DORIS USO Behavior Revealed by Jason-2/T2L2

F.G. Lemoine, *P. Exertier, A. Belli, N. Zelensky*

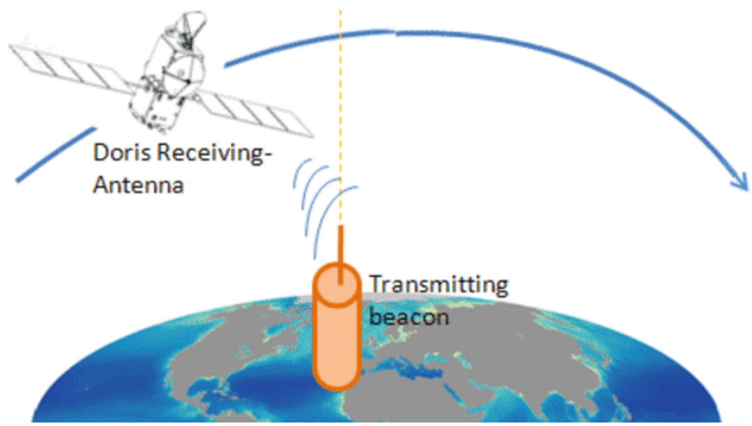
IERS Unified Analysis Workshop

Université Paris-Diderot

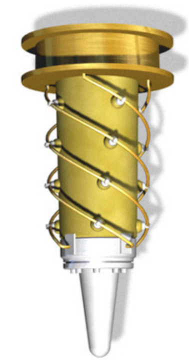
Paris, FRANCE

July 10-12, 2017

DORIS System Description



DORIS System Configuration



DORIS Satellite Antenna

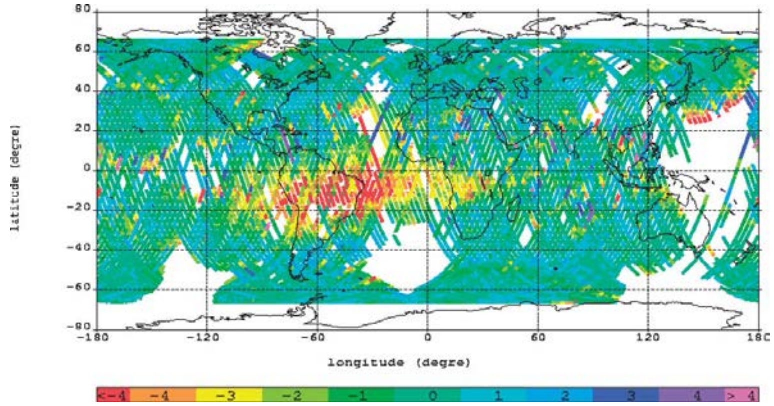
DORIS Oven-controlled USO

<u>USO Characteristics:</u>

- Heart of DORIS system is USO.
- Accuracy of phase measurements determined by stability of USO.
- USO is a crystal-oscillator that is pre-hardened to reduce sensitivity to radiation (e.g. Jason-2, Jason-3).
- DORIS USO's have a sensitivity to radiation exposure through passage in the South Atlantic Anomaly. Jason satellites more affected @ 1336 km); Discernible on other satellites (SPOT-5, @ ~800 km).

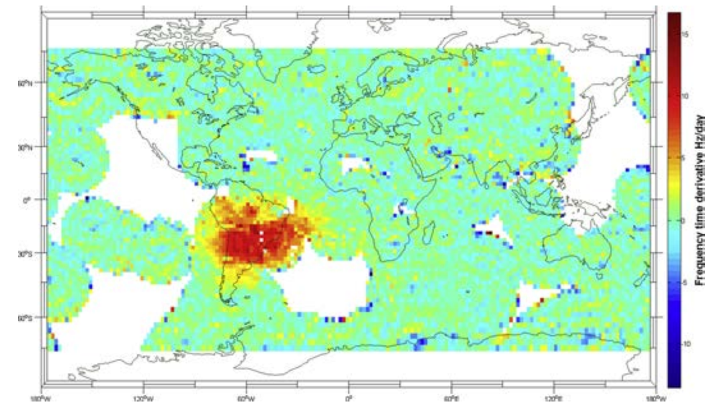
Auriol and Tourain, Adv. Space Res., (2010)

DORIS/USO – Previous Experiences



DORIS TOPEX vs. Jason-1 Frequency Anomalies, Apr. 2003

Willis et al, CR Geoscience. (2004)



SPOT-5 Freq Drift from 2011, Hz/day

Stepanek et al. Adv. Space Res. (2013)

1. Anomalous frequency (Δf/f) leads to anomalous height estimation for stations in heart of SAA.
2. For stations on border, behavior is complicated because ascending or descending passes are more affected.
3. A correction model (JM Lemoine & Capdeville, 2006) allows data to be used for POD. Not suitable for pos-vel. estimation (SAA stations).

