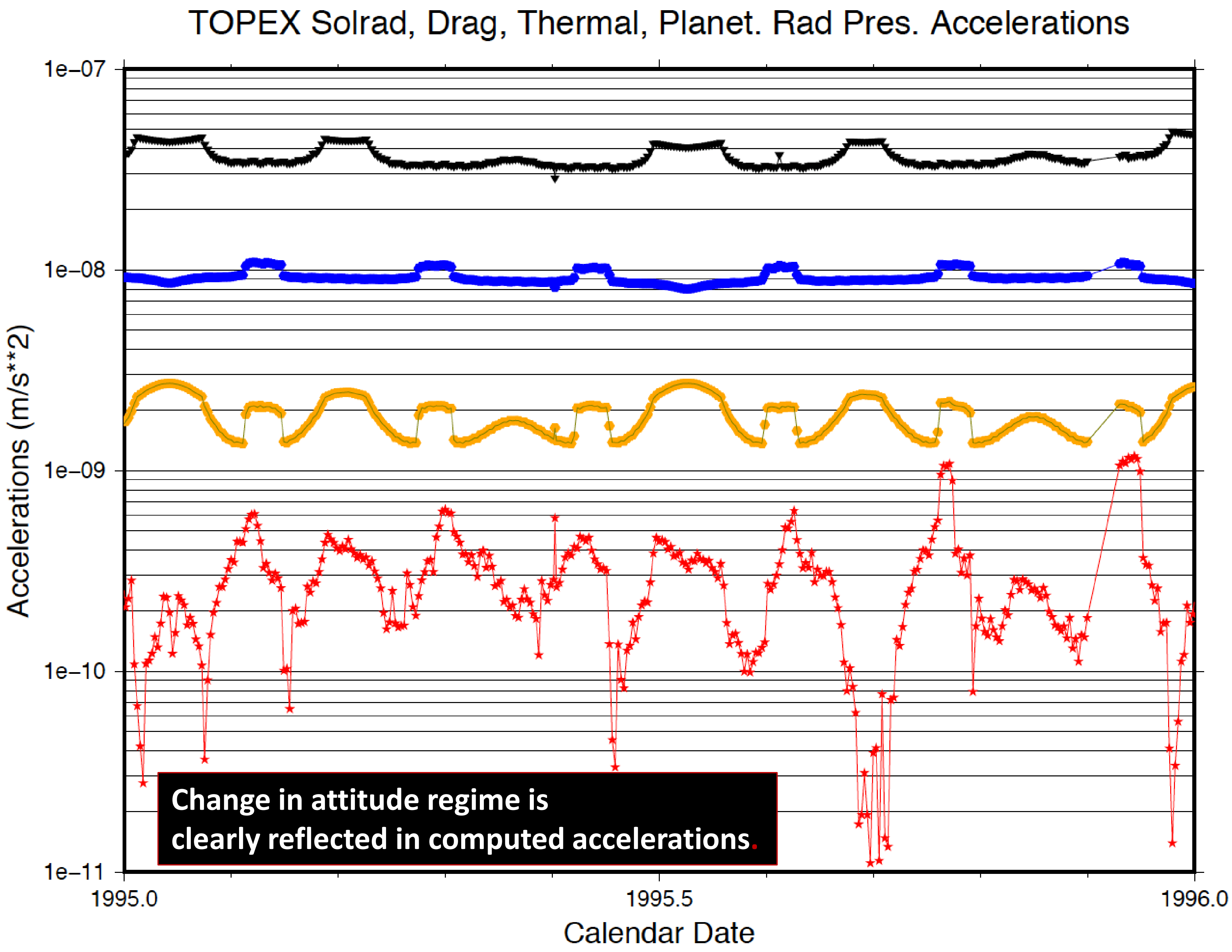


Alt = 1336 km

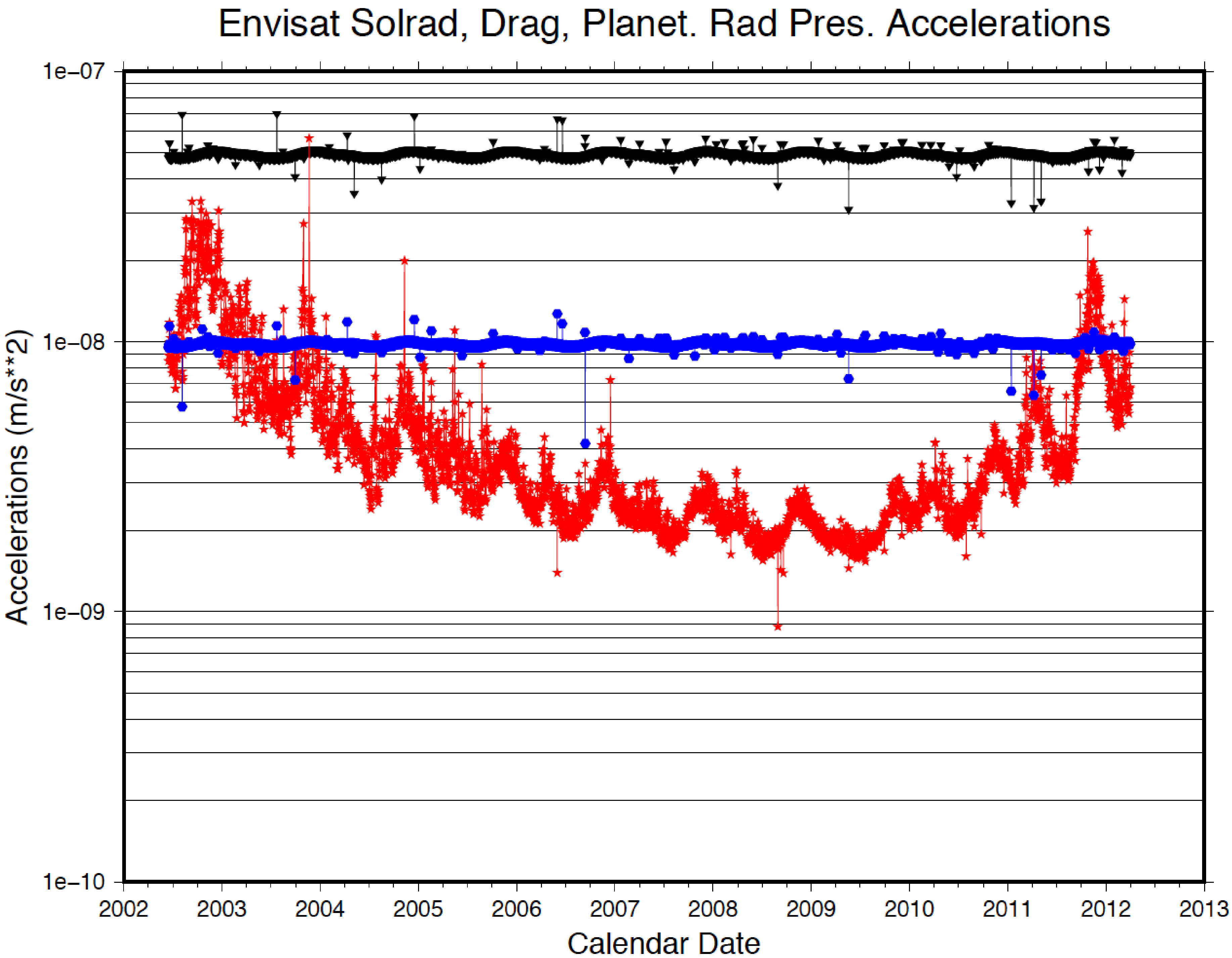
Inclin. = 66.5°



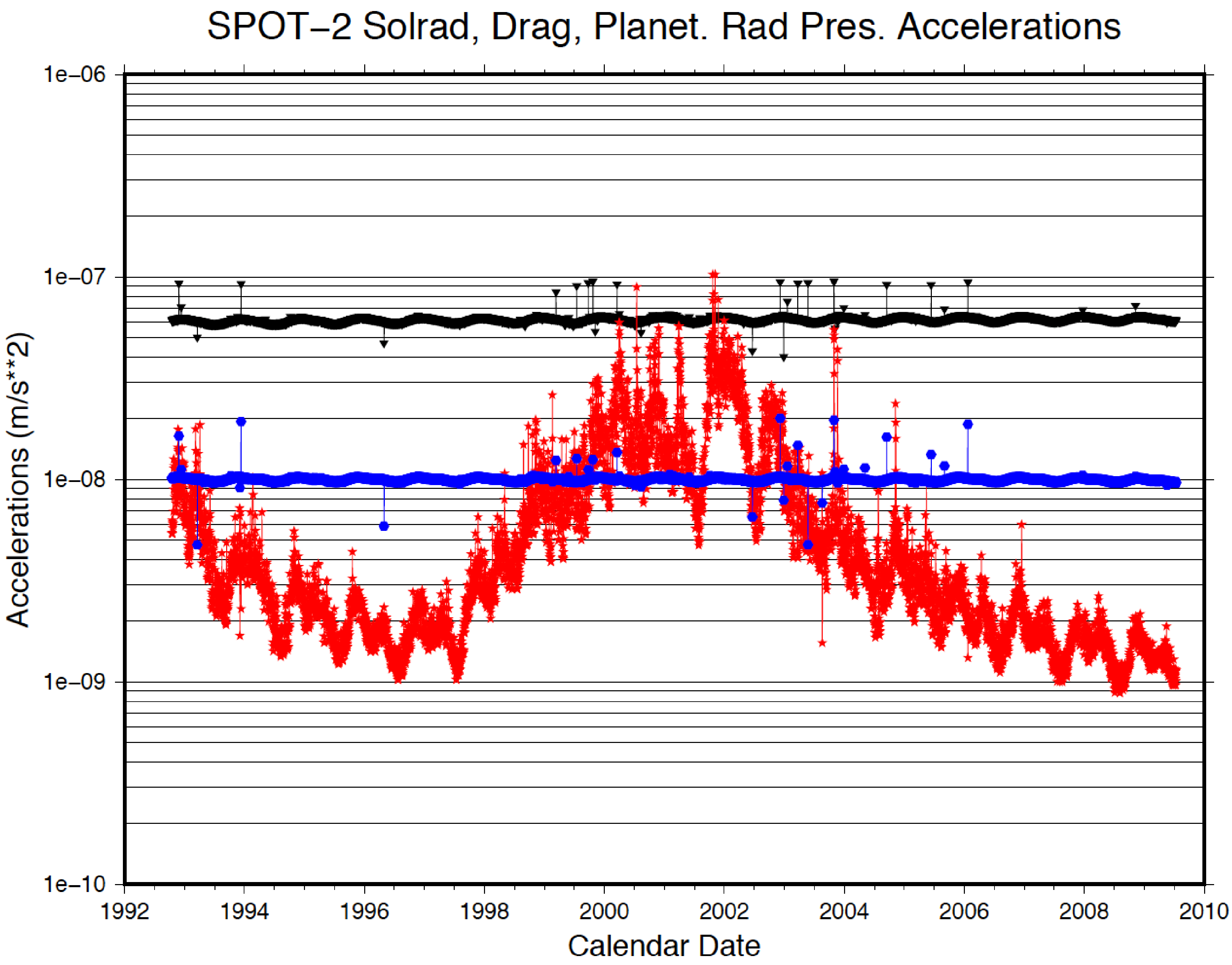
Alt = 1336 km
Inclin. = 66.5°



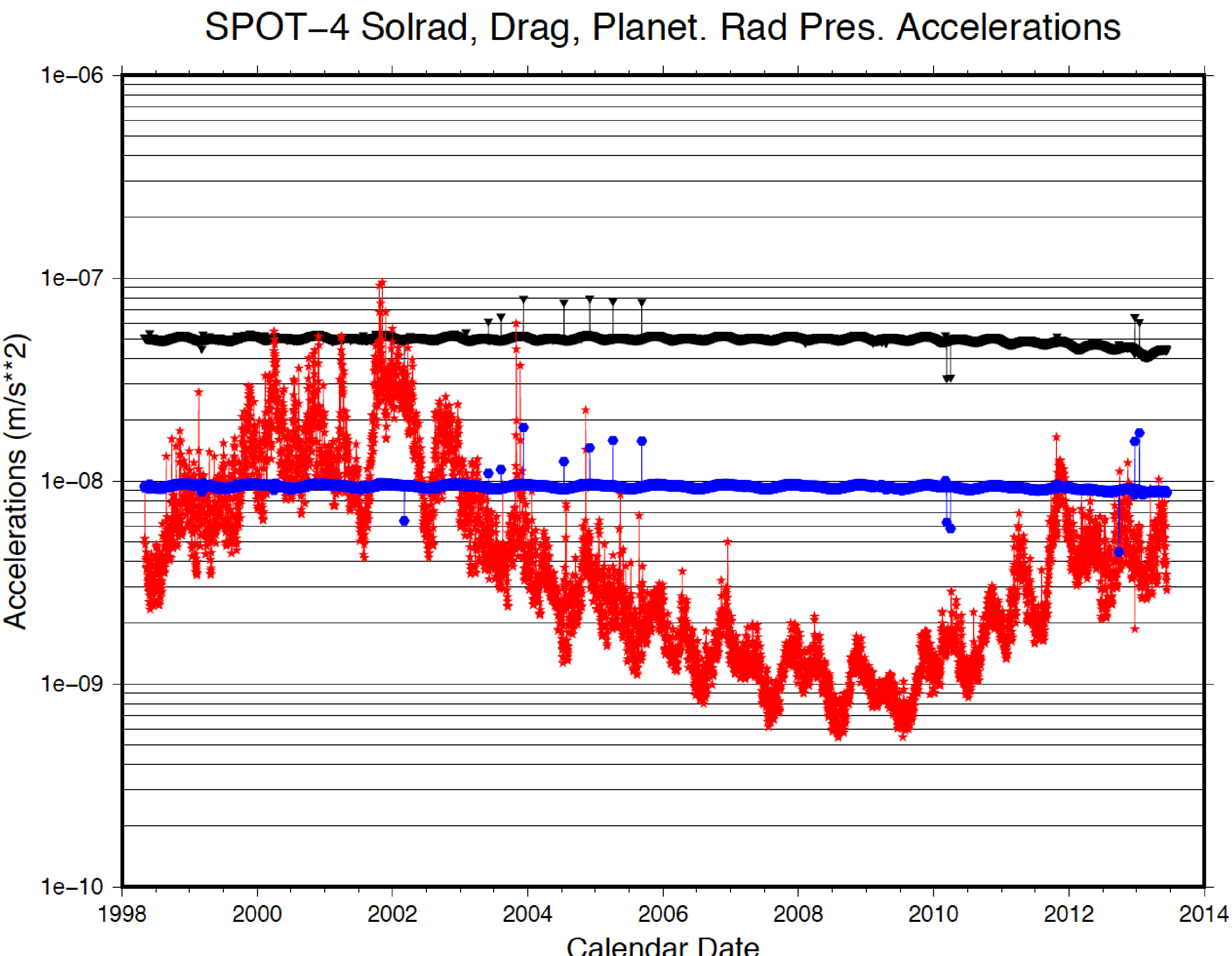
Alt = 1336 km
Inclin. = 66.5°



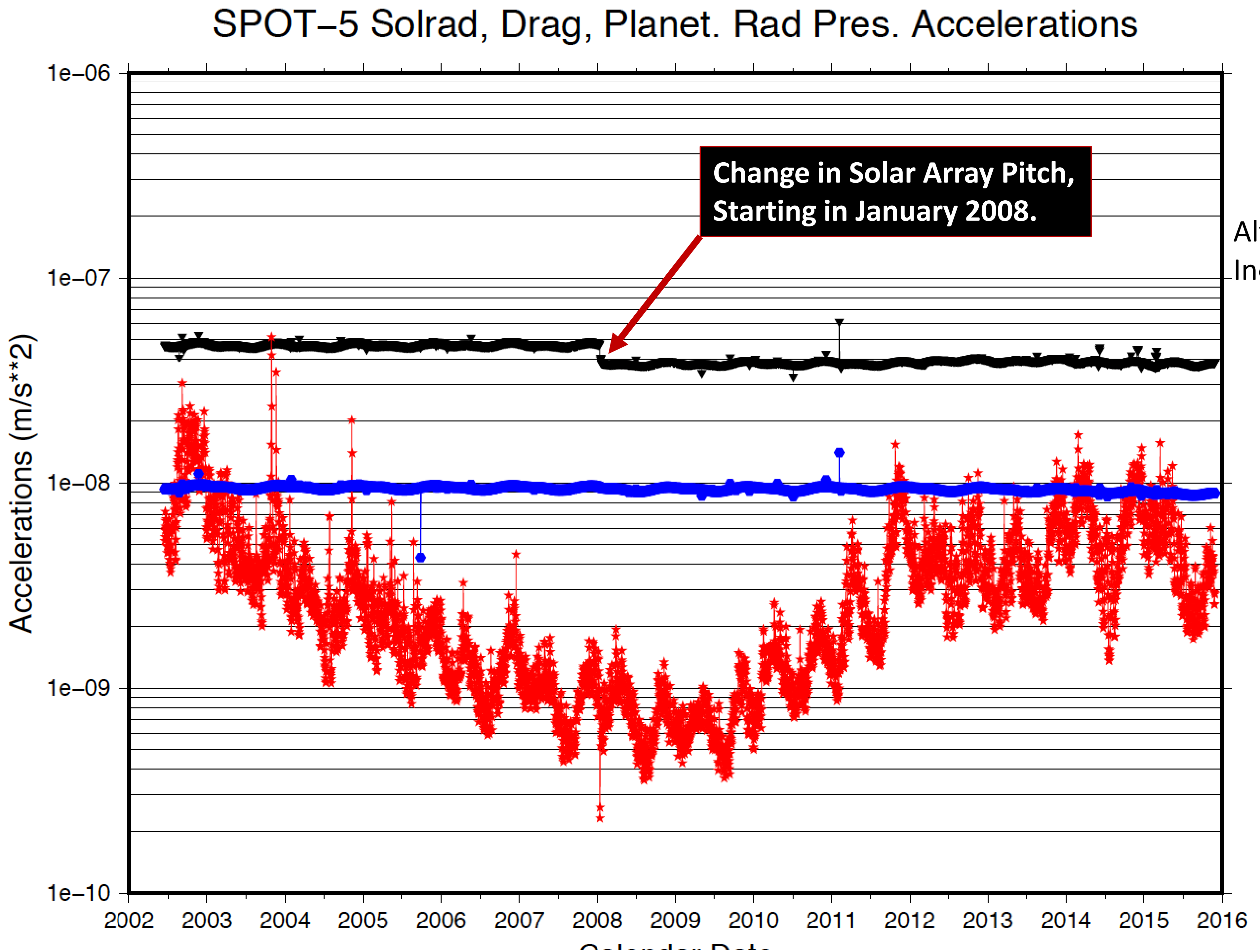
Alt. = 788 km
Inclin. = 98.6°



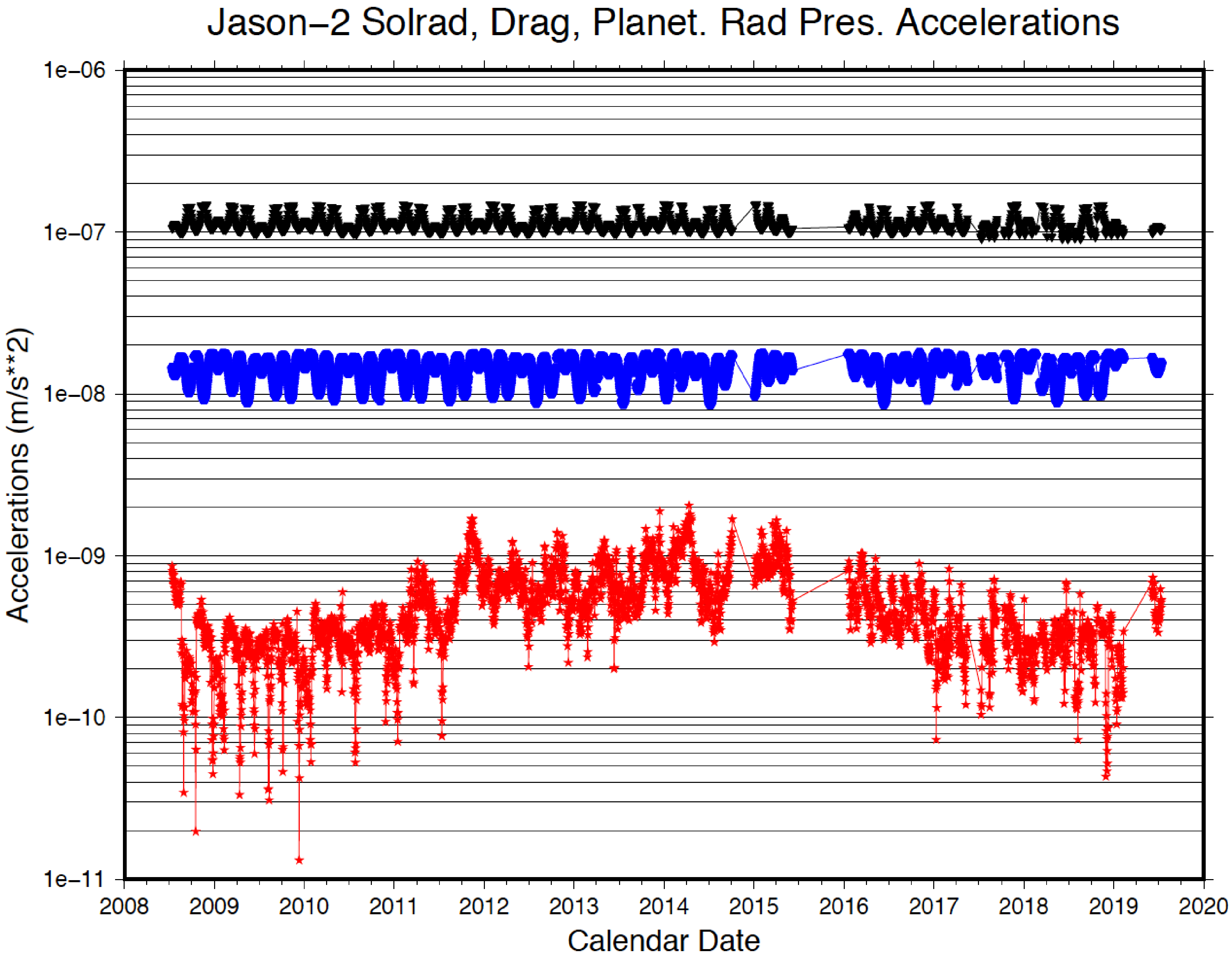
Alt. = 816 km
Inclin. = 98.7°



Alt. = 801 km
Inclin. = 98.8°

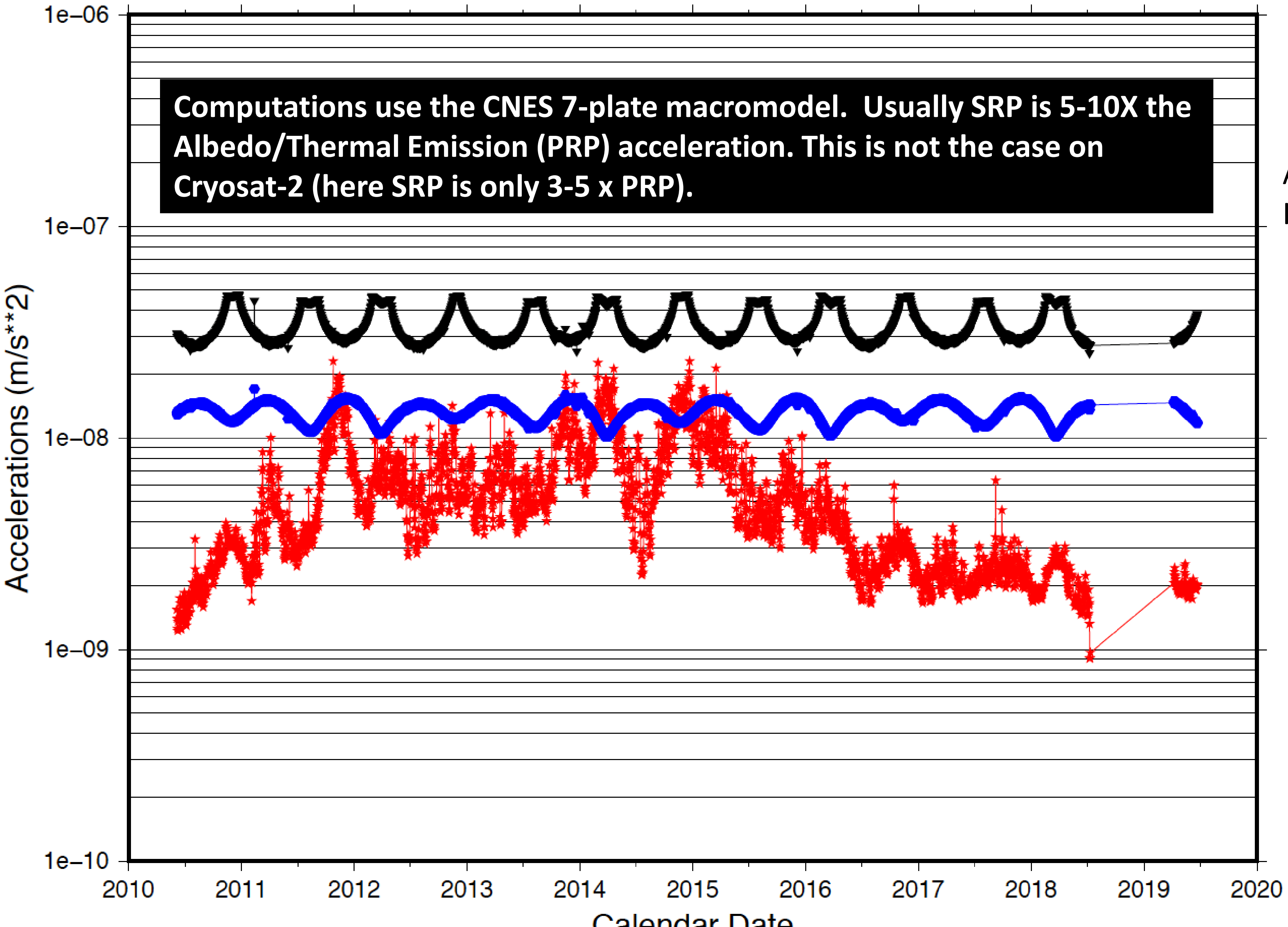


Alt. = 825 km
Inclin. = 98.8°

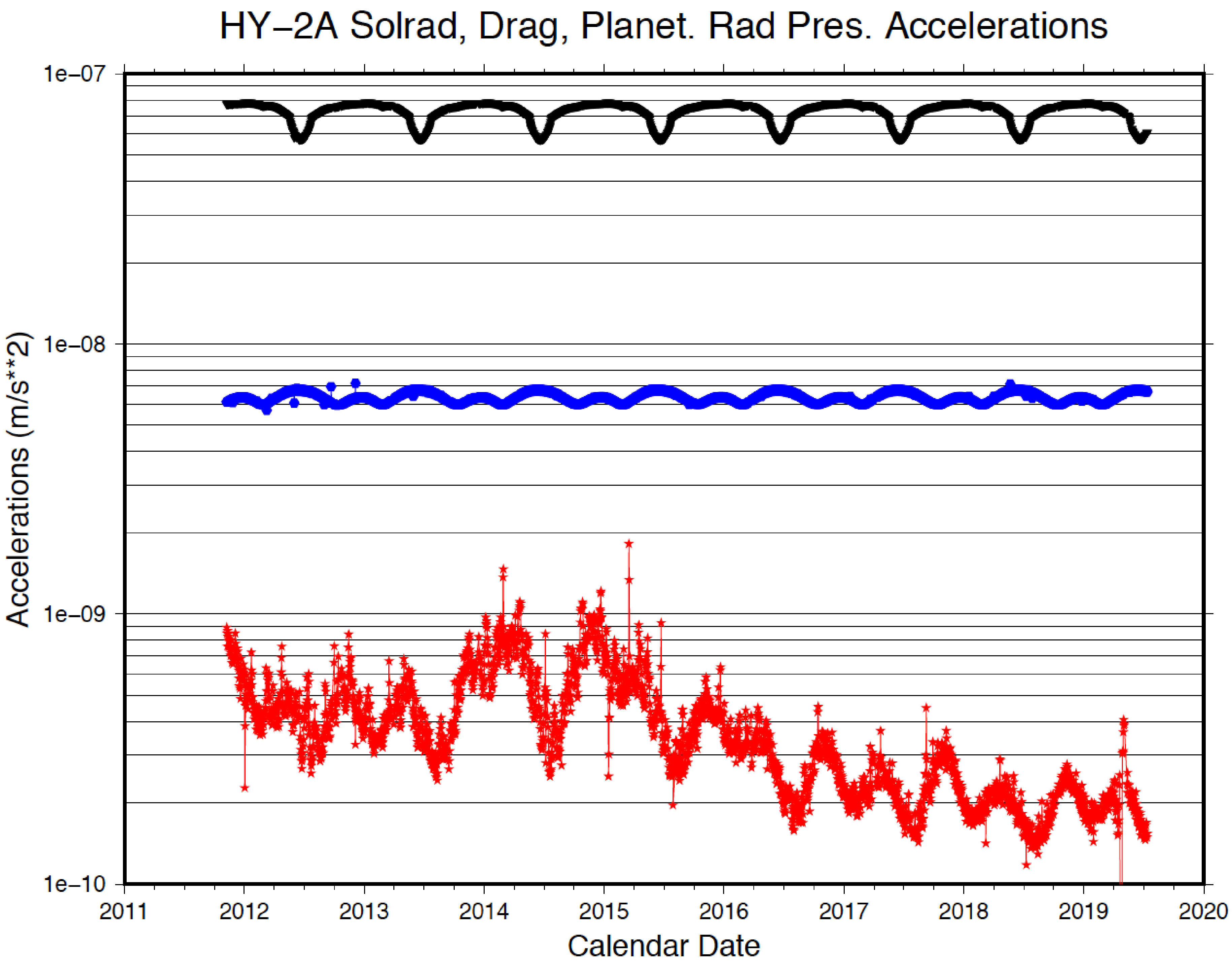


Alt = 1336 km
Inclin. = 66.5°

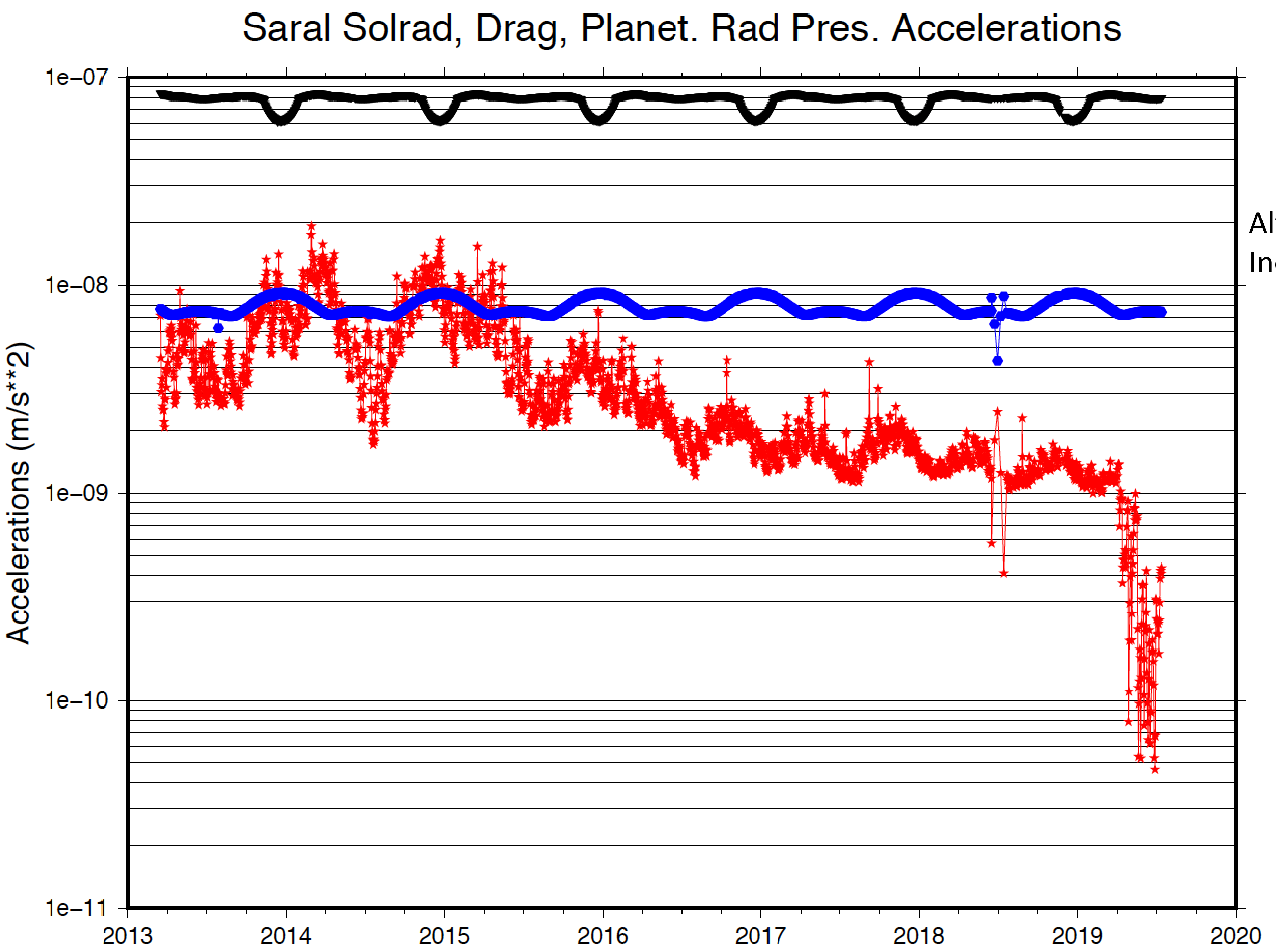
Cryosat–2 Solrad, Drag, Planet. Rad Pres. Accelerations



Alt. = 717 km
Inclin. = 99.4°



Alt. = 963 km
Inclin. = 99.4°



Alt. = 706 x 772 km
Inclin. = 98.65°

Some conclusions regarding the surface accelerations

I. Atmospheric density and the computation of atmospheric drag is a limiting error source for the DORIS satellites near 800 km altitude, when the s/c are near Solar Maximum. We were fortunate that the maximum in 2009-2012 was not as great as in the period from 1999-2002. We will face a similar problem again during the next solar maximum, especially with large satellites (Sentinel-3A and SWOT).

