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Update of the South-Atlantic Anomaly corrective model for JASON-1 DORIS data using the maps of energetic particles from the CARMEN dosimeter onboard JASON-2

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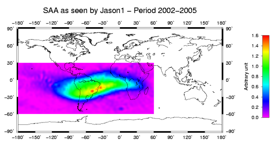
Introduction

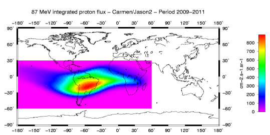
The sensitivity of the ultra stable oscillator (USO) of DORIS/Jason-1 to the high energy protons trapped in the Van Allen belts is now well known. This sensitivity causes a fluctuation of the frequency when the satellite crosses the area of the South-Atlantic Anomaly (SAA). The principal consequence is the impossibility of using the measurements of the DORIS beacons located in the SAA area for cm-precision positioning since the real frequency of the on-board oscillator is varying rapidly in that area. Moreover, these DORIS measurements do not contribute (or little) to the determination of the orbit of Jason-1 because they are eliminated during the pre-processing on residuals criteria.
To correct for this sensitivity to the effects of solar radiation, a model of the frequency evolution of the USO was designed and validated by Lemoine and Capdeville in 2006. This model allows a significant improvement in the orbit adjustment. It takes into account the geographical characteristics of the SAA region (1x1 degree SAA grid) as well as the parameters of the USO's response to this external stimulation: an amplitude, a relaxation time-constant and a memory effect of the SAA disturbance.
In the framework of the IDS contribution to the new realization of ITRF (2014), the Jason-1 DORIS data from the end of TOPEX' life (November 2004) to the launch of Jason-2 (July 2008) have been used, corrected by this model. The corrected DORIS data have been provided to the data center for the use of the IDS Analysis Centers.
The Jason-2 satellite carries a dosimeter instrument (CARMEN). The purpose here is to take the advantage of this instrument to improve our SAA corrective model by using the maps of energetic particles provided by CARMEN. First, a correlation study between the SAA DORIS grid and the CARMEN maps has been done to determine the dosimeter map which has the best agreement. Then, this map is used to calculate the others parameters of the model. The new model will be used to correct the DORIS data and we will examine its impact on the orbit and on the stations positioning.

Correlation study of the SAA grid from DORIS data and from CARMEN data

The correlation study has been done using two different maps of the SAA from Jason-1 : the one based on 2002-2005 DORIS measurements, currently used for the corrective model, and a more recent one, based on 2009-2011 measurements. These two maps, initially build on 1°x1° grids, have been downsampled to 2°x2° by computing grid block means, to match CARMEN data grid step.
For the CARMEN part of the data, the ONERA provided integrated proton flux maps at 5 different energy levels (>63, >76, >87, >97 and >138 MeV), in order to cover as much as possible the expected sensitivity range of Jason-1. The CARMEN data are organized, for each energy level, as a global 2°x2° regular grid of the annual average of the year 2011. In addition, we have also used a multi-year average (2009-2012) for the >87 and >138 MeV levels.
The study is based on spatial linear correlations between the two sets of data, performed with the GMT software. In order to only keep the effect of the SAA, all the operations were applied on a sub-domain limited in longitude from -180° to 60°E and in latitude from 60°S to 30°N. The method also includes a search for a geographical offset between the two grids, by discrete multiple values of the grid steps.



SAA Grid from Jason-1 DORIS data
•1°x1° grid (2002-2005)
(converted in 2°x2° grid for this study)



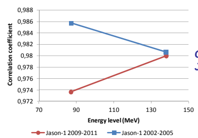
SAA Grid from Jason-2 CARMEN data
• 5 energy band tested
>63, >76, >87, >97 and >138 MeV
• 4 annual grids (2°x2°) from 2009 to 2012
• 2 mean grids 2009-2011 (2x2°) for >87 MeV *(given here) and >138 Mev*

Between each grid pairs, a scale factor "k" is computed as the least square solution of the equation : $(Carmen\ Grid)_{offset} = k \times (Jason1\ Grid)$

Finally, a residual grid is deduced using the scale factor and the offsets, in the arbitrary unit of Jason-1 grids : $(Residual\ Grid) = (Jason1\ Grid) - \frac{1}{k} \times (Carmen\ Grid)_{offset}$

The correlation has been first computed between the 5 energy levels of the CARMEN maps on the year 2011, and the Jason-1 map on the period 2002-2005. The correlation maximum was found at both >76 and >87 MeV, with very few differences between the first 4 levels (>63 to >97 MeV), and a minimum at >138 MeV. The rest of the study was thus only based on the 2 energy levels >87 MeV and >138 MeV.

The two multi-year Jason-1 maps (periods 2002-2005 and 2009-2011) were compared to the CARMEN maps at the 2 different energy levels, both averaged over the period 2009-2011. The maximum of correlation was found between Jason-1 2002-2005 map and CARMEN 2009-2011 map at >87 MeV, with a coefficient of 0.9858 (see figure on the right).