1. SPOT-5 SAA effect undetected until pointed out by Stepanek et al. (2010).
2. Smaller than Jason-1, but still noticeable effect; Important after 2006.
3. Stations in and near SAA are most perturbed; e.g. CADB, ARFB, SANB,KRWB, HEMB, ASEB.
4. Corrective model used for ITRF2014. Capdeville et al. (2016).

Radiation Exposure

(from CNES Engineering tables)

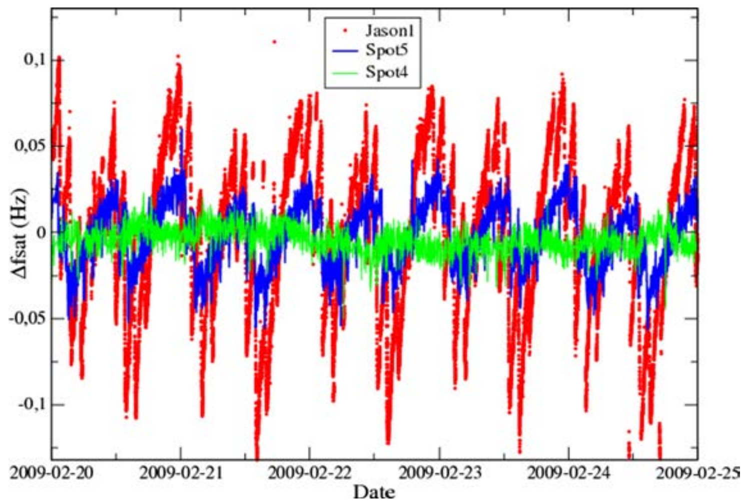
km / °	0	15	30	45	60	75	90
36000	1062,02	837,09	505,15	369,52	313,98	292,21	291,47
34000	1591,68	1273,07	788,17	548,4	461,56	423,6	411,54
32000	2509,33	2026,37	1248,13	840,76	691,34	627,64	609,29
30000	3858,56	3133,92	1940,93	1282,93	1042,78	938,95	906,6
28000	5783,9	4737,35	2972,89	1942,81	1559,35	1396,68	1348,62
26000	8343,46	6934,36	4425,04	2878,37	2295,66	2047,58	1969,35
24000	11362,21	9632,96	6338,59	4109,87	3246,64	2886,92	2777,21
22000	15777,46	13421,91	8976,2	5846,92	4596,84	4069,04	3912,51
20000	20175,89	17562,4	12104,74	7924,85	6162,78	5451,96	5245,02
18000	24011,77	21454,28	15410,17	10196,69	7836,68	6915,93	6657,84
16000	22585,46	21570,6	16894,15	11385,25	8618,85	7577,93	7284,74
14000	14779,27	16125,29	14741,68	10512,99	7731,49	6744,47	6476,95
12000	6725,73	8552,99	10106,44	8172,61	5779,74	4962,67	4749,26
11000	3269,78	5006,79	7467,25	6662	4626,29	3915,14	3740,56
10000	1724,44	2780,89	5266,56	5325,58	3685,09	3062,75	2913,15
9000	1926,22	2106,92	3818,95	4284,66	3052,35	2495,58	2369,88
8000	3780,52	3120,58	3363,93	3678,61	2839,87	2305,02	2187,22
7000	7953,98	6160,39	4226,75	3880,96	3233,35	2667,89	2540,78
6000	16400,2	12729,73	7344,28	5602,25	4756	4033,64	3860,53
5000	32228,47	24964,25	13978,63	9664,53	8034,36	6967,32	6681,35
4500	43909,04	34171,28	19143,22	12913,86	10625,02	9287,2	8905,32
4000	60984,15	46468,09	26127,29	17374,55	14180,68	12464,9	11957,75
3500	75299,65	58046,68	33198,95	21861,36	17714,66	15633,4	15025,15
3000	79941,44	63062,99	37234,74	24277,23	19491,59	17265,36	16607,48
2500	66696,34	55179,64	34409,08	22134,2	17550,29	15570,3	14956,14
2000	37946,19	33648,06	22851,83	14663,66	11480,94	10153,37	9760,13
1700	20536,29	19050,83	13718,53	8906,63	7001,32	6192,35	5970,18
1500	11730,95	11307,83	8629,75	5682,23	4496	3911,08	3757,43
1400	8370,05	8267	6561,9	4381,07	[illegible]	2989,59	2874,24
1300	[illegible]	[illegible]	[illegible]	[illegible]	2507,83	[illegible]	2087,77
1200	3669,37	3772,93	3396,91	[illegible]	1799,89	1574,81	1507,71
1100	2135,46	2283,3	2307,3	1653	1250,18	1128,37	1082,27
1000	1072,35	1292,08	1538,08	1149,1	881,68	789	752,55
900	500,24	706	1016,48	791,03	594,75	542,72	[illegible]
800	180,39	358,89	653,73	537,49	404,29	[illegible]	358,89
700	25,82	156,45	389,77	348,51	263,73	252,52	236,77
600	0	49,55	206,88	212,59	162,18	157,88	148,92
500	0	4,53	89,56	115,37	89,64	99,62	92,06