II. Unfortunately per Sean Bruinsma of CNES/GRGS (message of 09/26/2019), there are no new models available now (in 2019) that would improve thermospheric modeling at the DORIS satellite altitudes. The new models that have been developed (for example incorporating derived-density data from CHAMP and GRACE) improve modelling at the lower altitudes, but not at the altitudes of interest to DORIS satellites.

III. The lack of attitude information (quaternions) for articulating appendages (solar arrays and/or the SAR antenna on Envisat) on some satellites limits the ability to accurately the surface accelerations. This compounds the effects of lack of knowledge of the density or modeling of radiation interactions (e.g. shadowing or re-radiation).

IV. In tuning macromodels to improve SRP modelling, it is probably wiser to avoid “high-drag” periods (e.g. near the Solar Maxima). For polar orbiting satellites, the SRP and the effects of drag can both be along track and correlated, at least over part of the orbit. This was the approach followed by Lemoine et al. (2016), and Le Bail et al. (2010) in retuning the macromodels for different satellites.

Cryosat-2 Residual Accelerations (OPRs) by IDS AC

Alt. = 717 km
Inclin. = 99.4°

Avg. or RMS of Daily OPR Amplitudes

IDS AC	Dates	N-along	Along-track (nm/s^2)		N-cross	Cross-track (nm/s^2)	
			Avg	RMS		Avg.	RMS
ESA							
GOP	2018/01-01 to 2019/07-06	529	2.793	2.944	529	4.263	4.794
GRG	2015/12-14 to 2019/04-14	1354	2.750	2.900	1352	2.406	2.636
GSC	2015/12-14 to 2019/04-14	1213	2.308	2.656	1213	2.917	4.360
IGN							
INA							

HY-2A Residual Accelerations (OPRs) by IDS AC

Alt. = 963 km
Inclin. = 99.4°

Avg. or RMS of Daily OPR Amplitudes

IDS AC	Dates	N-along	Along-track (nm/s^2)		N-cross	Cross-track (nm/s^2)	
			Avg	RMS		Avg.	RMS
ESA							
GOP	2018/01-01 to 2019/07-05	521	0.691	0.861	521	3.654	3.981
GRG	2015/12-19 to 2019/04-07	1362	0.554	0.617	1360	2.563	2.930
GSC	2015/12-14 to 2019/04-14	1195	0.444	0.559	1195	2.171	2.658
IGN							
INA							

Jason-2 Residual Accelerations (OPRs) by IDS AC

Alt = 1336 km
Inclin. = 66.5°

Avg. or RMS of Daily OPR Amplitudes

IDS AC	Dates	N-along	Along-track (nm/s^2)		N-cross	Cross-track (nm/s^2)	
			Avg	RMS		Avg.	RMS
ESA							
GOP	2018/01-01 to 2019/07-06	383	0.805	1.282	383	2.695	3.051
GRG	2015/12-19 to 2019/02-15	1129	3.962	4.078	1121	2.416	2.948
GSC	2015/12-14 to 2019/02-10	977	0.592	0.816	977	2.371	2.791
IGN							
INA							

Jason-3 Residual Accelerations (OPRs) by IDS AC

Alt = 1336 km
Inclin. = 66.5°

Avg. or RMS of Daily OPR Amplitudes

IDS AC	Dates	N-along	Along-track (nm/s²)		N-cross	Cross-track (nm/s²)	
			Avg	RMS		Avg.	RMS
ESA							
GOP	2018/01-01 to 2019/06-30	505	0.738	1.101	505	3.295	3.719
GRG	2016/03-23 to 2019/04-06	1261	1.136	0.993	1261	2.343	2.829
GSC	2016/02-24 to 2019/04-14	1127	0.718	0.856	1127	1.657	2.109
IGN							
INA							

Sentinel-3A Residual Accelerations (OPRs) by IDS AC

Alt = 804 km
Inclin. 98.65°

Avg. or RMS of Daily OPR Amplitudes

IDS AC	Dates	N-along	Along-track (nm/s^2)		N-cross	Cross-track (nm/s^2)	
			Avg	RMS		Avg.	RMS
ESA							
GOP	2018/01-01 to 2019/07-01	535	0.644	0.822	535	2.826	3.208
GRG	2016/03-05 to 2019/05-18	1299	2.414	2.544	1293	1.711	1.991
GSC							
IGN							
INA							

Sentinel-3B Residual Accelerations (OPRs) by IDS AC

Avg. or RMS of Daily OPR Amplitudes

Alt = 804 km
Inclin. 98.65°

IDS AC	Dates	N-along	Along-track (nm/s^2)		N-cross	Cross-track (nm/s^2)	
			Avg	RMS		Avg.	RMS
ESA							
GOP	2018/06-07 to 2019/07-02	372	0.699	0.922	372	2.841	3.220
GRG	2018/05-09 to 2019/05-18	398	1.510	1.661	395	1.828	2.078
GSC							
IGN							
INA							

Saral Residual Accelerations (OPRs) by IDS AC

Alt. = 706 x 772 km
Inclin. = 98.65°

Avg. or RMS of Daily OPR Amplitudes

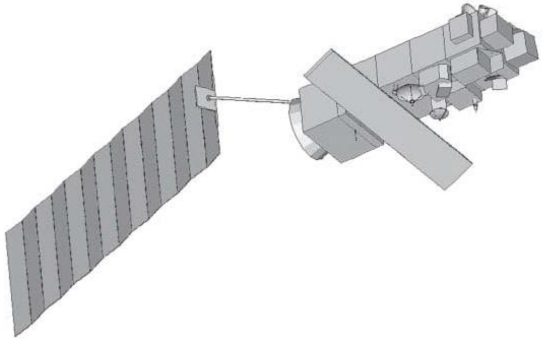
IDS AC	Dates	N-along	Along-track (nm/s^2)		N-cross	Cross-track (nm/s^2)	
			Avg	RMS		Avg.	RMS
ESA							
GOP	2018/01-01 to 2019/07-06	542	2.197	3.060	542	4.024	4.802
GRG	2015/12-19 to 2019/04-06	1368	1.370	1.645	1368	2.026	2.419
GSC	2015/12-14 to 2019/04-14	1216	1.993	2.759	1216	1.031	1.398
IGN							
INA							

Thermal Accelerations on DORIS satellites

I. Thermal accelerations are not generally modelled with the exception of TOPEX (for GSC), or in the event an advanced model is used (UCL model for Envisat by GSC for example, or ANGARA for ESA).

II. Modelling the Thermal acceleration requires at a minimum to prescribe a temperature history on each s/c face around the orbit and the mean emissivity of that surface. One must make an attempt to account for oblique illumination effects, spacecraft thermal inertia, and occultation effects.

III. The GSC TOPEX thermal model is based on the work of Antreasian and Rosborough ("Prediction of Radiant Energy Forces on the TOPEX/POSEIDON Spacecraft", Journal of Spacecraft and Rockets, 1992), adapted by Marshall and Luthcke ("Modeling Radiation Forces Acting on TOPEX/Poseidon for Precision Orbit Determination", Journal of Spacecraft and Rockets, 1994).

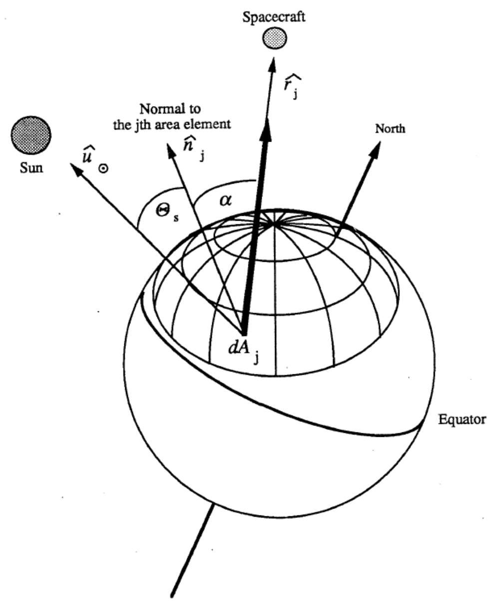


ANGARA model for ENVISAT from Doornbos et al (2002, Can. J. Rem. Sensing, 28(4), 535-543)

ERS-2 maximum non-gravitational accelerations from Doornbos et al (2002, Table 1).

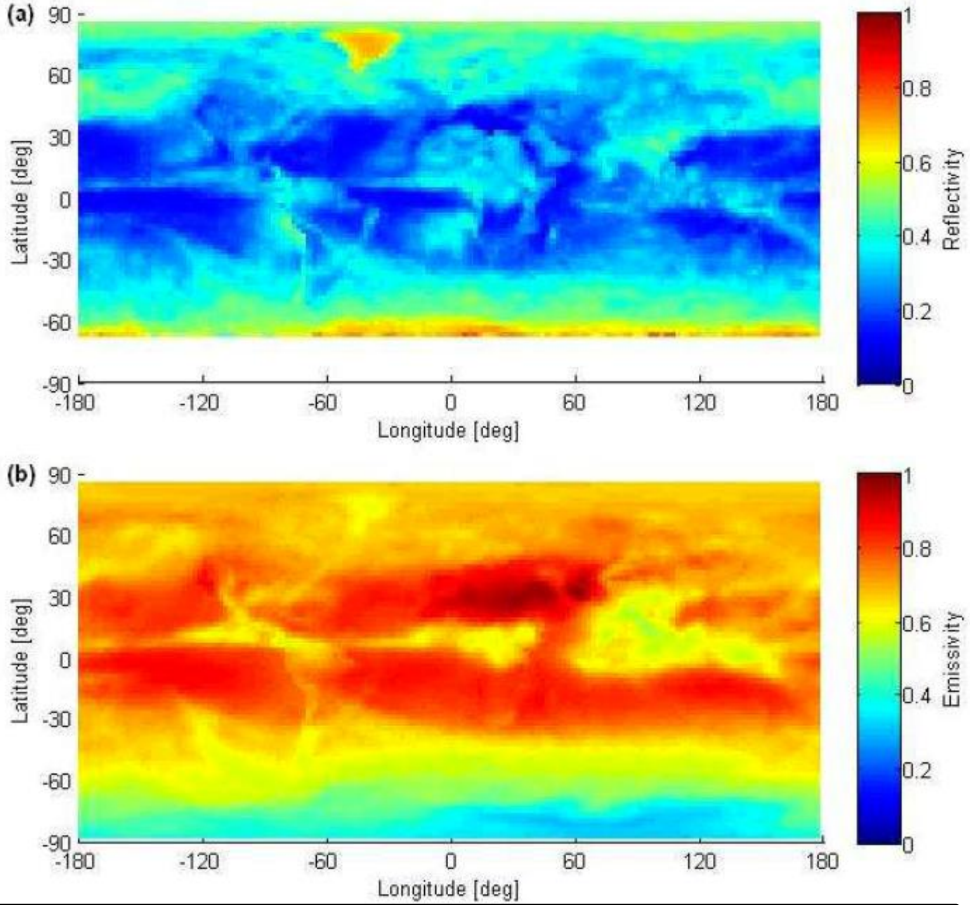
Source of acceleration	Along track (nm/s^2)	Cross track (nm/s^2)	Radial (nm/s^2)
Drag at low solar activity	5	<1	<1
Drag at high solar activity	35	3	4
Drag at high solar activity and geomagnetic storms	200	15	20
Solar radiation pressure	90	40	110
Earth albedo and infrared radiation pressure	5	3	30
Spacecraft thermal radiation	15	8	20

Planetary Radiation Pressure Perturbations on DORIS Satellites (1)



Earth radiation pressure geometry
from Antreasian (Ph.D. Thesis, Univ. Colorado, 1992)

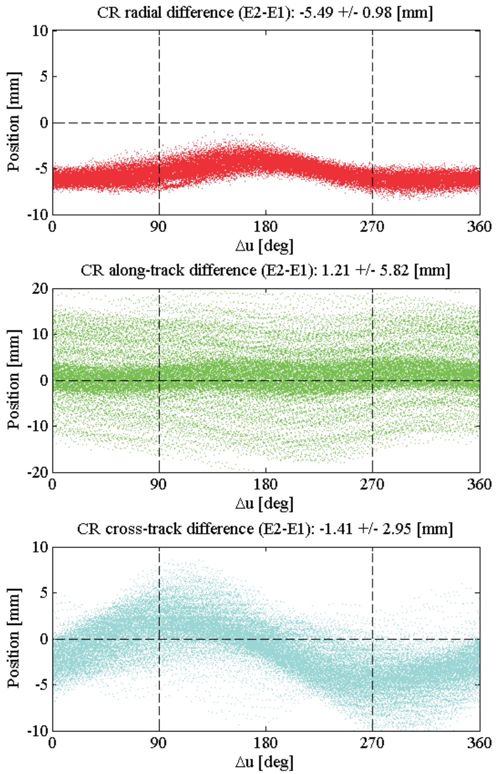
Except for GRG who use ECMWF-derived albedo and thermal-emission grids, most IDS ACs use the Knocke et al. (1988) model. This model uses time-variable low-degree zonal coefficients to model the albedo and emissivity. The visible surface seen from the satellite is then divided into discrete elements and the total acceleration is summed. This approach still works with a macromodel.



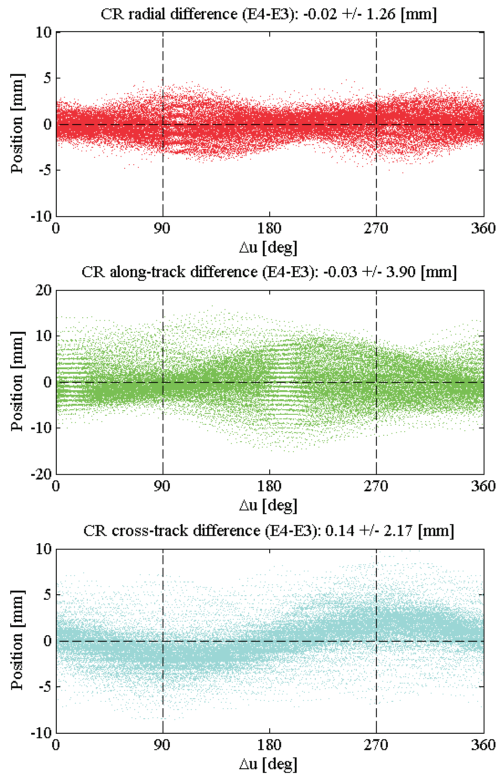
CERES-derived albedo/emissivity for July 2007, from Rodriguez-Solano, MS Thesis, 2012, Fig. 2.10.

The CERES (Clouds and Earth's Radiant Energy System) project furnishes monthly grids of short-wave and long-wave radiance that can be converted into monthly albedo and emissivity maps, which can then be adapted into a particular POD software.

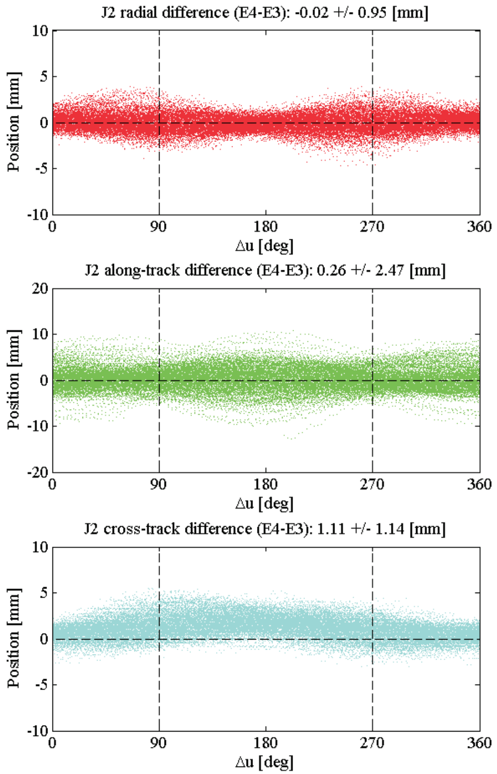
Planetary Radiation Pressure Perturbations on DORIS Satellites (2)



C2 rad, alg-track, cross-track differences, no albedo vs constant model



C2 rad, alg-track, cross-track differences, Knocke vs CERES



J2 rad, alg-track, cross-track differences, Knocke vs CERES

Stepanek (IDS Workshop 2012) looked at the impact of using different PRP models. If no model is used, one incurs a radial bias of 5-6 mm (1 ppb). However if a CERES model is used instead of the Knocke et al model, the effects on the Jason-2 & Cryosat-2 orbits are 1 -4 mm in std. deviation in the radial, along-track & cross-track directions. It is possible that adjustment of empirical parameters (Cds and OPRs) accommodates not using the more complex model, as also observed by P. Knocke.

Planetary Radiation Pressure Perturbations on DORIS Satellites (3)
Conclusions & Recommendations

• It would be preferable to adopt a more detailed model of the albedo and thermal emission than Knocke et al. (1988), which is now a very old model.

• It's not clear that using the CERES Level-3 grids (monthly grids @ 2.5 deg resolution) is the best option. It offers perhaps too much spatial resolution but not enough temporal resolution. One could interpolate between the grids between months as one way to compensate for inadequate temporal resolution.

• An alternative would be to use the same ECMWF-derived grids used by GRGS:

There several sets of grids available acc. to J.M. Lemoine:
9 deg, 4.5 deg or 0.5 deg compiled in daily grids of albedo and IR data.

