OVERALL SYSTEM PERFORMANCE SYNTHESIS REPORT

Project code SO-TN-CB-SYS-1184

Version 3.0

Date 30/01/2007

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DOCUMENT STATUS SHEET

Version / Rev.	Date	Pages	Changes	Visa
0	16/04/2004		First draft	
1	04/05/2004		First issue	
2	06/10/2005		Major update for PLM-CDR	
2.1	12/06/2006		Revision for SAT-CDR	
3.0	30/01/2007		Major update for M-CDTP Key Point. Geolocation biases calibration method description included.	

REFERENCES

Applicable documents

AD1.	System Requirement Document	4.2	SO-RS-ESA-SYS-0555
AD2.	Error Budget Summary Update	2.2	SO-TN-UPC-PLM-0038
AD3.	SMOS satellite budgets and margins	2.0	SMOS-ASP-BT-0062
AD4.	Definition of Antenna position and Antenna Errors for SMOS Performance Calculations	1.0	SO-TN-CASA-PLM-0726
AD5.	SMOS In-Orbit Calibration plan. Phase C/D	1.2	SO-TN-UPC-PLM-0019

References

Boutin J., Waldteufel Ph., Martin N., Caudal G., and E. Dinnat, Surface salinity retrieved from SMOS measurements over global ocean: Imprecisions due to sea surface roughness and temperature uncertainties, *J. Atm. and Ocean. Tech.*, In press, 2004.

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ACRONYMS

AF-FOV	Alias Free Field Of View
CERFACS	Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique
CESBIO	Centre d'Etudes Spatiales de la BIOsphère
CNES	Centre national d'Etudes Spatiales
DCW	Digital Chart of the World
ECMWF	European Centre for Medium-range Weather Forecasting
ESA	European Space Agency
ESL	Expert Support Laboratory
FOV	Field Of View
LICEF	Light Cost Effective Front-end
NIR	Noise Injection Radiometer
PSU	Practical Salinity Unit
OS	Ocean Salinity
SMOS	Soil Moisture and Ocean Salinity Mission
SRD	System Requirement Document
TB	Brightness temperature
TBC	To Be Confirmed
TEC	Total Electronic Content
UPC	Universitat Politecnica de Catalunya

TABLE OF CONTENTS

1. INTRODUCTION

This document presents an overall synthesis of the SMOS system performances evaluation, at the present stage of development.

The basic principle of this error budget is to evaluate at each processing level what can be the expected noise level, and to assess how they add up through the whole processing chain. It is a compilation of various studies and error budget done at this point.

Section 3, will introduce the geolocalisation error budget as estimated by Alcatel, including both platform and payload contributors, and will shortly present the selected method to calibrate geolocation biases once in orbit, along with its expected accuracy. It also summarizes the radiometric error budget at levels 1b and c, based on the work done at UPC, including complementary error sources, such as sun and residuals from corrections based on auxiliary data sets.

Section 4 will present preliminary analysis of error propagation through level 2 processing, and its sensitivity to the various auxiliary data sets that are needed for that processing, for ocean salinity and soil moisture.

A basic estimate of the expected accuracy of level 3 will finally be given in section 5.

2. SYSTEM REQUIREMENTS SUMMARY

The system requirements addressed in this document concern the level 1 and 2 mission products. They are summarized as of what is included in version 4.2 [AD1]. They mainly focus on:

Localization

After ground processing of orbit restitution elements and attitude determination, the final localization accuracy of brightness temperature products geographical grid must be better than 400m (R-4.2.4-006)

Level 1b

General

Systematic radiometric error on retrieved brightness temperature maps shall be lower than 1.5K RMS at boresight and lower than 2.5K within 32° from boresight, after calibration (R-4.5.1-008)

Soil moisture

Radiometric sensitivity on retrieved brightness temperature maps shall be better than 3.5K RMS at boresight and lower than 5.8K within 32° from boresight (R-4.5.2-002)

Ocean salinity

Radiometric sensitivity on retrieved brightness temperature maps shall be better than 2.5K RMS at boresight and lower than 4.1K within 32° from boresight (R-4.5.3-002)

Level 2

Soil moisture

Accuracy of the soil moisture data products outside mountainous, urban and partially frozen or snow-covered areas shall be better than 4% of volumetric soil moisture when the biomass is less than 4 kg/m2, after corrections using the auxiliary data (R-4.6.1-003)

Ocean salinity

Accuracy of the ocean salinity data products with a 50 km spatial resolution shall be better than 1.2 PSU (R-4.6.2-004)

3. LEVEL 1

3.1 GEOMETRY

The pointing budget (AD3) has been completely reworked in the frame of the SAT-PDR and compiled by Alcatel Alenia. Based on PLM inputs from EADS/CASA, allows to account for all PLM contributors.