- < 1 krad / year
- 1-3 krad / year
- 3-10 krad / year
- 10-20 krad / year
- 20-30 krad / year
- > 30 krad / year

Jason-2,3:
~2500 rads/yr

SPOT-4,5, SARAL, ENVISAT:
~360 rads/yr

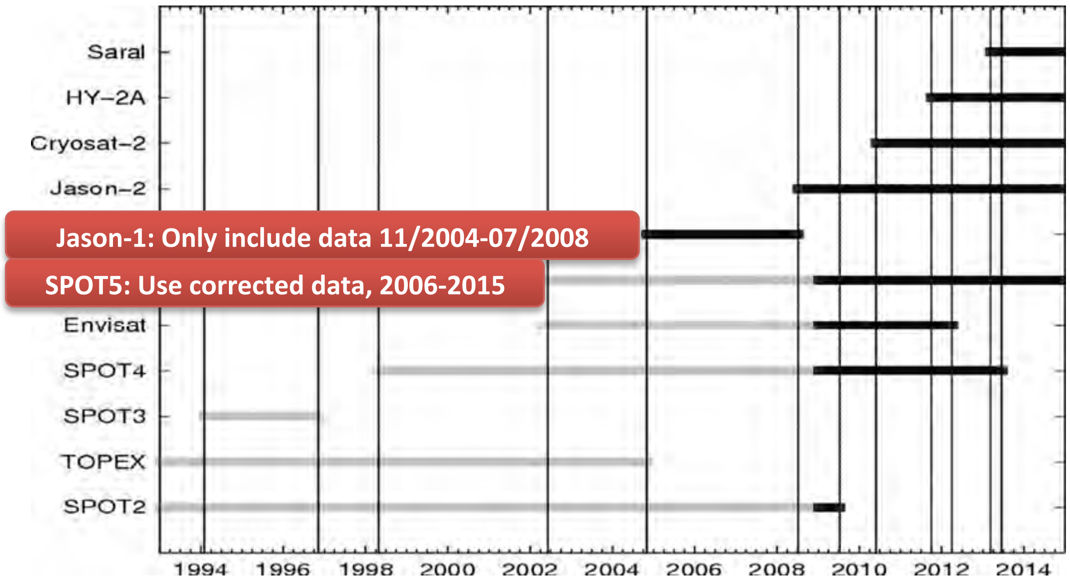
Impact on DORIS/ITRF2014



SAA On-board Freq signal over 5-days, Jason-1, SPOT-5, SPOT-4

Capdeville et al. Adv. Space Res. (2016)

1. ITRF2008 station positions & velocities for "SAA" stations directly affected by uncorrected SPOT-5 data.
2. <u>For ITRF2014</u>: All ACs used corrective model and/or downweighting elimination of SAA station data for SPOT-5 & Jason-1.



Satellite data used in ITRF2008/ITRF2014

Moreaux et al. Adv. Space Res. (2016)

1. Jason-1 included since its inclination complements the other satellites.
2. Use "corrected data" + downwt/ eliminate SAA stations.
3. No other satellite USOs receive special treatment in ITRF2014.

Jason-2/T2L2

1. "Time Transfer by Laser Link"
2. Two photon detectors + event timer with ps resolution linked to the DORIS USO.

T2L2 records in time scale provided by DORIS the arrival time of laser pulses at Jason-2.

In combination with precise ground clocks at SLR stations (H2 masers), it is possible to determine Δf/f over time intervals of T=60 secs.