The 4.5 deg grid-data is suitable for satellites at the Stella/Starlette altitudes (ie the DORIS satellites).

In principle these data could be made available to IDS ACs if they are interested.

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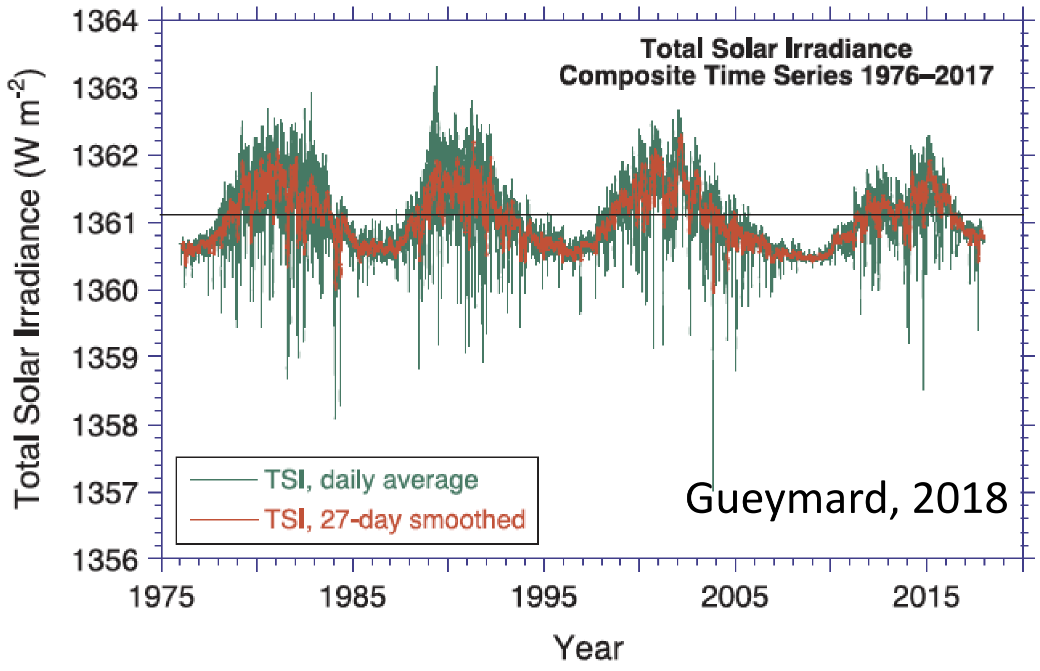
Reevaluation of the Total Solar Irradiance (TSI)

In the space geodesy era, accepted values of the TSI have ranged from 1365 to 1367 W/m^2. A number of papers have re-evaluated the satellite instrument data in recent years including the paper below. The most recent TSI data comes from the **SORCE satellite (Solar Radiation and Climate Experiment)**. The new value recommended for an ISO standard is 1361.1 $\pm$ 0.5 W/m^2.

Gueymard, Christian A., (2018). "A reevaluation of the solar constant based on a 42-year total solar irradiance time series and reconciliation of spaceborne observations", Solar Energy, 168(2-9), doi:10.1016/j.solener.2018.04.001.

This is close to the solution of Koop and Lean(2011) who redetermined the TSI to be 1360.8 W/m^2 using data from SORCE.

Kopp, G., Lean, J.L.. (2011). A new, lower value of total solar irradiance: Evidence and climate significance. Geophys. Res. Lett. 38. doi: 10.1029/2010GL045777.



The data show that the TSI varies over a solar cycle by about 4 W/m^2. IDS ACs may wish to adopt either the new mean value or the time-variable values.

If they do, then they must rescale or redetermine their solar radiation pressure models to be consistent with the new TSI (see next slides).

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How do we Improve Modelling of Radiation Pressure over previous IDS-related work? (1)

How do we improve modelling?:

1. Use best available macromodel, or a more detailed model ("UCL-type" model), bearing in mind the intrinsic assumptions of the particular approach.
2. Use quaternions rather than an attitude model, if they are available for s/c and/or appendage orientation.
3. Retune parameters if necessary using mission data.
4. Adjust C_R **"per arc",** as in Flohrer et al. (2011) ["*Generating precise and homogeneous orbits for Jason-1 and Jason-2*", Adv. Space Res. 48, 152-172. doi:10.1016/j.asr.2011.02.017].

- Adjustment of C_R per arc can help to accommodate failure of model to account for any unmodelled effects, and reduce amplitude of resultant empirical accelerations.
- CAVEAT EMPTOR! This approach will reduce size of along-track accelerations but not the cross-track OPR amplitudes!

How do we Improve Modelling of Radiation Pressure over previous IDS-related work? (2)

Test	N	Along-track (nm/s²)		Cross-track (nm/s²)	
		mean	median	mean	median
A priori Panel, Cr=0.945, Old TSI	521	0.895	0.689	2.328	2.304
A priori Panel, Cr=0.945, new TSI	521	1.089	1.018	2.262	2.225
New Panel, Cr=1, new TSI	521	0.986	0.876	2.127	2.051
New Panel, new TSI, Adj. Cr	521	0.441	0.314	2.207	2.139

Old Total Solar Irradiance (TSI) = 1367 W/m^2

New Panel, adjusts specular reflectivity of solar arrays, and -X panel.

Tests used 78 SLR+DORIS arcs, 2008-07-13 to 2009-12-31).

Tests all performed using GOCO05S + VMF1 as background models.

For Jason-2 & Jason-3 Steps were:

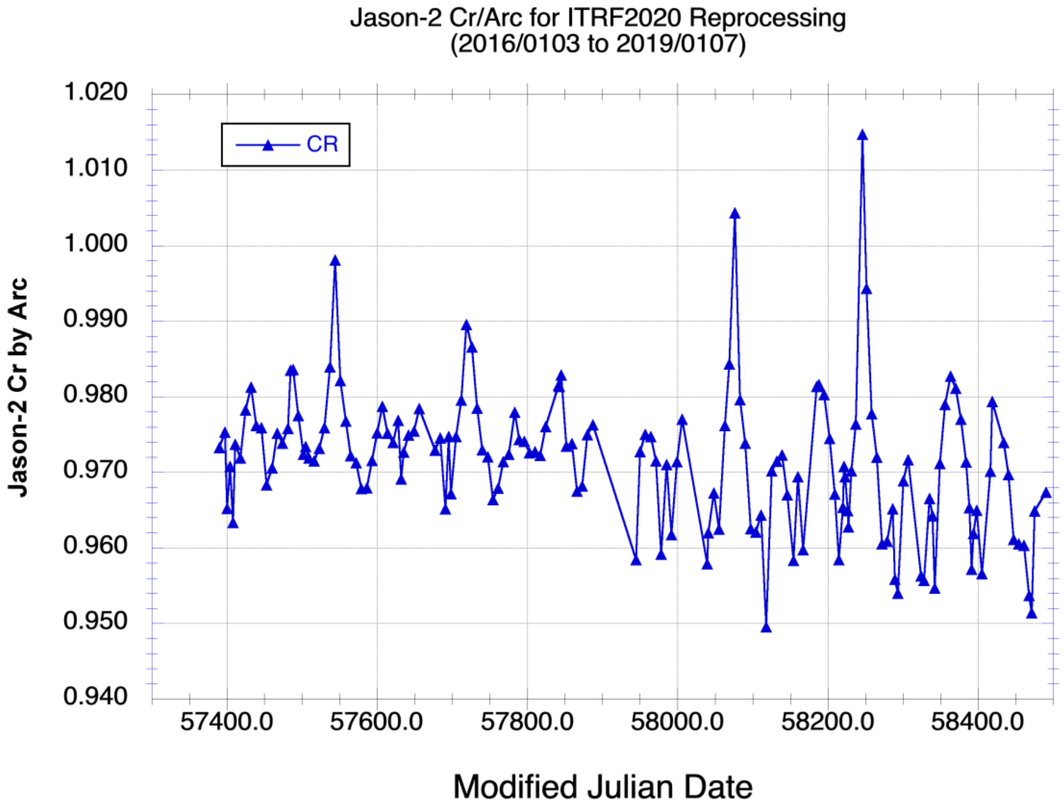
1. Tune macromodel by adjusting specific parameters using new TSI as a priori.

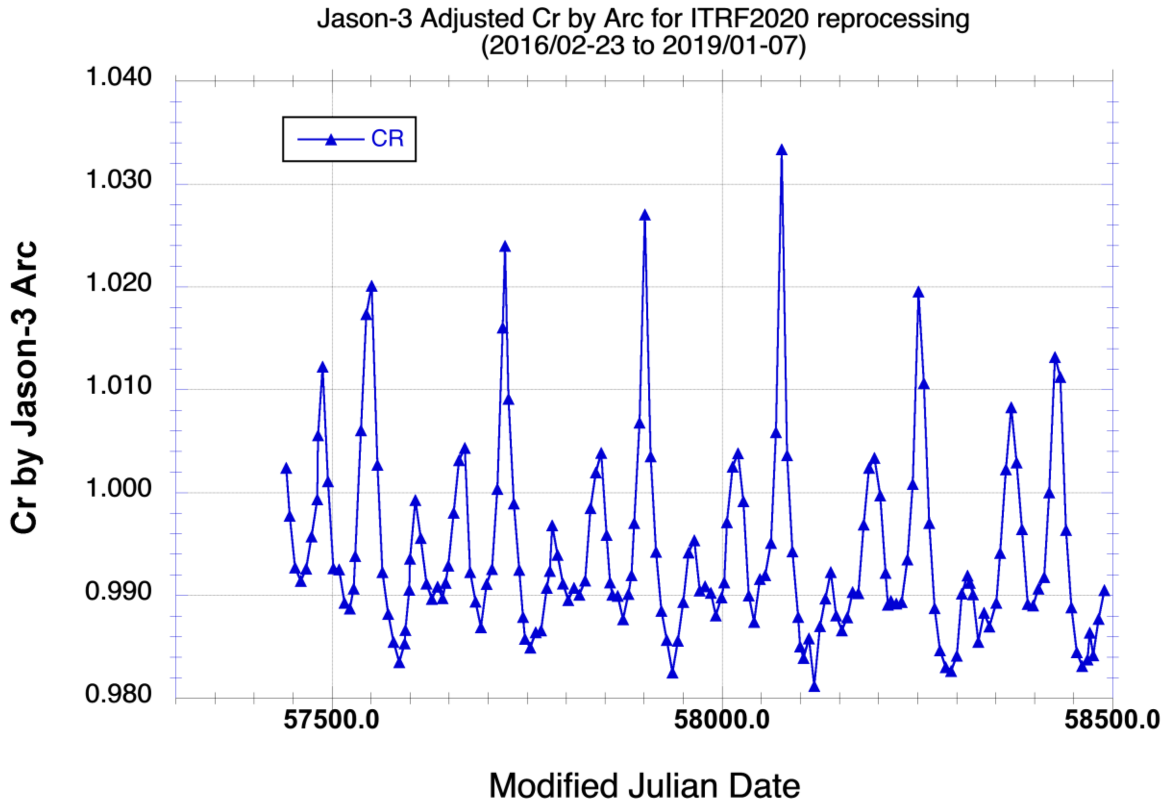
2. Re-edit enter time series of data using SLRF2014 & latest DPOD2014 (August 2019) (Constant Cr).

3. Adjust Cr/arc (no OPRs adjusted in arc), with cleaned up data (SLR & DORIS).
4. Generate final orbits and normal equations with arc-dependent Cr.

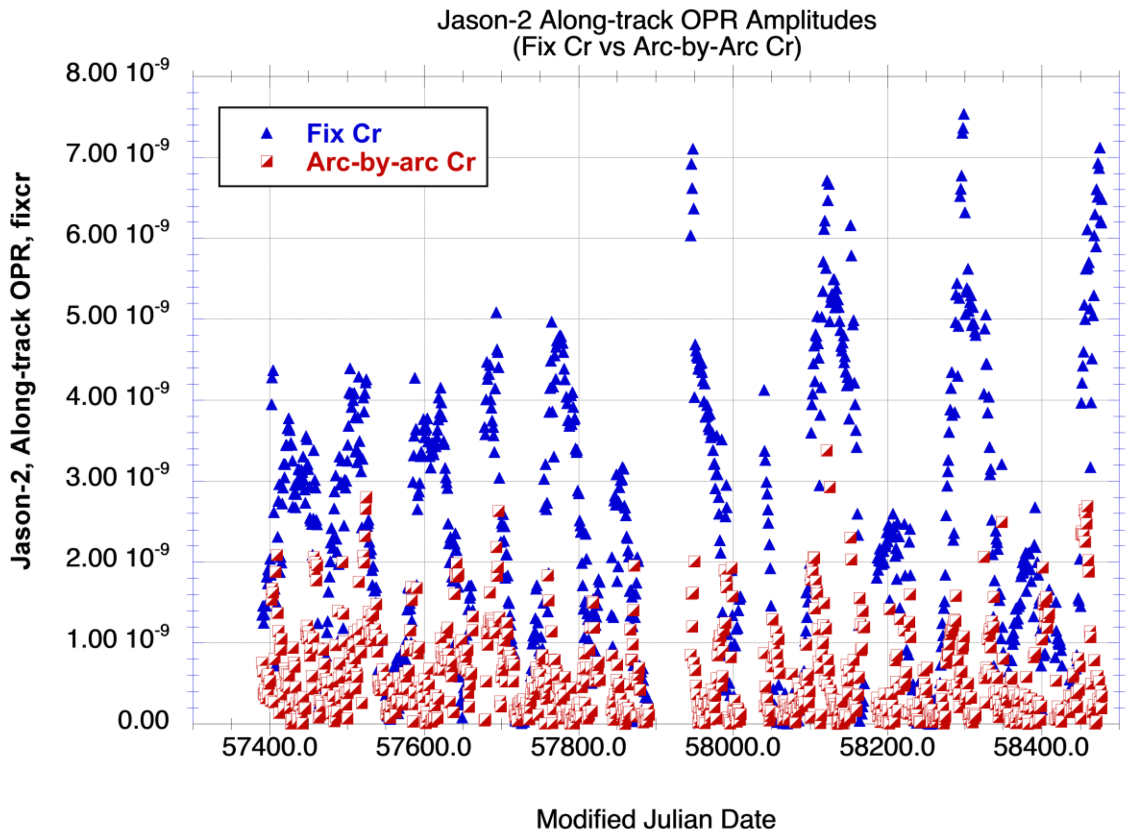
So Three complete sets of runs over the entire time series!

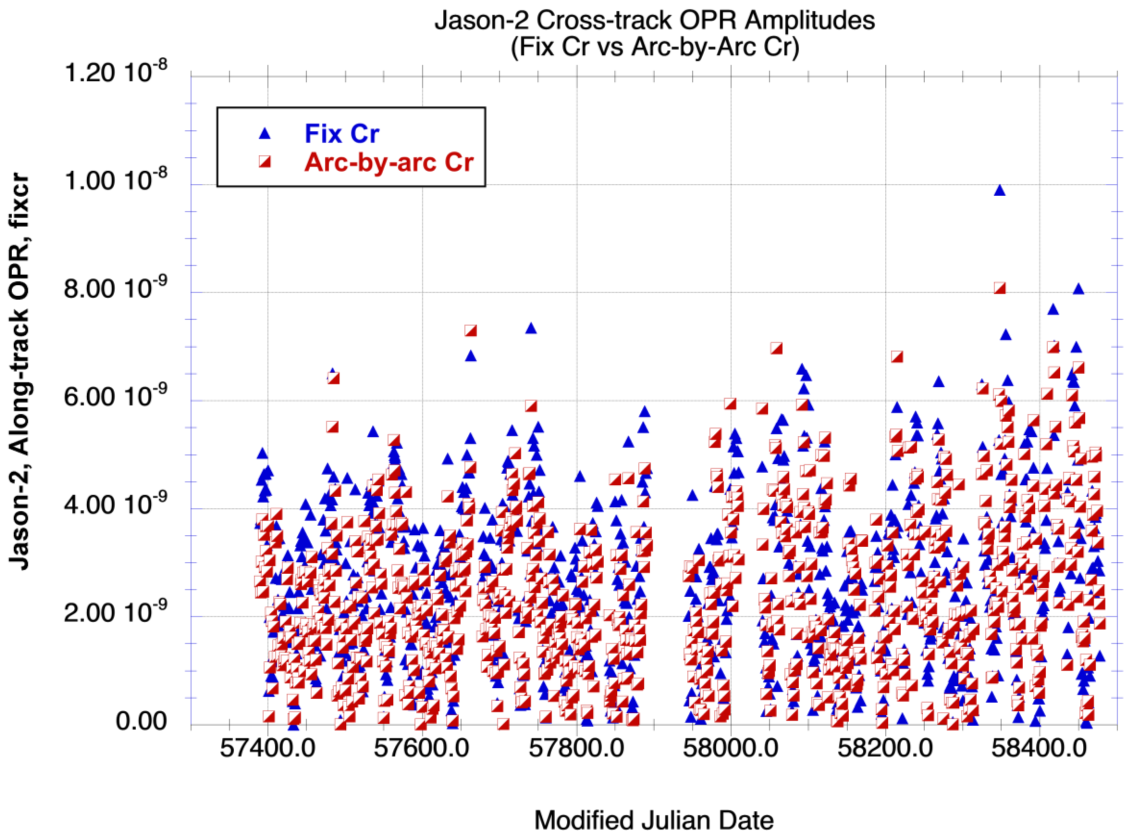
Jason-2 & Jason-3 Arc-by-arc Crs (2016-2018)