Correlation results between Jason-1 and CARMEN maps

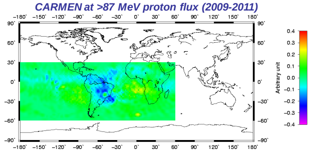
Geographical offsets, correlation coefficient and scale factors between Jason-1 and CARMENJason2 maps

Jason-2 CARMEN Grids (MeV)		Jason-1 Grid (2002-2005)			
		Latitude offset	Longitude offset	Correlation coefficient	Scale factor K
Mean 2009-2011	>87	0	6	98.58	631.54
	>138	-2	8	98.05	385.42
Year 2011	>63	0	6	98.35	827.09
	>76	0	6	98.45	730.46
	>87	0	6	98.56	632.78
	>97	-2	4	98.25	566.15
	>138	-2	8	98.04	386.96

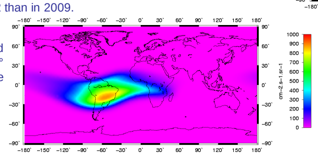
At the correlation maximum, the latitude offsets are centered around zero, but unexpected significant longitude offsets were found between the two data sets: in all cases the SAA is observed more west by CARMEN than by Jason-1. Finally, the scale factors are slightly higher with Jason-1 map on the period 2009-2011 than on the period 2002-2005, by comparing at same energy levels. The numeric results obtained with Jason-1 2002- 2005 map are summed up in the table on the left.

The residual map of the best correlated pair (CARMEN 2009-2011 and Jason-1 2002-2005) shows relatively homogeneous values, mostly negative in the SAA, meaning that the SAA maximum is seen less pronounced by Jason-1 than by CARMEN (see figure on the right).
In parallel, the time sequence of CARMEN annual average maps at >87 MeV was used to evaluate the temporal evolution of the SAA between 2009 and 2012. The known temporal variations at the altitude of Jason-1 and -2 are mainly long term effects, of 2 kinds:
- a westward drift of 0.3°/year, linked to the secular variation of the terrestrial magnetic field
- an amplitude fluctuation opposite to the 11 year solar cycle.
The time span of CARMEN maps was not long enough to identify these effects quantitatively, but a difference map showed consistent results with both a more west location and a smaller extent in 2012 than in 2009.

Residual map between Jason-1 (2002-2005) and CARMEN at >87 MeV proton flux (2009-2011)



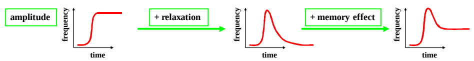
Based on the good correlation results, the CARMEN >87 Mev integrated proton flux map averaged over the period 2009-2011, and resampled to 1°x1° (Figure on the right) was finally chosen to be used in the update of the corrective model, provided that the 6° longitude offset is taken into account.

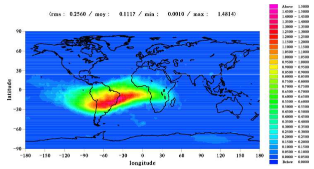


1° × 1° SAA Grid from Jason-2 CARMEN data
>87 MeV integrated proton flux map (2009-2011 average)

Definition of the original model

The model involves, on the one hand, the physical source of the perturbations of the DORIS oscillator, in the form of a 1° × 1° map of the SAA at the altitude of Jason-1 (1,300 km), and on the other hand, it involves the response of the oscillator to this excitation, through a set of parameters that can vary with time
Basically, under exposure to high-energy protons, a quartz oscillator will react by a frequency drift (positive or negative), proportional through an amplitude factor to the level of exposure (the "dose exposure"); by an exponential relaxation behaviour once the exposure is stopped; and by a "memory effect" corresponding to the fact that the frequency does not come back to its initial level, even a long time after the exposure has been stopped. The following set of parameters has therefore been defined:
- A: amplitude factor relating the dose received by the quartz oscillator to the dose exposure
- τ : time constant of the relaxation behaviour
- μ: memory effect coefficient
- 1°×1° geographical map of the mean SAA intensity at the altitude of Jason-1





1° × 1° grid of the SAA at the altitude of Jason-1
The SAA map was therefore determined on a 2°×2° grid (approximately 11,000 parameters). This grid was converted to spherical harmonics, limiting the expansion to degree 60, and converted back to grid points, with a 1° spacing in order to allow a precise interpolation of the grid by users. The result is shown in Figure 1. The "dose exposure" grid in Figure 1 is in dimensionless units. Multiplied by A(t), it gives an upper bound of the drift rate of Jason-1 frequency on the 2GHz channel, at any date t and at any location on the globe. This grid can then be interpreted only in a relative way. Since the mean value of the grid and the mean value of the A parameter are one to-one correlated, an additional condition had to be imposed in order to enable solving for both the grid and the A parameter. This arbitrary condition was that the grid maximum value be 1.5.