Precision is dependent on short term stability of USO, quantity & quality of range measurements. 3-5 x 10^{-13}

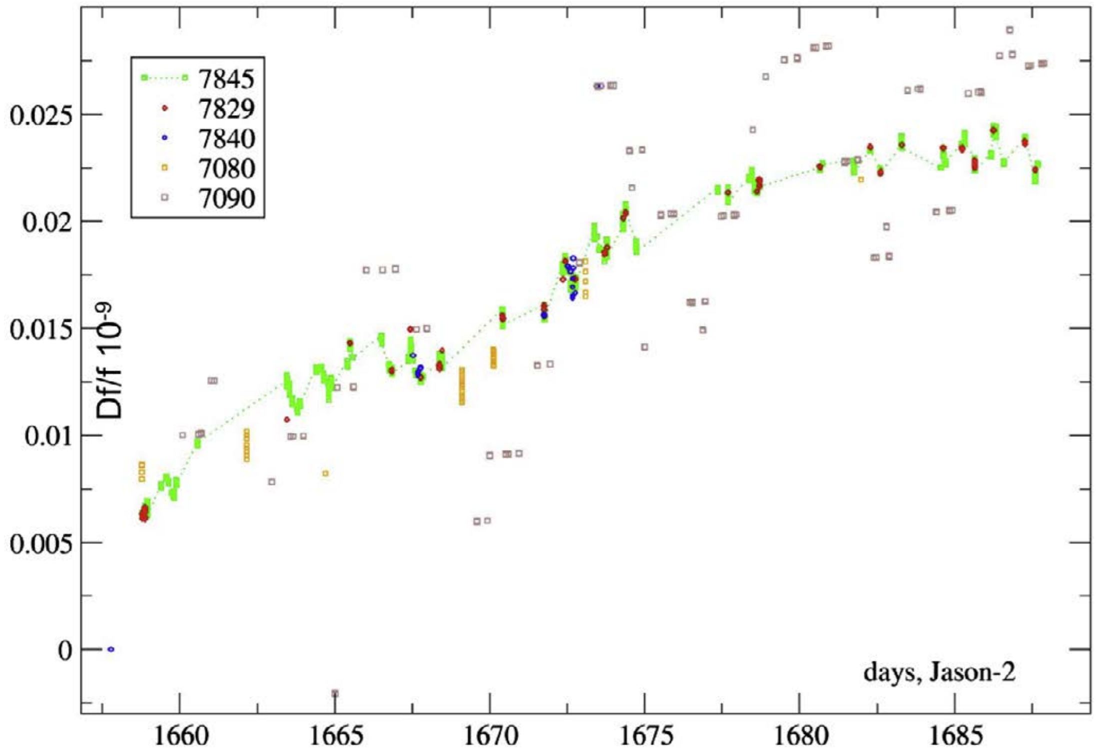
Exertier et al. Adv. Space Res. (2010)

Jayles et al. Adv. Space Res. (2016)

Laser Retroreflector Array

Two Applications:
(1) "Synchronize" Timing of SLR network.
(2) Study in detail behavior of USO in space environment and characterize different effects (radiation, thermal effects, aging).

T2L2 Data: Example



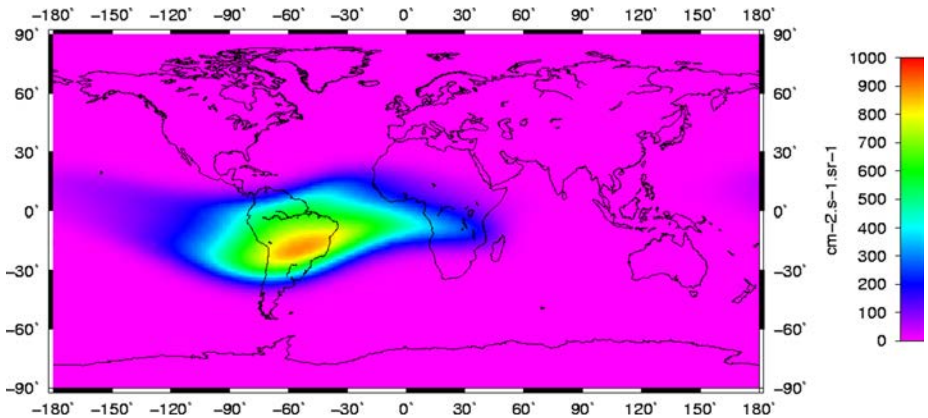
Δf/f in Jan. 2013 from five SLR stations.