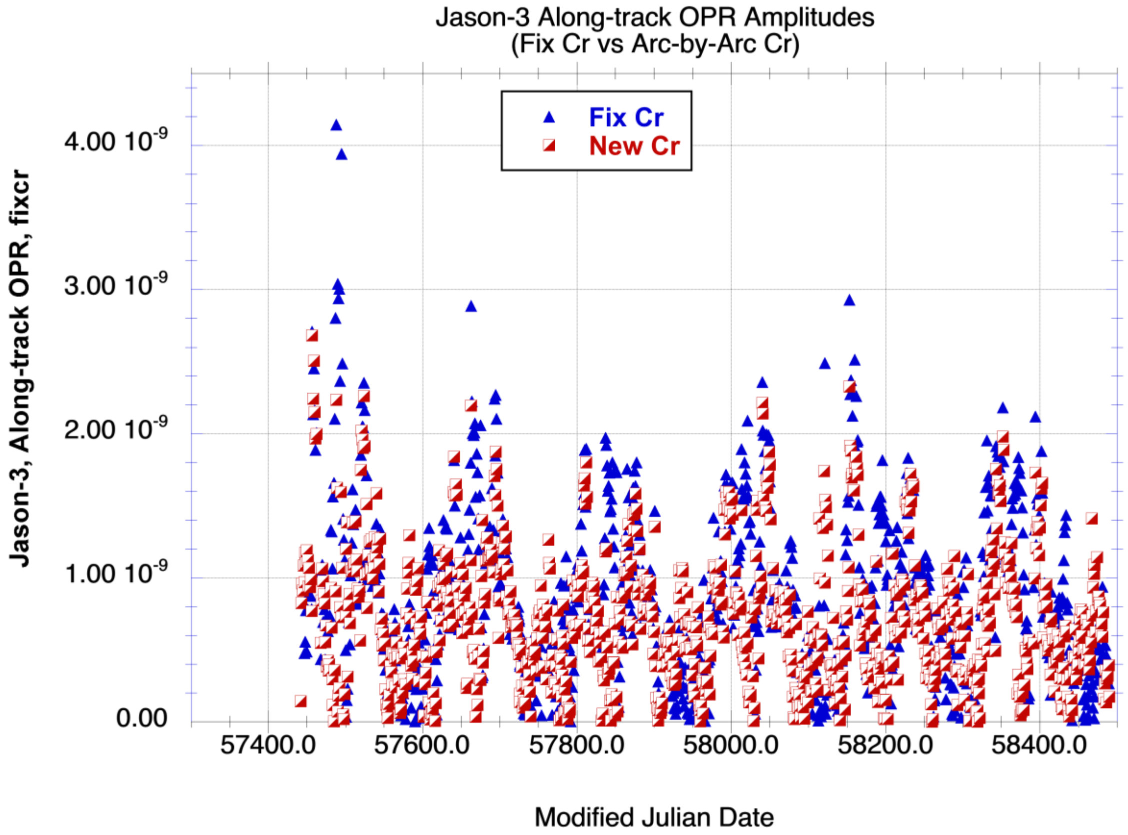
GSC Jason-2 Along-track & Cross-track OPR Amplitudes (2016-2018)

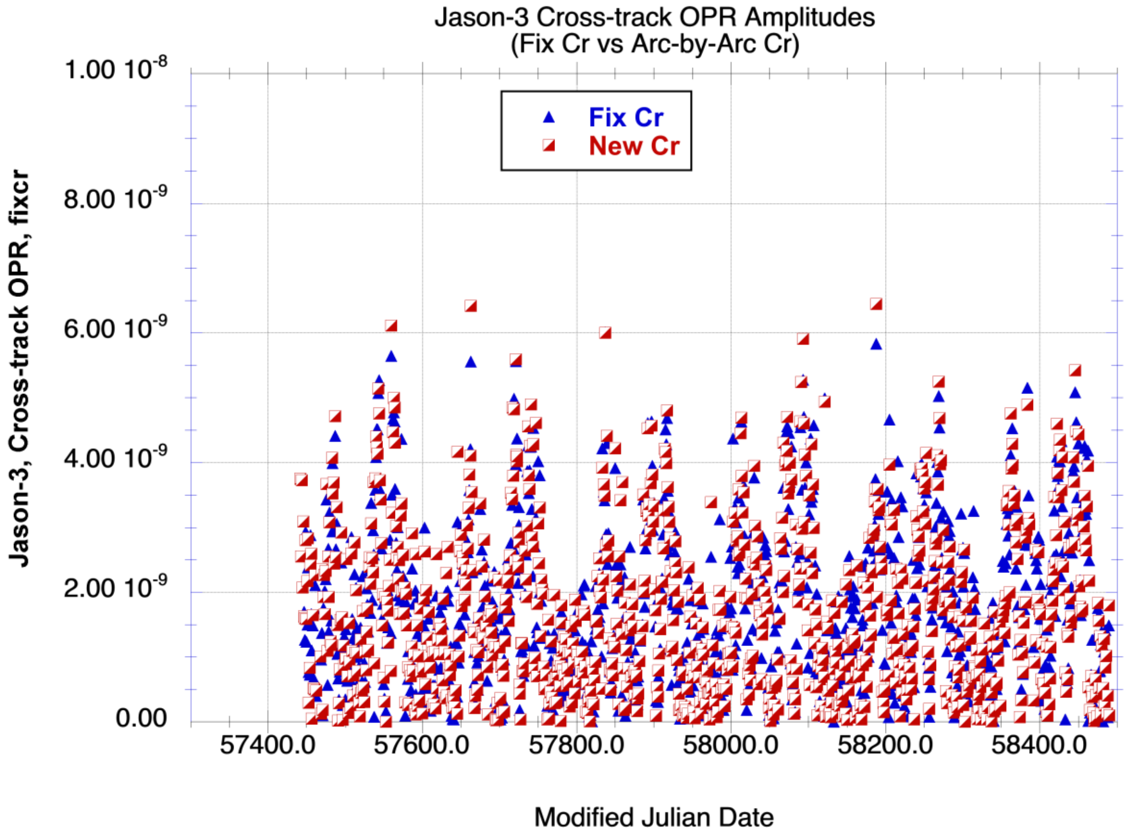




Jason-2 Series	Along-track (nm/s^2)		Cross-track (nm/s^2)	
2008/0714- 2019/0707	Avg	RMS	Avg	RMS
Fix Cr (n=3633)	2.157	2.741	2.591	2.994
Cr/Arc (n=3630)	0.455	0.649	2.223	2.589

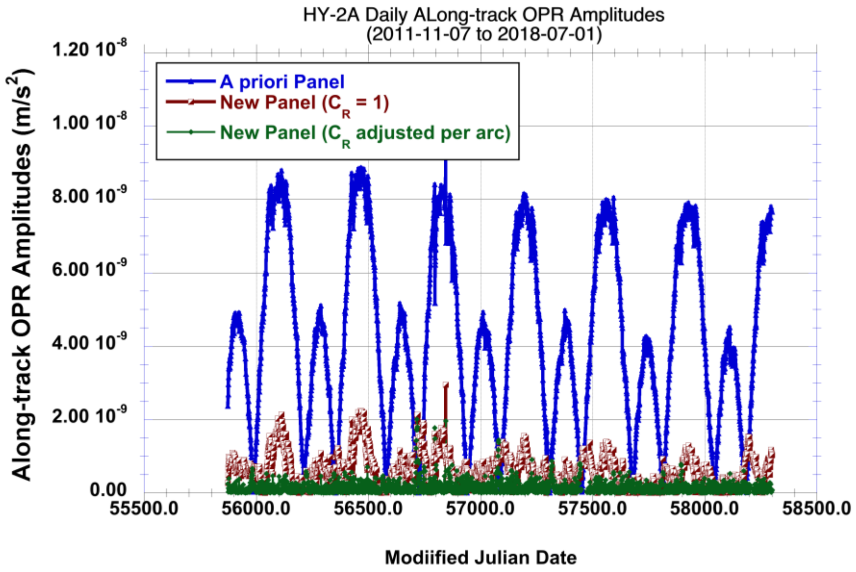
GSC Jason-3 Along-track & Cross-track OPR Amplitudes (2016-2018)

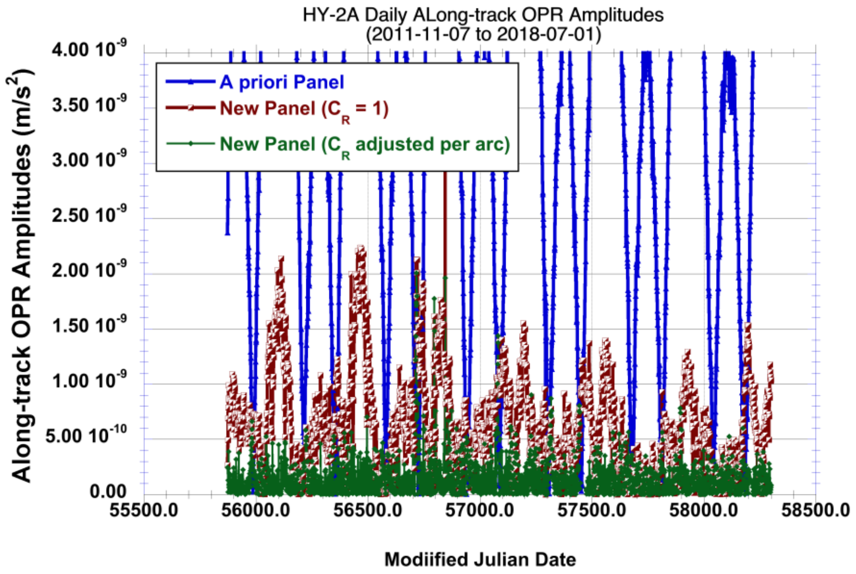




Jason-3 Series	Along-track (nm/s^2)		Cross-track (nm/s^2)	
2016/0224- 2019/0707	Avg	RMS	Avg	RMS
Fix Cr	0.872	1.064	1.777	2.158
Cr/Arc	0.706	0.840	1.674	2.098

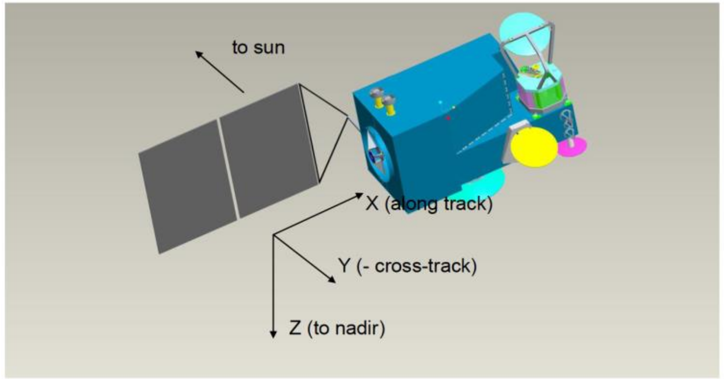
Improving the Macromodel for HY-2A (1)





Tests all performed using GOCO05S + VMF1 as background models.

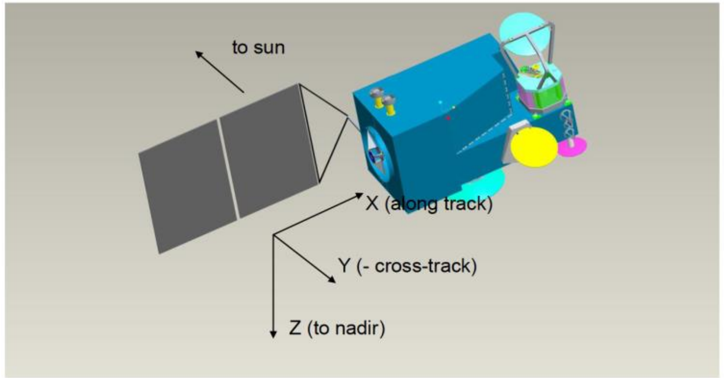
1. A priori Panel: Similar to values supplied in IDS documentation.
2. New Panel: Adjust specular reflectivity of panel that represents solar array. The *a pri*ori value of zero is unrealistic.



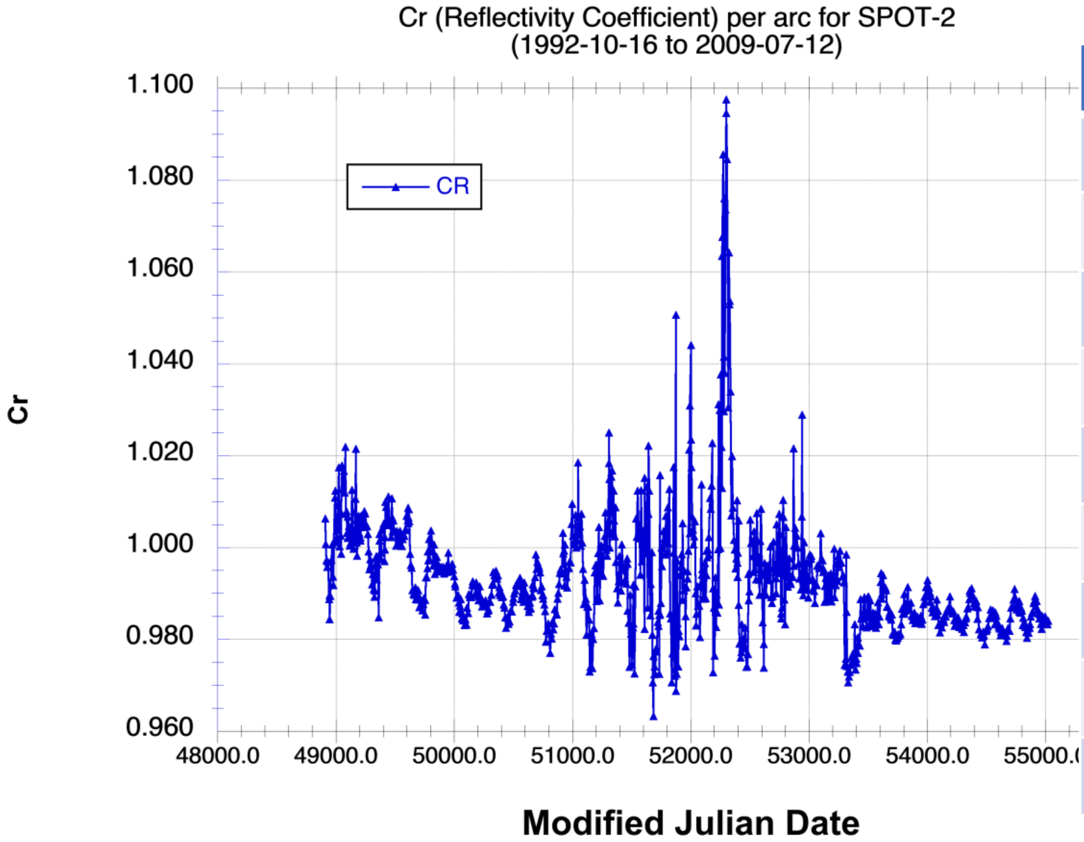
Improving the Macromodel for HY-2A (2)

A priori Values From "DORISsatelliteModels.pdf"

Panel Parameter	+X	-X	+Y	-Y	+Z	-Z
Area (m^2)	3.21	3.52	15.79	15.80	6.43	6.40
A priori visible Specular Refl.	0	0	0	0	0	0
A priori visible Diffuse Refl.	0.97	0.97	0.45	0.64	0.96	0.96
~~A priori infrared Specular Refl.~~	~~0~~	~~0~~	~~0~~	~~0~~	~~0~~	~~0~~
~~A priori infrared Diffuse~~	~~0.83~~	~~0.86~~	~~0.41~~	~~0.52~~	~~0.82~~	~~0.78~~
New visible specular reflectivity	-	-	0.22054	0.17185	-	-
New visible Diffuse reflectivity	0.56384	-	-	-	-	-