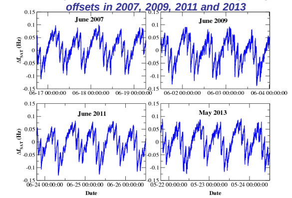
Data corrective model for Jason-1 by using CARMEN map

Determination of the SAA Jason-1 onboard frequency offsets

We have determined the SAA Jason-1 onboard frequency offsets from the end of 2006 to the Jason-1 end of life in June 2013. We took into account all the DORIS data available for this period, beginning with Spot-2, Spot-4, Spot-5, Envisat, and Jason-2 in July 2008, Cryosat-2 in June 2010 and Hy-2a in October 2011.
First, we computed precise orbits of Jason-1 and of all DORIS satellites. With the station parameters (frequency bias and tropospheric bias adjusted per pass) from the others satellites we calculated a combined value which is assigned to Jason-1 parameter and by using the previously saved Jason-1 orbit, we recomputed Jason-1 measurement residuals.
By conversion from equation $\frac{\Delta f_{SAT}}{f_{SAT}} = -\frac{1}{c} \bullet \dot{\rho}_{residual}$ we obtained the Jason-1 onboard frequency offsets Δf_{SAT}.

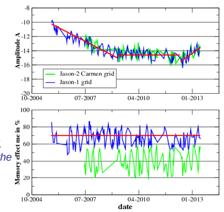
We give an example on 2,5 days on the figure on the right for years 2007, 2009, 2011 and 2013.

Example of Jason-1 DORIS USO n°1 frequency offsets in 2007, 2009, 2011 and 2013



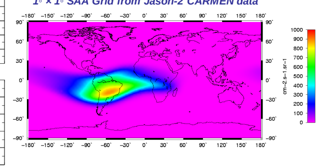
Determination of the model parameters

By using the SAA CARMEN grid (figure on the right) we determined the model parameters by taking into account the scale factor and longitude offset of 6° compared to the Jason-1 map. For that, we adjusted the model parameters amplitude *A* and the memory effect *μ* (the relaxation time *τ* being set to a value of 60 min) over the period from July 2007 to June 2013. For the amplitude parameter *A*, we find the same evolution than the one obtained with the model based on the Jason-1 map (see Figure on the right). The memory effect is around 40% against 70% with Jason-1 map.



Time-evolution of the model parameters for DORIS USO n°1
The blue line when the Jason-1 map is taking into account and the green line when CARMEN Jason-2 map

1° × 1° SAA Grid from Jason-2 CARMEN data



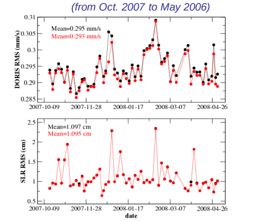
Impact of the model on the orbit and positioning

Now we apply the model based on the CARMEN map to correct the Jason-1 DORIS data. The orbit residuals are systemically lower with CARMEN map but the differences are small. We compare Jason-1 weekly solutions obtained with SAA data corrective model using Jason-1 map and CARMEN (Jason-2) map to DPOD2008 (values are calculated after the application of the Helmert transformation parameters). In the bottom table we give the RMS3D and RMS and STD by component (Mean values on 26 weeks, from July 2007 to May 2008).
The RMS3D, RMS by component and STD by component are lower when we use model with CARMEN map but, as on the orbit residuals, the differences are small. These results show that the Jason-1 map determined from DORIS data was at a good level. And, even by using the CARMEN maps (dosimeter data) the correction is not complete.

Comparison between a Jason-1 single solution and DPOD2008
(Mean values on 26 weeks of the RMS3D and RMS by component of the differences)

Solutions	RMS3D (mm)	RMS Lat (mm)	RMS Lon (mm)	RMS Up (mm)	Std Lat (mm)	Std Lon (mm)	Std Up (mm
with Jason-1 map	52.5	46.5	57.7	52.2	46.4	57.7	52.2
with Jason- 2 (CARMEN) map	50.1	42.3	52.3	52.1	42.1	52.3	52.1

Jason-1 SLR and DORIS residuals per arc of 3.5 days
(from Oct. 2007 to May 2006)



Conclusion and Perspective

Updating the Jason-1SAA corrective model by using CARMEN maps showed:
- the SAA Jason-1 map calculated from DORIS data was at a good level
- even by using the CARMEN map the correction is not complete
So, we plan
- **to continue work on the SAA data corrective model using the CARMEN maps** (new tests)
- **to improve the SAA correction by correcting the DORIS data directly from the SAA onboard frequency signal observed** (a filtering will be necessary)
- **to submit to DORIS Special Issue (Adv. Space Res) a paper on SAA models:** *"Update of the corrective model for Jason-1 DORIS data in relation to the South Atlantic Anomaly and a corrective model for Spot-5"*

REFERENCES
•Lemoine, J.M.; Capdeville, H. 2006. A corrective model for Jason-1 DORIS Doppler data in relation to the South Atlantic Anomaly, in DORIS Special Issue, P. Willis (Ed.), JOURNAL OF GEODESY 80(8-11):507-523, DOI: 10.1007/s00190-006-0068-2
•Boscher, D., Bourdarie, S. A. & Falguere, D., 2011. Flight Measurements of Radiation Environment on Board the French Satellite JASON-2. *IEEE Transactions on Nuclear Science*, 58(3), pp. 916-922.