Belli et al. Adv. Space Res. (2016)

See also A. Belli, PhD Thesis (2017)

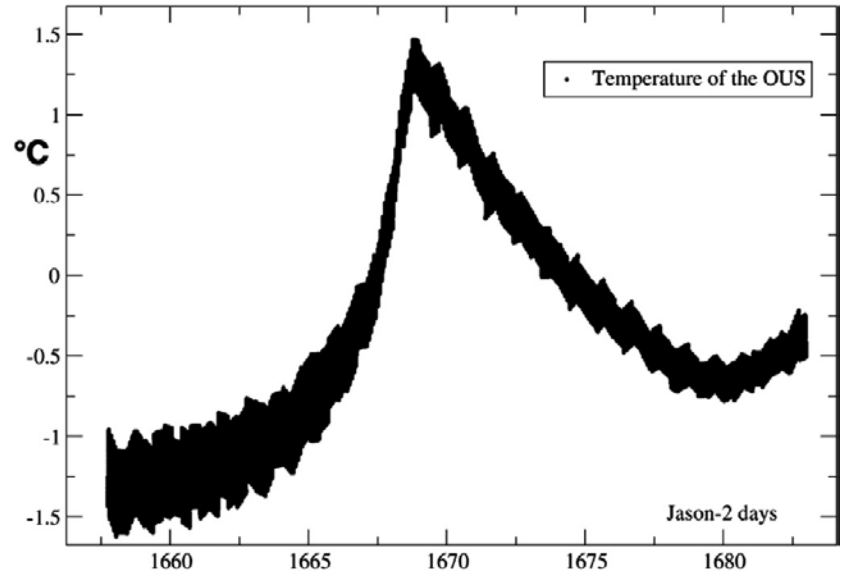
1. Best data comes from stations with H2 masers: Grasse (7845), Herstmonceux (7840).
2. Data can read variations caused by radiation dosage (SAA), temperature variations, and aging.
3. The data benefit two techniques: both DORIS & SLR giving us an understanding and global perspective.

USO Effects & Model Derivation



Jason-2 CARMEN 87 MeV integrated proton flux map (2009–2011 average).

Capdeville et al. Adv. Space Res. (2016)



Temperature Effects on Jason-2 USO Jan. 2013, showing orbit-to-orbit effects & impact of change in Jason-2 attitude.

$$\delta\widetilde{v}_{SAA}(t) = \gamma_1 \int_{t_0}^{t_{SAA}} \gamma_Q\, D(t)$$

$$\delta\widetilde{v}(t > t_{SAA}) = \delta\widetilde{v}_{SAA}\left[\exp^{-(t-t_{SAA})/\tau} + \gamma_2 t\right]$$

Radiation Model

$$\delta\widetilde{v}_T = \sum_{i=1}^{3} \alpha_i (T(t) - T_0)^i$$

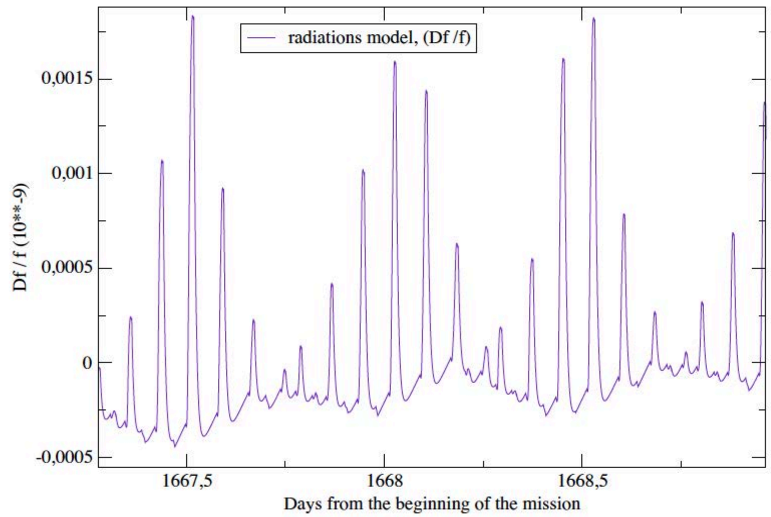
$$\delta\widetilde{v}_D(t) = \sum_{j=0}^{2} \beta_j t^j$$

Drift Model

Belli et al. Adv. Space Res. (2016)

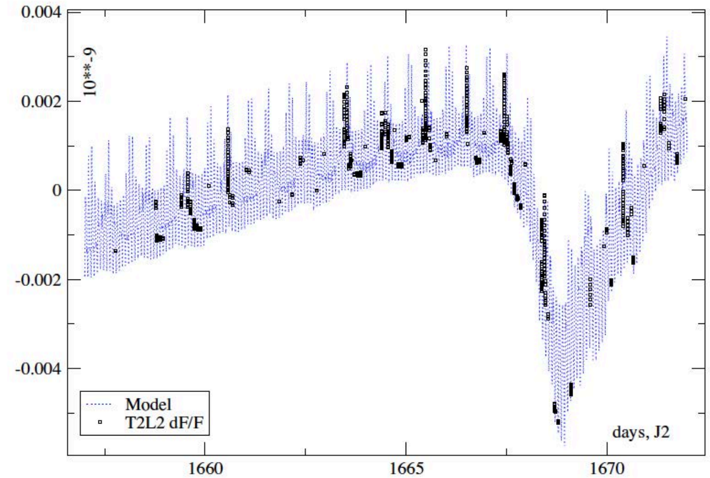
See also A. Belli, PhD Thesis (2017)