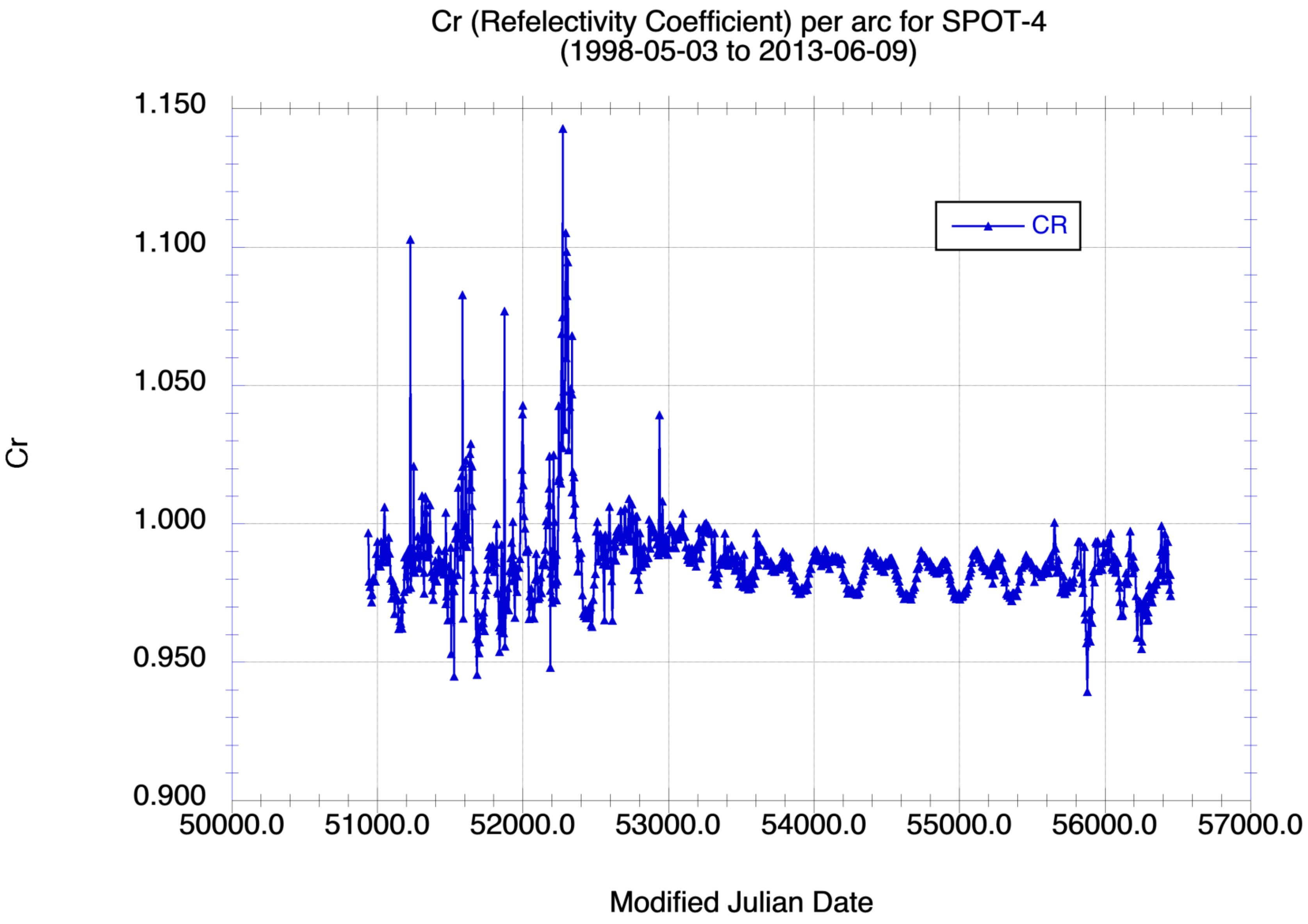
Adjusting Cr/arc for SPOT-2 (w.r.t GSFC macromodel)



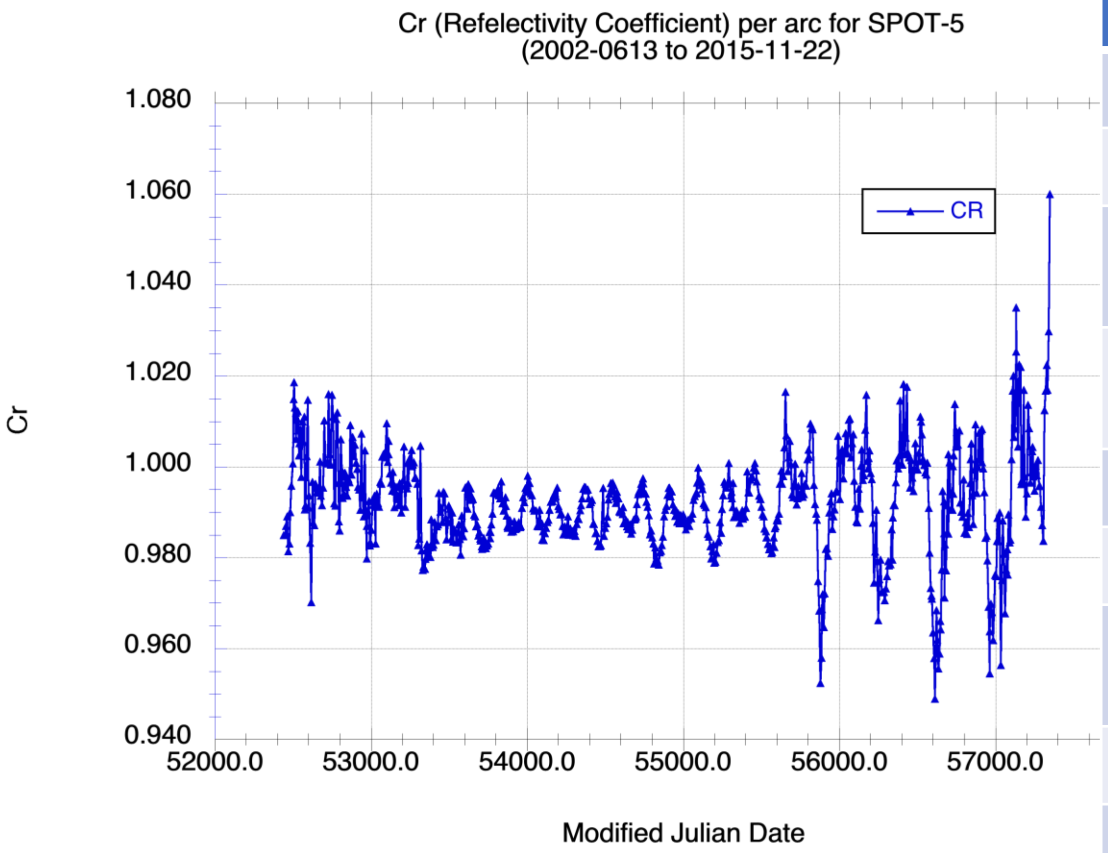
Dates	Avg. Cr	Dates	Avg Cr
1992-10 to 1993-12	1.0022 ± 0.0078	2001-01 to 2001-12	1.0015 ± 0.0186
1994-01 to 1994-12	1.0006 ± 0.0066	2002-01 to 2002-12	1.0077 ± 0.0322
1995-01 to 1995-12	0.9933 ± 0.0047	2003-01 to 2003-12	0.9964 ± 0.0081
1996-01 to 1996-12	0.9892 ± 0.0030	2004-01 to 2004-12	0.9908 ± 0.0082
1997-01 to 1997-12	0.9891 ± 0.0043	2005-01 to 2005-12	0.9845 ± 0.0050
1998-01 to 1998-12	0.9932 ± 0.0100	2006-01 to 2006-12	0.9859 ± 0.0031
1999-01 to 1999-12	0.9966 ± 0.0108	2007-01 to 2007-12	0.9854 ± 0.0027
2000-01 to 2000-12	0.9931 ± 0.0162	2008-01 to 2008-12	0.9841 ± 0.0026
2001-01 to 2001-12	1.0015 ± 0.0186	2009-01 to 2009-07	0.9847 ± 0.0023

1. High correlation between SRP & drag near Solar Maximum (1999-2003); Are the arc-by-arc values really useful?
2. The annual averages look stable and the values perhaps reflect two things: (1) TSI variability over the Solar Cycle; (2) Imprecise knowledge of mass of spacecraft vs. time (*SPOT-2 & SPOT-3 are the satellites where this info. is least well known*).
3. Cr. Values depend on (1) TSI variability; (2) unmodeled mass consumption; (3) background atmosphere density model used (4) background albedo/IR model used. ➔ **With those caveats perhaps annual average Cr's should be used for SPOT-2 & the other SPOT satellites; ACs would need to determine their own values in their software and implementation of macromodels and background models. TBC.**

Adjusting Cr/arc for SPOT-4 (w.r.t GSFC macromodel)

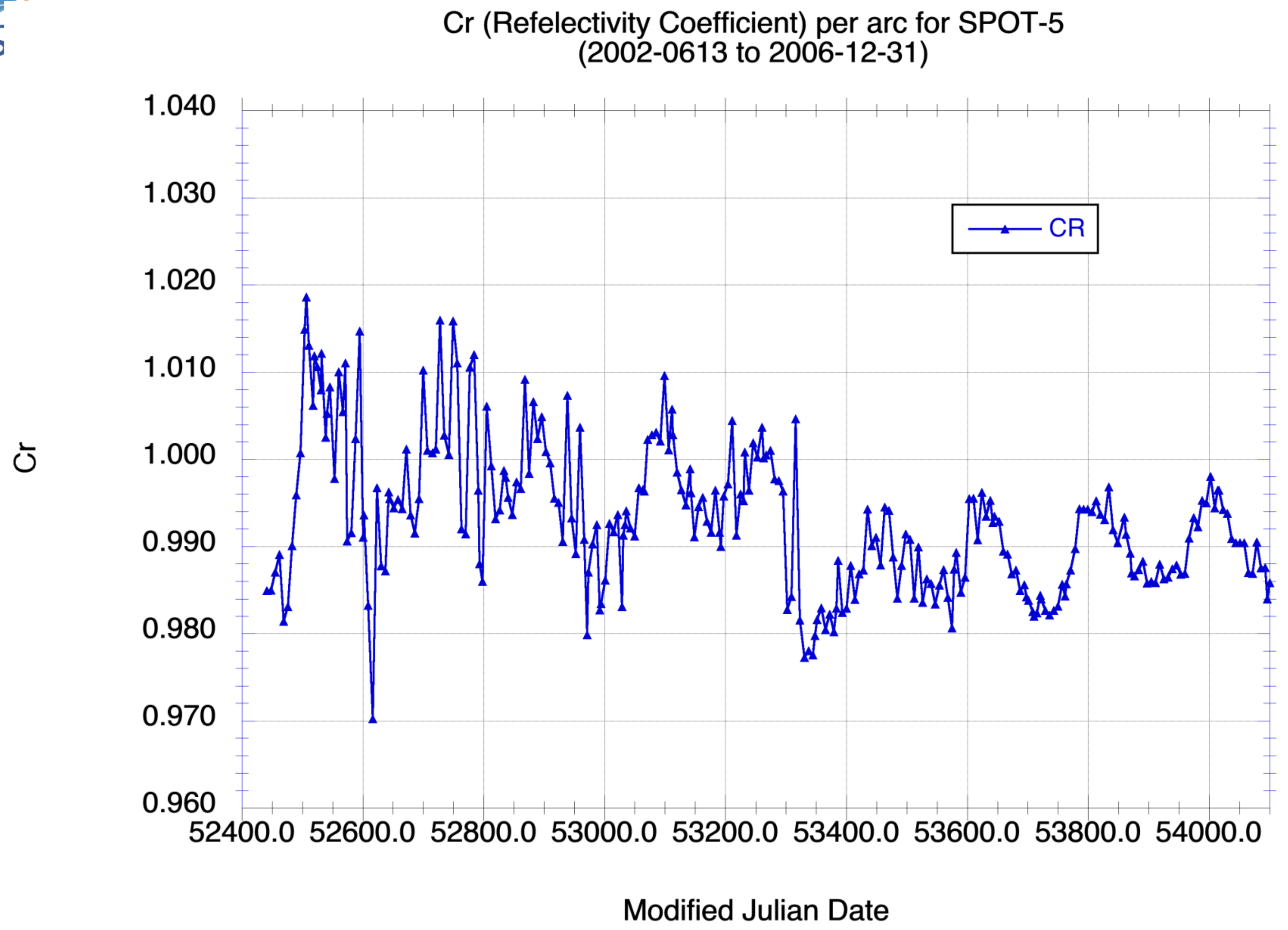


Adjusting Cr/arc for SPOT-5 (w.r.t GSFC macromodel)



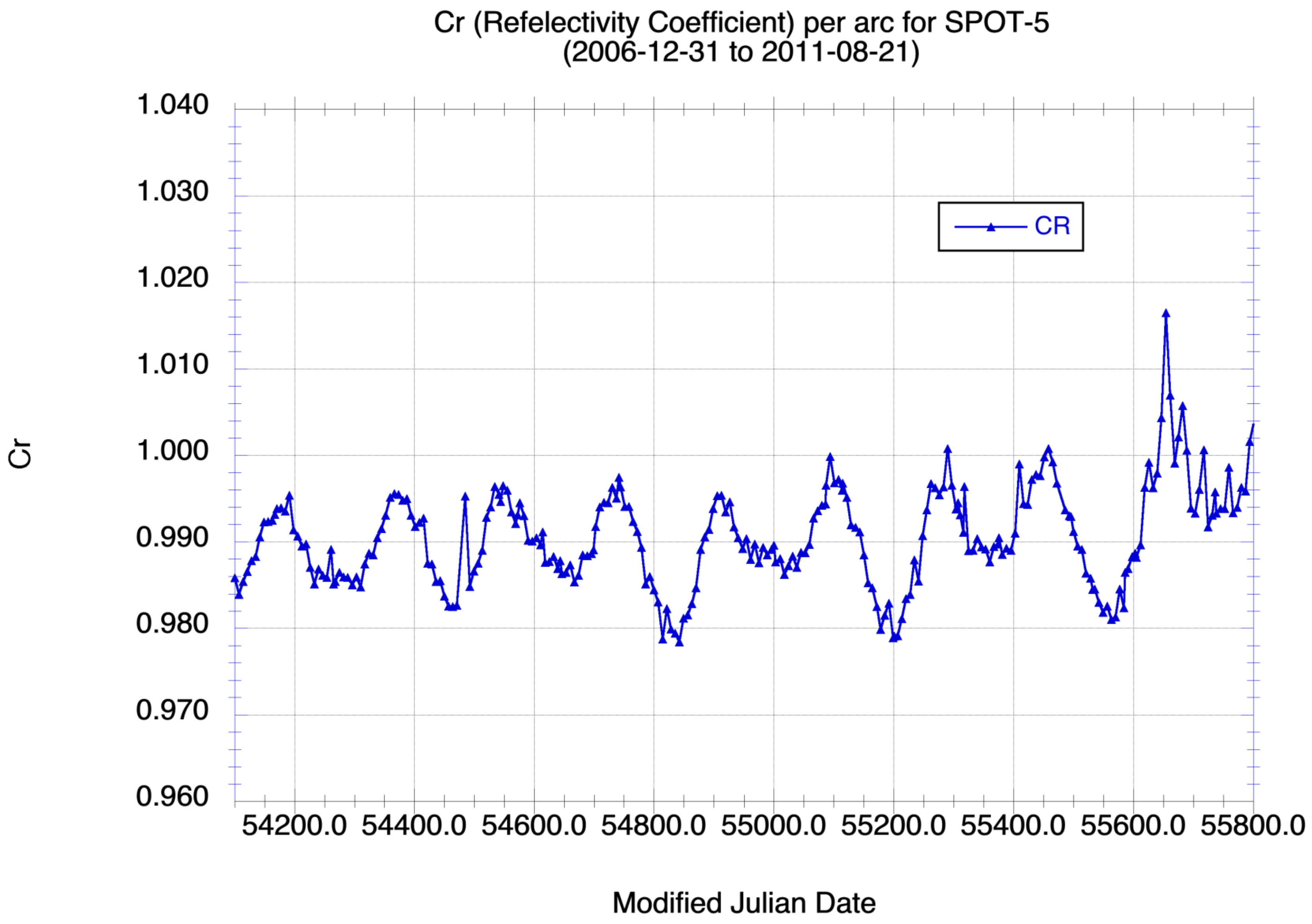
Dates	Avg. Cr	Dates	Avg Cr
2002-06 to 2002-12	0.9984 $\pm$ 0.0121	2011-01 to 2011-12	0.9914 $\pm$ 0.013
2003-01 to 2003-12	0.9975 $\pm$ 0.0081	2012-01 to 2012-12	0.9940 $\pm$ 0.0116
2003-01 to 2003-1003	0.9969 $\pm$ 0.0051	2013-01 to 2013-12	0.9898 $\pm$ 0.0023
2003-1003 to 2005-12	0.9872 $\pm$ 0.0055	2014-01 to 2014-12	0.9907 $\pm$ 0.013
2006-02 to 2006-12	0.9899 $\pm$ 0.0041	2015-01 to 2005-11	1.001 $\pm$ 0.0183
2007-01 to 2007-12	0.9892 $\pm$ 0.0038		
2008-0127 to 2008-12	0.9902 $\pm$ 0.0044		
2009-01 to 2009-12	0.9856 $\pm$ 0.0050		
2010-01 to 2010-12	0.9906 $\pm$ 0.0058		

Adjusting Cr/arc for SPOT-5 (w.r.t GSFC macromodel)