Jason-2 USO Model & Comparison w. T2L2



Radiation Model over ~1.5-days for Jason-2 showing effects of SAA passage.

Belli et al. Adv. Space Res. (2016), Fig 4



Jason-2 Frequency variations from Temperature and Radiation: Model vs T2L2 data.

Belli et al. Adv. Space Res. (2016)

USO Effects & Model Refinement for Jason-2 & Jason-3

Temperature Effects

$$\delta\widetilde{v}_T = \sum_{i=1}^{3} \alpha_i (T(t) - T_0)^i$$

- Sufficient to calculate only rate term:

$\alpha_1 [\, T(t) - T_o]$

- Coefficients for J2 (2008), J3 (2016) similar magnitude but opposite sign.

Radiation Effect @ 60-days

- A 60-day signal was observed in the T2L2 data when the s/c is in fixed yaw. Increase over ten days, then relaxation over 45-50 days.
- **Belli et al. (2017)** propose this is due to alignment of Yaxis of s/c with magnetic field lines, leading to increased sensitivity to radiation in SAA area in fixed-yaw regime.
- It is possible to solve explicitly for coefficients to model this behavior.
- The significance is that **Belli et al. (2017)** have identified an additional signal at a Jason-sub-draconitic period (~60 days) that is in the current data, and is not driven by radiation pressure mismodeling. ***

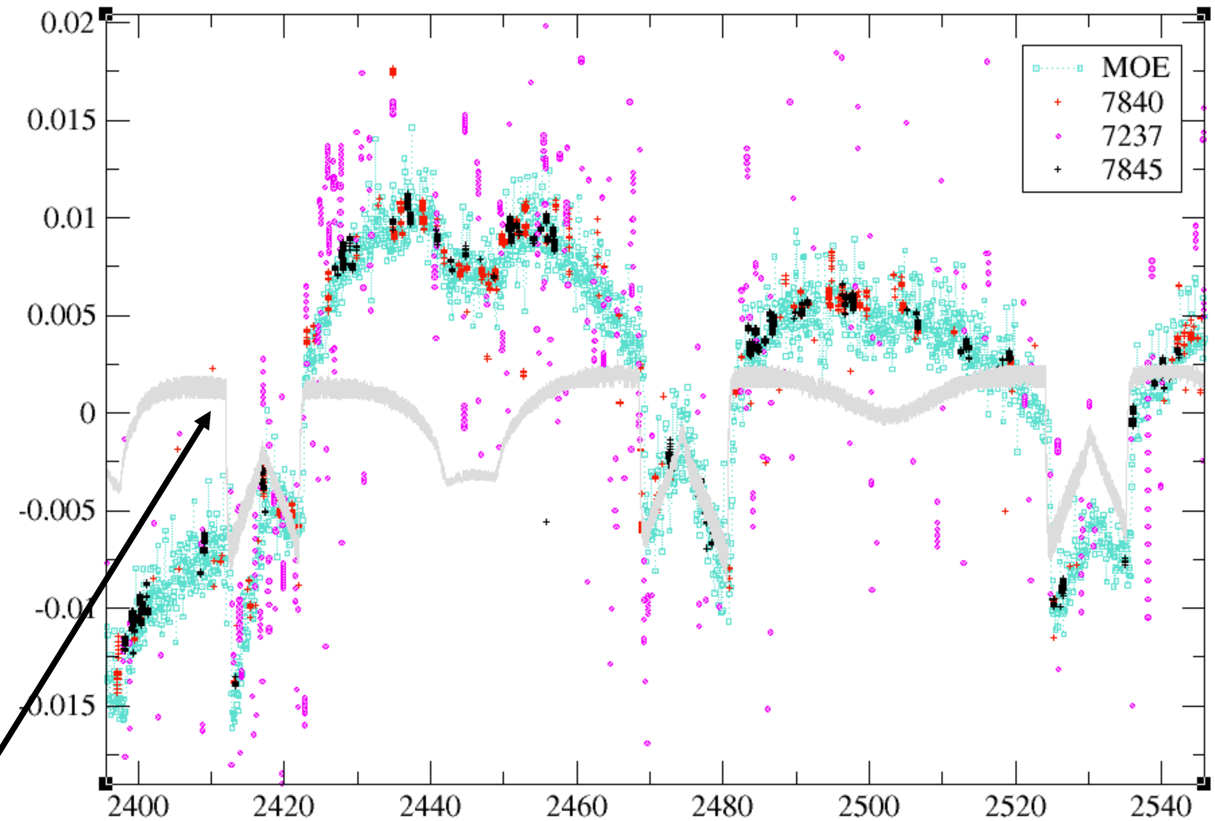
*** AC's must still improve SRP model, include motion of solar arrays using quaternions.

Belli et al., European Frequency & Time Forum (2017) proceeding paper

Jason-2 USO Behavior vs. CNES MOE Freq. biases

CNES POD (MOE) can "read" USO for H2 maser (time, frequency) beacons – since freq. biases (range-rate) biases estimated per pass.
Sees freq. variations with precision of ~1-1.2 x 10^{-12}

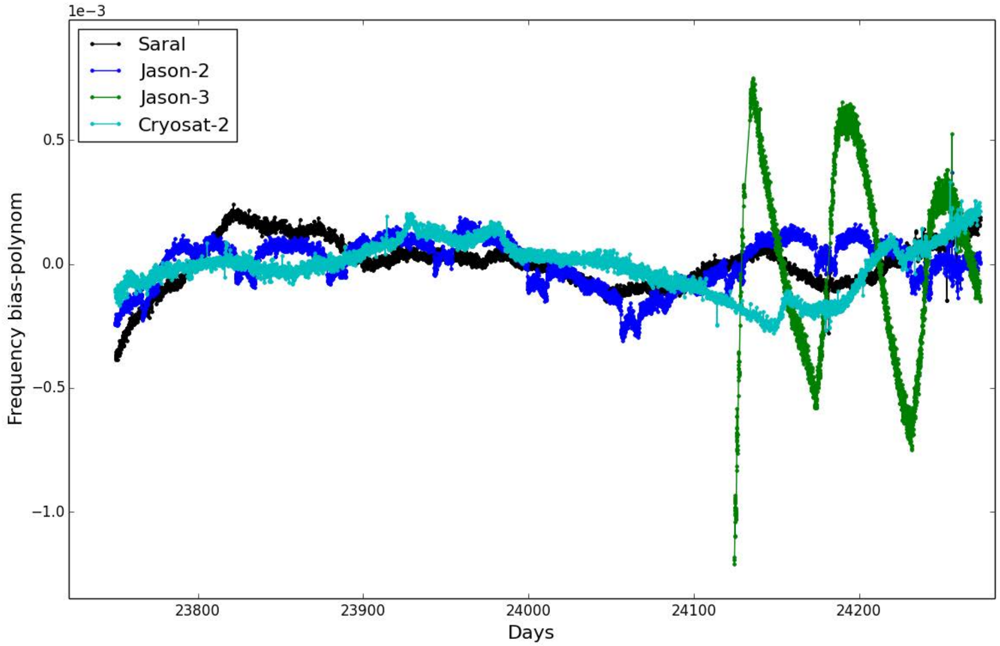
compared to ~3 x 10^{-13} for T2L2



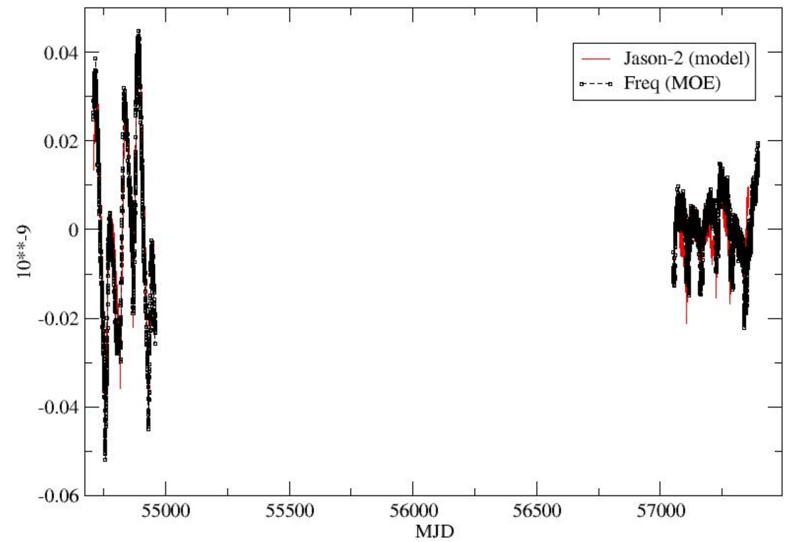
Data used:
MOE
SLR stations (T2L2)