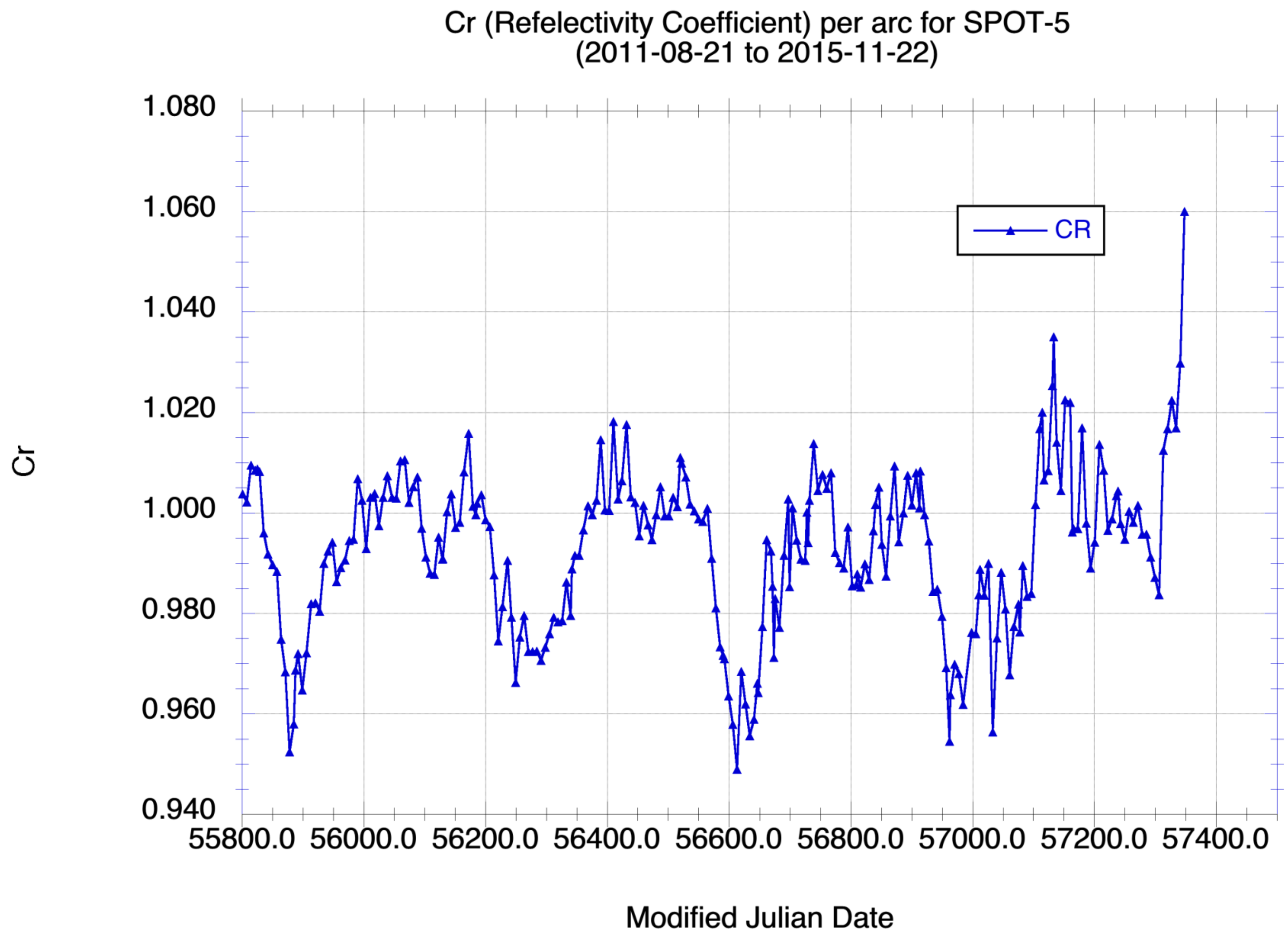


It seems around MJD 53300 (2004-10-24), give or take a few weeks, there was a change in state of SPOT-5; Somehow the mean area projected to the Sun changed appreciably around that date. Perhaps we are seeing a change in solar array pitch?

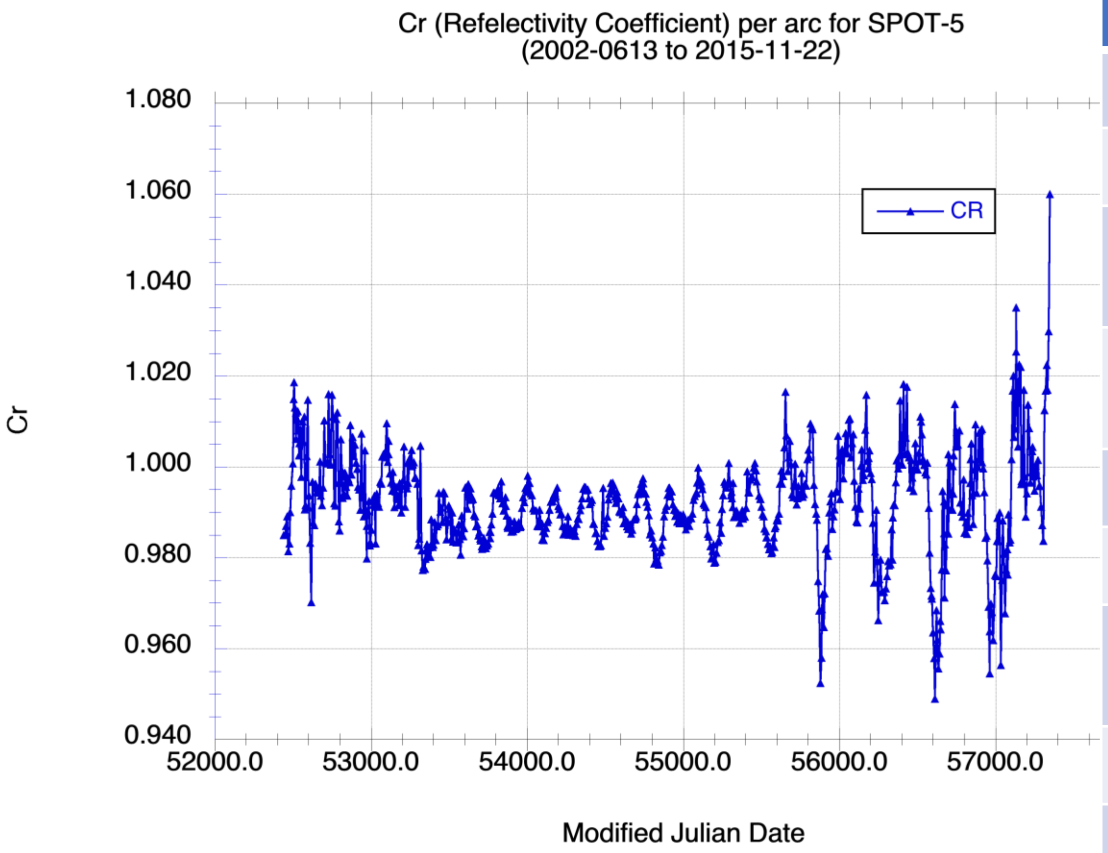
Adjusting Cr/arc for SPOT-5 (w.r.t GSFC macromodel)



Adjusting Cr/arc for SPOT-5 (w.r.t GSFC macromodel)



Adjusting Cr/arc for SPOT-5 (w.r.t GSFC macromodel)

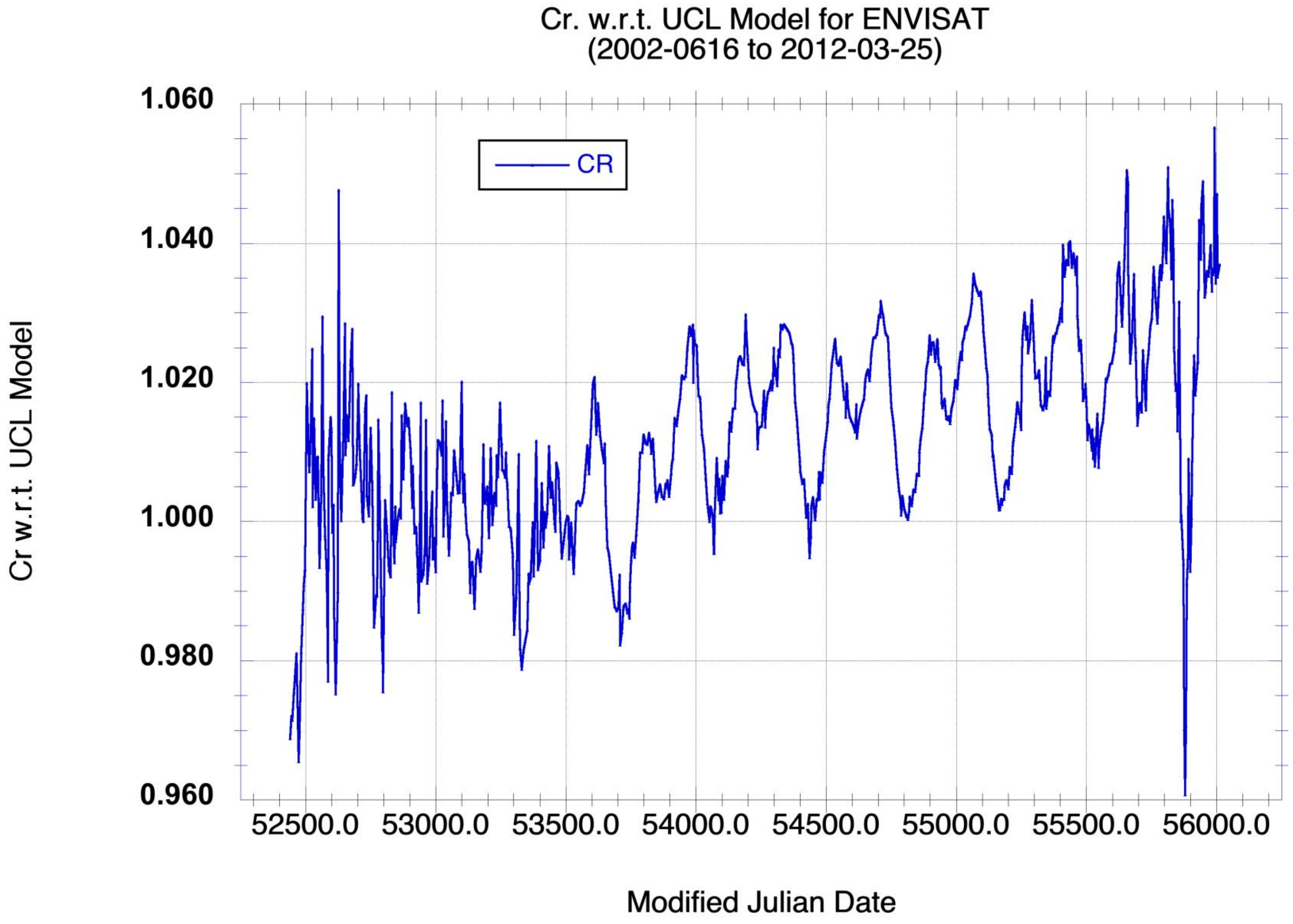


Dates	Avg. Cr	Dates	Avg Cr
2002-06 to 2002-12	0.9984 ± 0.0121	2011-01 to 2011-12	0.9914 ± 0.013
2003-01 to 2003-12	0.9975 ± 0.0081	2012-01 to 2012-12	0.9940 ± 0.0116
2004-01 to 2004-1003	0.9969 ± 0.0051	2013-01 to 2013-12	0.9898 ± 0.0023
2004-1003 to 2005-12	0.9872 ± 0.0055	2014-01 to 2014-12	0.9907 ± 0.013
2006-02 to 2006-12	0.9899 ± 0.0041	2015-01 to 2005-11	1.001 ± 0.0183
2007-01 to 2007-12	0.9892 ± 0.0038		
2008-0127 to 2008-12	0.9902 ± 0.0044		
2009-01 to 2009-12	0.9856 ± 0.0050		
2010-01 to 2010-12	0.9906 ± 0.0058		

1. High correlation between SRP & drag near Solar Maximums (2002-2003; 2010-2012); Are the arc-by-arc values really useful?
2. Modelling after January 2008 includes changes in solar array pitch as specified in DORIS system documents.
3. The annual averages look stable, except for a system change near 2004-1003..

Adjusting Cr/arc for Envisat

(w.r.t UCL model for SRP & 10-plate macmodel for drag & albedo/IR)



I	**Nonconservative Force Model Accelerations on DORIS Satellites.** A. Overview. B. SRP, Albedo/IR, Drag Acceleration Magnitudes, by satellite. C. OPR Residual Comparison with DORIS ACs D. “Other” accelerations: Thermal, more detailed Albedo/IR.
II	**Impact of Using new Total Solar Irradiance (TSI).**
III	**Improving a macromodel.** A. Example with Jason-2 or Jason-3. B. Adjusting Cr/arc for Jason-2/Jason-3. C. Cr/arc history for other satellites.
IV	**Jason-2/3 Orbit comparison among ACs.**
V	**Survey of modelling for IDS ACs.**
VI	**Conclusions and Recommendations**

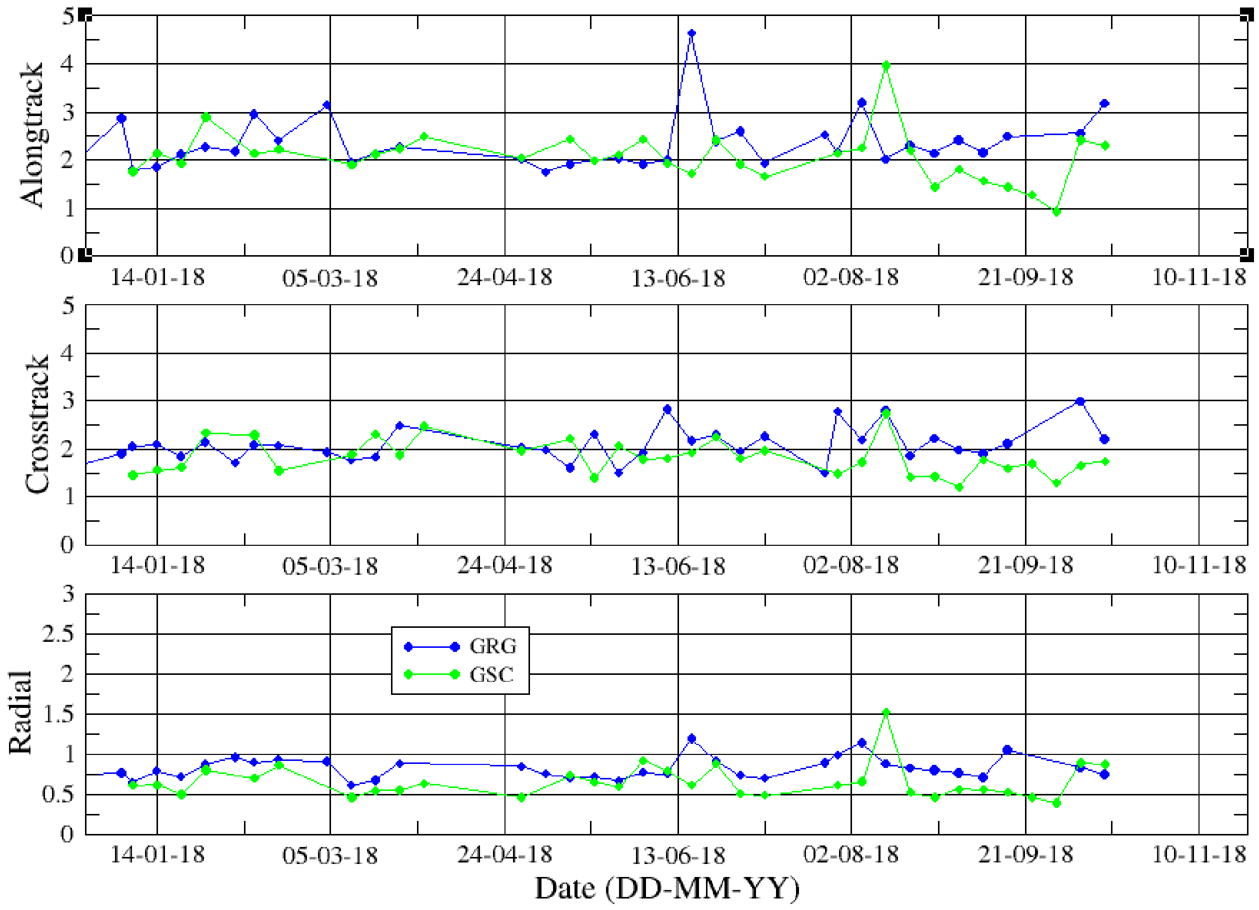
Comparison to CNES (GDR-E) orbit

❑ **Jason-2 orbit differences**

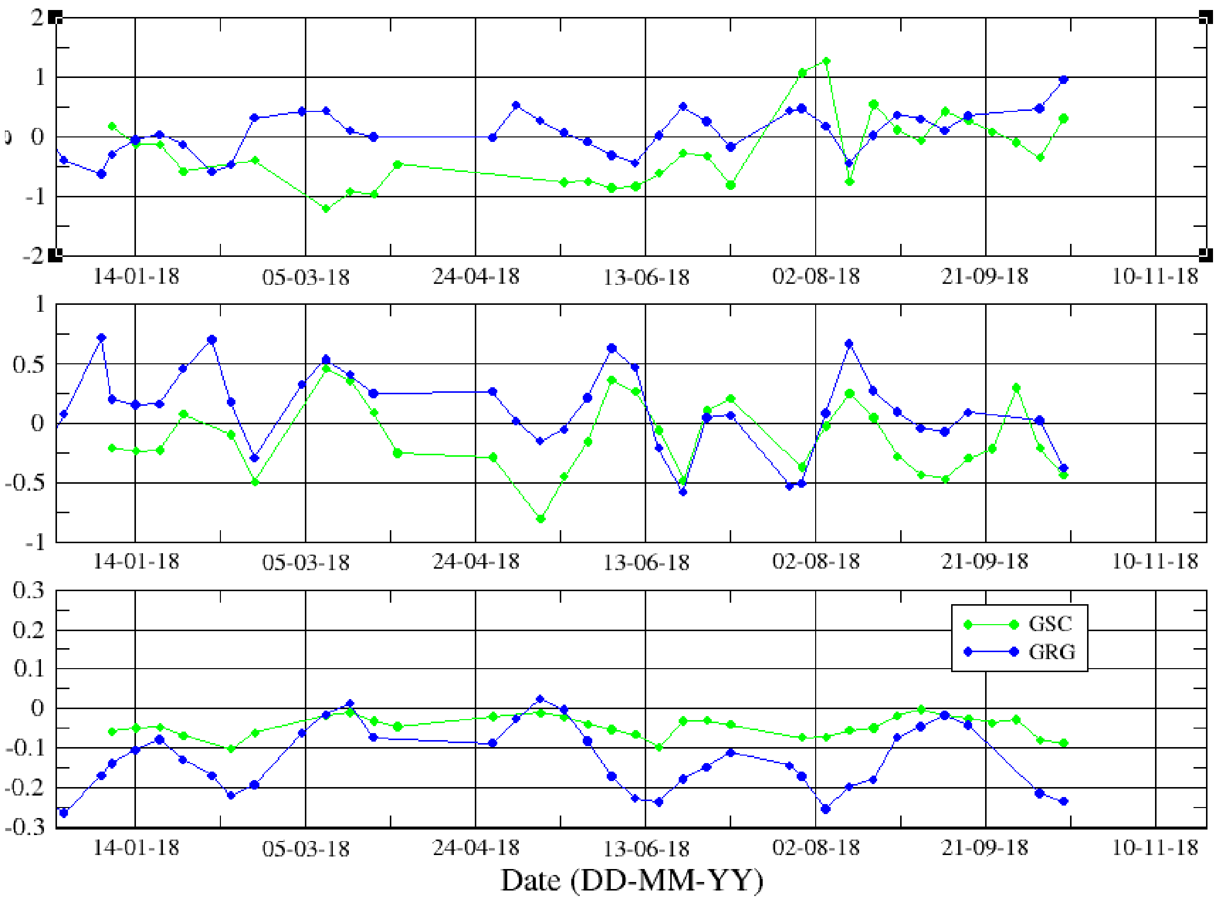
Orbits GSC, GRG

REF = CNES-GDR-E orbit

RMS of orbit differences (in cm)