Temperature of the box
=> df/f_0 with 1.85 10^{-12} /degree

DORIS USO (frequency bias): long term



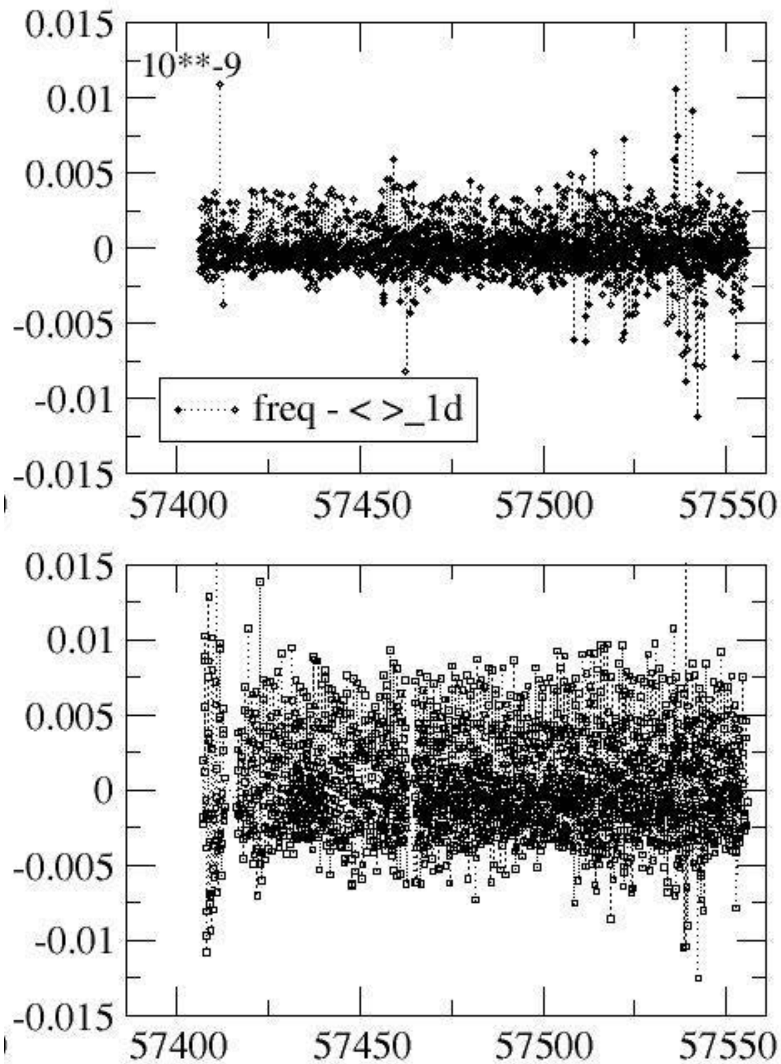
Relative frequency variations 2015-2016



Jason-2 freq variations 2008 vs 2016
Radiation sensitivity has decreased with time.

Frequency variations of J3 are >> J2 in 2016 but not in 2008

Jason-2 vs Jason-3 Sensitivity



Belli et al. IDS Workshop (2016)

<u>Here, MOE Δf/f are filtered with 1-day filter to eliminate medium & long-term signal</u>

Jason-2 Δf/f (2008) (TOP)
vs
Jason-3 Δf/f (2016) (BOTTOM)
from MOE solutions.

Jason-3 sensitivity to radiation is about ~3X that of Jason-2 at the same age of space exposure.

Summary

DORIS USO Sensitivity Summary

1. USOs show sensitivity to temperature, radiation, and have aging effects.
2. A "60-day" effect on DORIS-USO is identified that is related to Jason attitude law and anisotropy of incident radiation flux into the USO box.
3. Sensitivity is affected by "pre-treatment" and amount of shielding on s/c.
4. A general model that accounts parametrically for these effects can be derived for Jason-2 and eventually for Jason-3.
5. Lower satellites (SPOT-5) not immune. Suggests there is a need for general treatment of these effects on all DORIS satellites.

Immediate Future Actions

1. PIerre Exertier/A. Belli to make available corrected DORIS/V2 Data (Jason-2) for testing by the DORIS Analysis Centers.
2. Improved Frequency model of Jason-2 & Jason-3 can be implemented in DORIS/RINEX processing – to be tested by NASA GSFC and other DORIS ACs.