Mean of orbit differences (in cm)



by H. Capdeville, CLS (Toulouse)

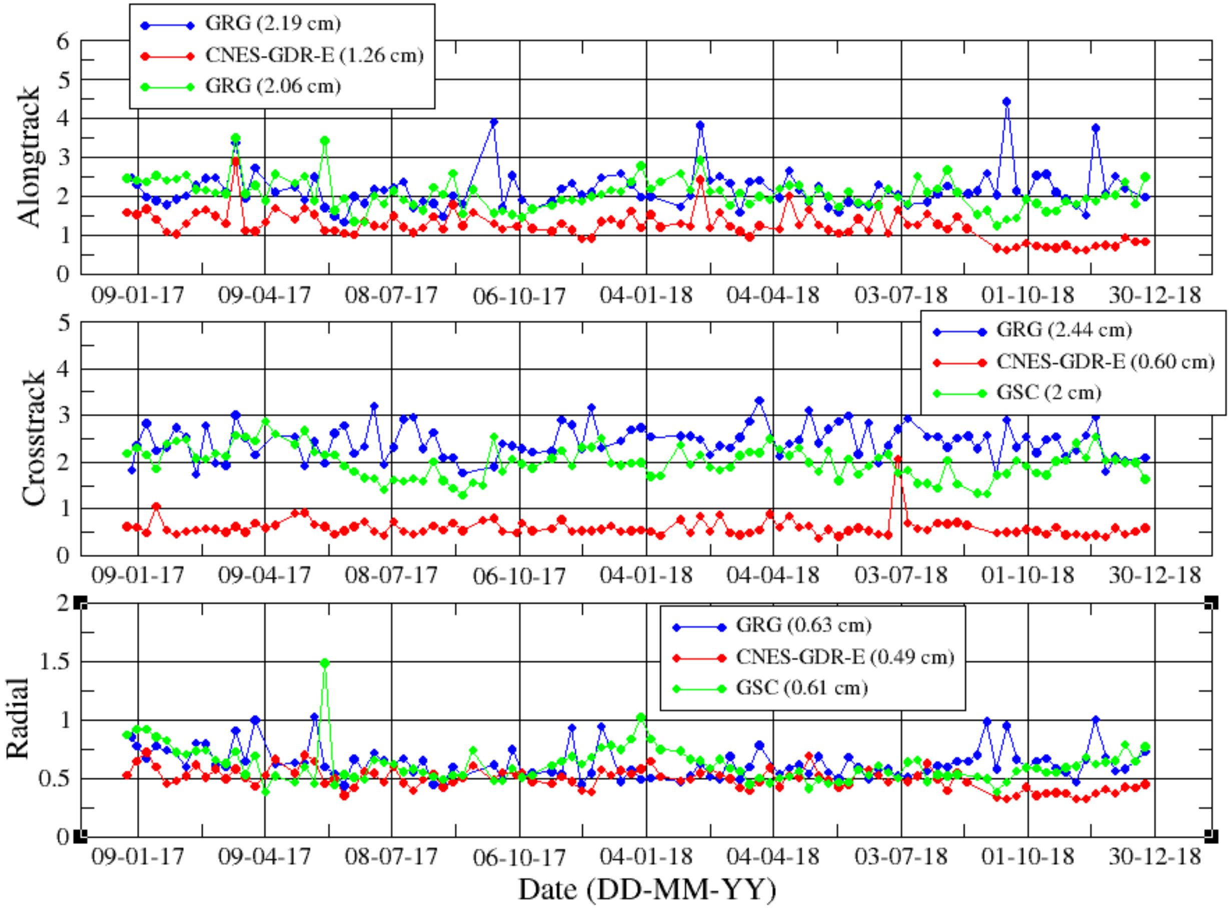
Comparison to JPL orbit

- Jason-3 orbit differences

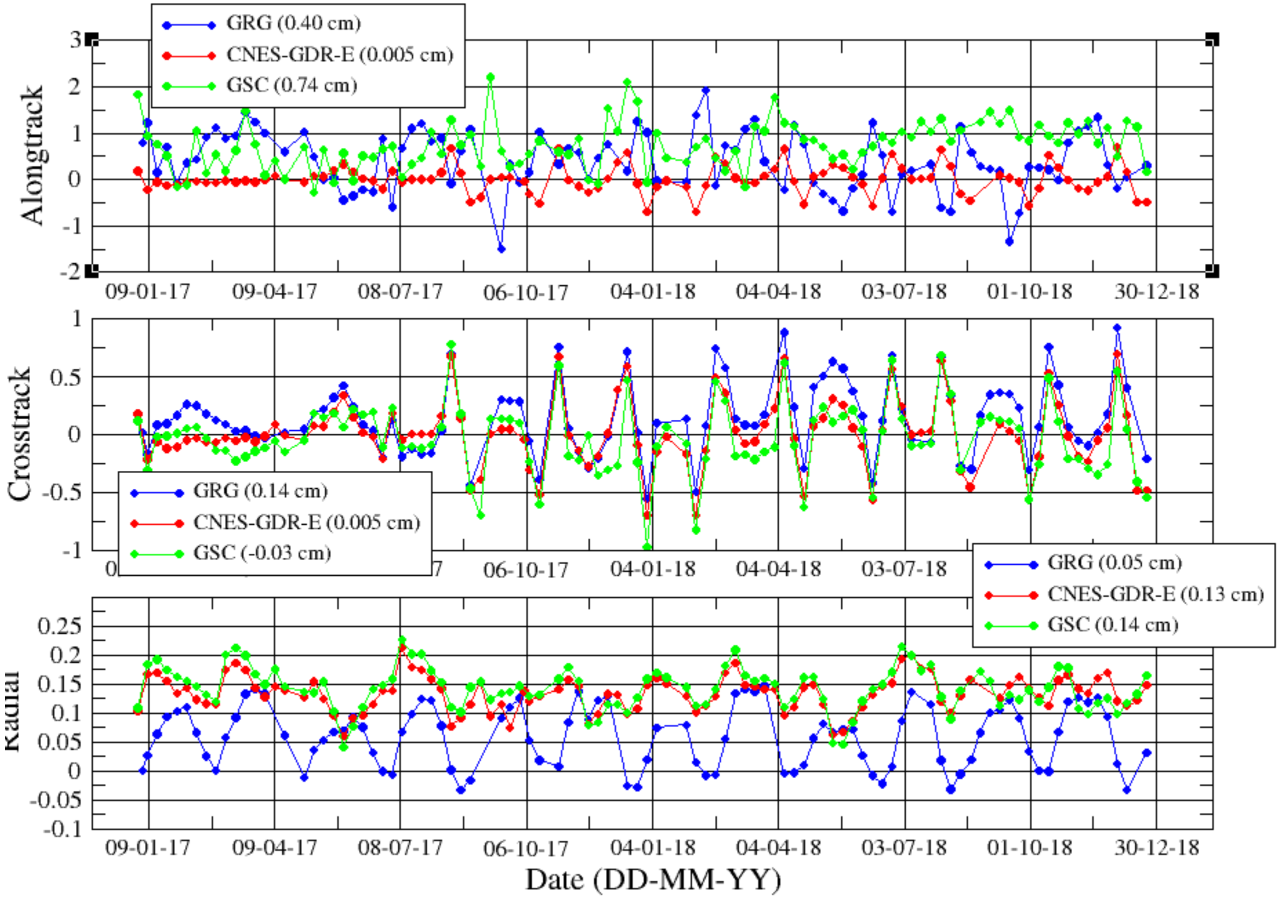
Orbits GSC, GRG, CNES-GDR-E

REF = JPL orbit

RMS of orbit differences (in cm)



Mean of orbit differences (in cm)



by H. Capdeville, CLS (Toulouse)

Perspectives

Future work

- *Comparison between other orbits (GOP, …?)*
- *Other satellites: Topex, …*
- *SSH Crossover variance*

I	**Nonconservative Force Model Accelerations on DORIS Satellites.** A. Overview. B. SRP, Albedo/IR, Drag Acceleration Magnitudes, by satellite. C. OPR Residual Comparison with DORIS ACs D. "Other" accelerations: Thermal, more detailed Albedo/IR.
II	**Importance of Accurately Modelling Satellite Attitude** A. Jason-3 Example.
III	**Impact of Using new Total Solar Irradiance (TSI).**
IV	**Improving a macromodel.** A. Example with Jason-2 or Jason-3. B. Adjusting Cr/arc for Jason-2/Jason-3. C. Cr/arc history for other satellites.
V	**Jason-2/3 Orbit comparison among ACs.**
VI	**Survey of modelling for IDS ACs.**
VII	**Conclusions and Recommendations**

Nonconservative Force Modelling
For attitude: specify quaternions or attitude model

THEME		ESA	GOP	GRG	GSC	IGN	INA
Nonconserv-ative Force Modelling	Jason-2 Macromodel Update since ITRF2014? If Yes, how.		**No, adjust Cr/arc**	**No (Estimated Cr= 0.97)**	**Yes + adjust Cr/arc**		
	Jason-2 Attitude Modelling (spacecraft)		**quaternions**	**quaternions**	**quaternions**		
	Jason-2 Solar array attitude		**quaternions**	**quaternions**	**quaternions**		
	Jason-3 Macromodel (tuned, Yes or No. If Yes How)		**No, adjust Cr/arc**	**No (Estimated Cr= 0.99)**	**Yes + adjust Cr/arc**		
	Jason-3 Attitude Model (spacecraft)		**quaternions**	**quaternions**	**quaternions**		
	Jason-3 Solar Array Attitude		**quaternions**	**quaternions**	**quaternions**		
	HY-2A Update since ITRF2014? If Yes, how.		**Yes. New value of DORIS CoP. Adjust Cr/arc**	**Yes. New value of DORIS CoP (Estimated Cr= 0.86)**	**Yes. Panel parameters re-estimated**		

Nonconservative Force Modelling
For attitude: specify quaternions or attitude model

THEME		ESA	GOP	GRG	GSC	IGN	INA
Nonconserv-ative Force Modelling	Sentinel-3A Macromodel Tuned or A priori		**Cr adjusted per arc**	**CoP estimated: +2 cm in cross-track (Estimated Cr= 1.0)**	**-**		
	Sentinel-3A Attitude Modelling (spacecraft)?		**Attitude model**	**Attitude model**	**-**		
	Sentinel-3A Solar array attitude ?		**As per attitude model**	**As per attitude model**	**-**		
	Sentinel-3B Macromodel Tuned or a priori		**Cr adjusted per arc**	**CoP estimated: +2 cm in cross-track (Estimated Cr= 1.0)**	**-**		
	Sentinel-3B Attitude Model (spacecraft) ?		**Attitude model**	**Attitude model**	**-**		
	Sentinel-3B Solar Array Attitude?		**As per attitude model**	**As per attitude model**	**-**		
	Cryosat-2 Update since ITRf2014? If Yes, how.		**Yes, Cr fixed = 0.88 *(to be revised)***	**No (Estimated Cr= 1.0)**	**No**		
	Saral Macromodel Tuned or a priori		**Yes, Cr fixed = 1.00**	**A priori (Estimated Cr= 1.0)**	**Yes. Retuned. Cr/Arc, TBD**		

Nonconservative Force Modelling
For attitude: specify quaternions or attitude model

THEME		ESA	GOP	GRG	GSC	IGN	INA
Nonconserv-ative Force Modelling	Jason-1 Macromodel Update since ITRF2014? If Yes, how.		**No, Cr adjusted per arc**	**No (Estimated Cr= 0.94)**	**Yes. Retuned + Cr/arc**		
	Jason-1 Spacecraft Attitude?		**quaternions (planned)**	**quaternions (planned)**	**quaternions**		
	Jason-1 Solar Array Attitude?		**quaternions (planned)**	**quaternions (planned)**	**quaternions**		
	TOPEX Macromodel update since ITRF2014?		**No, Cr adjusted per arc**	**No (Estimated Cr= 1.03)**	**Yes.**		
	TOPEX Attitude		**Attitude model**	**Attitude model**	**Attitude model**		
	TOPEX Solar array Attitude		**As per Attitude model**	**As per Attitude model**	**As per Attitude model**		

Nonconservative Force Modelling
For attitude: specify quaternions or attitude model

THEME		ESA	GOP	GRG	GSC	IGN	INA
Planetary Radiation Pressure Model (Albedo/Thermal Emission); Updated?			**Knocke et al. 1988**	**Albedo and IR pressure values interpolated from ECMWF 6hr grids**	**Knocke et al. 1988; CERES To be Implemented**		
Atmospheric Density Model & Update Since ITRF2014?			**MSIS86; No**	**DTM_94; No**	**MSIS86; No**		
Cd adjust			**Satellite and time dependent. Optimization of the settings is under development**	**Satellite and time dependent. No change from ITRF2014**	**Satellite and time dependent. No change from ITRF2014**		
Total Solar Irradiance (TSI) Value (1 AU), Used. Old or new Value, or Variable value			**(Old) 1367 W/m**2**	**(Old) 1367 W/m**2**	**(New) 1361.0 W/m**2**		
Integration Step Size			**90 sec (shorter to be tested)**	**60 sec As for ITRF2014**	**15 sec instead of 20-30 sec for ITRF2014**		

Summary & Conclusions (1)

I. Since the 117-day draconitic signal was identified in the DORIS geodetic products, the highest priority should be to mitigate any contributions of surface force mismodelling on the TOPEX and Jason satellites.

II. (A) Use quaternions for spacecraft and solar array if available;
(B) Adjust Cr/arc to accommodate empirically what the micromodel cannot absorb.
(C) For GSC, the Cr/arc adjustment really reduces the along-track OPR amplitudes for TOPEX, Jason-2, to a smaller extent on Jason-3.

III. For the sun-synchronous satellites, this Cr/arc strategy can also be applied, if one averages the arc-values per annum (TBC).

IV. No thermosphere model update is available that would be useful for DORIS satellites.

V. It seems improving the Knocke et al. (1988) model for albedo/IR is desirable. CERES Level-3 monthly products might not be the right fit especially in temporal resolution (1 month). ECMWF-derived products might be more useful (ie a better fit in terms of spatial and temporal resolution).

VI. Consider adopting the new TSI of 1361 W/m^2 with caveat that radiation pressure models would need to be retuned or rescaled.

VII. For software with fixed-step integrators, consider reducing the integration step size to better model low-beta prime (eclipse) transitions. GSC has noticed this improves the SLR fits at low beta prime (Already presented at the OSTST).

Summary & Conclusions (2)

VIII. The a priori micromodel for Hy2A has unrealistic values for specular reflectivity; Consider adopting the GSC model. Adjusting a Cr/arc might not be advisable since spacecraft is close to a full-Sun orbit, but experiences eclipse periods in February and August of each year.

IX. For Sentinel-3A/3B satellites, the ACs are using attitude model rather than quaternions. It behooves the Acs or AACs to quantify the magnitude of the deviations of the attitude law from the nominal attitude and the deviations of the orientation of the solar array from the nominal attitude.

X. For Cryosat-2 the CNES macrmodel (used in ITRF2014) still seems the best model. Any attempt to retune that model should be done in a low-drag period (2017-2018).

XI. Horizontal Wind Models in the thermosphere, and atmospheric lift (from free molecular flow) are not discussed in this presentation. There is a lack of information as to what the magnitude of the effects might be – they could be more important for the lower satellites. This is probably a research item that will have to be worked on but no recommendation is possible for the ITRF2020 reprocessing.

XII. We need to be aware of what we are not modelling in our respective orbit determination softwares with the micromodel approach (Thermal effects and self-shadowing for example).