Also, the allocation of errors due to the instrument has been refined. A clear separation has been agreed between contributions to radiometric error budget and geometric performances. Best example being the individual alignment of the LICEFs, allocated to radiometric budget whereas their individual positions are used to define a best fit frame (ref AD4), assumed to be representative of the true pointing of the instrument.

The updated satellite pointing budget accounts for the following contributors:

	Bias	**Harmonic Constant**	**Random**
PF contributors			
Star Tracker errors (intrinsic and mounting)	x	x	x
Gyros Errors	x	X	
PLM contributors			
Ground measurement alignment accuracy	x		
Arm deployment repeatability	x		
Zero-g effect	x		
Moisture bias	x		
Thermo-elastic deformation bias	x		
Thermo-elastic deformation harmonic		X	
Launch shift	x		

Timing and orbit restitution have proven to be only very marginal.

It has to be pointed out that all these contributors have impacts only on the overall localization of the image, that is they do not introduce any distortion within the image. This is due to the way the images are reconstructed from visibility measurements.

The pointing budget is computed for several points within the FoV as described in (ref AD3) and the final localisation accuracy amounts to:

Position FoV	P1 - centre	P2 - Nadir	P3 – Lower	P4 – Upper corner	P5 – Narrow upper corner
Typical err (m)	664	451	450	676	784
Maximal err (m)	1490	1052	1075	1759	2042

About 90% of this budget is constituted by biases, principally acquired at launch time. Since the retrieval of soil moisture is highly sensitive to biases, it is essential to maximize the knowledge of this effect.

3.2 CALIBRATION OF GEOLOCATION BIASES

A study has been initiated to develop a method able to characterize the geolocalisation bias, making use of images acquired on specific landscapes. First aimed at finding suitable isolated islands, the study later showed that its accuracy over such targets where badly conditioned by the selected island characteristics. It appeared more robust a technique to aim at linear coastlines. Use of such targets allows oversampling at will the position of the footprint with respect to the coast.
The area under specific study is the oriental coast of Madagascar. The method makes use of the nearly perfect linear coast almost parallel with descending orbit tracks.

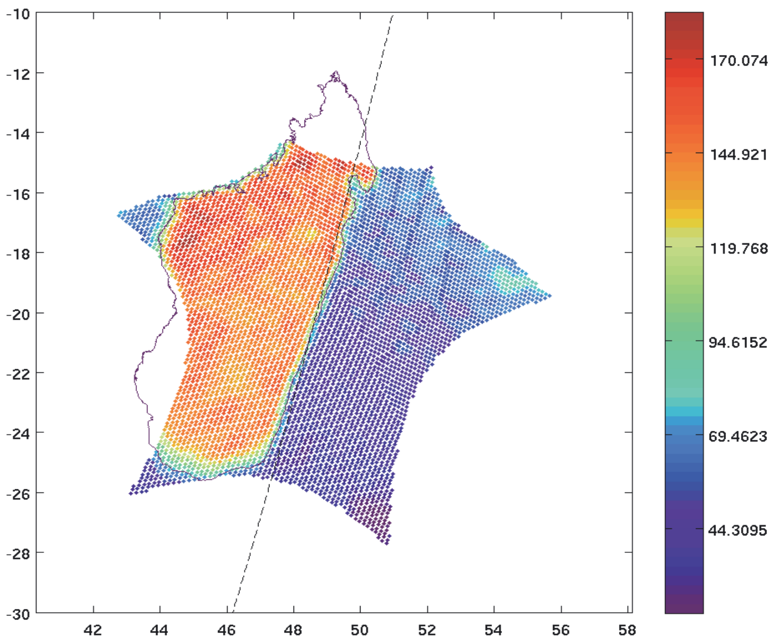

Figure 1 - Reference temperature over Madagascar, X pol.

The measurement of distance is done perpendicularly to the coast by minimising the difference between the measurement and a very simple model of acquisition considering a perfectly straight coast and a theoretical weighting function. The optimisation process yields 4 values: horizontal shift between theoretical and actual coast, brightness temperature for land and ocean and the width of the weighting function. It is done for 11 ranges of incidence angle, for all DGG falling within 80 km of the coast, all along the region of linear coastline. Results from these different ranges allow to separate resolution issues and geolocation accuracy. A global statistic can be elaborated to assess the overall accuracy of the method.

This method has been tested on simulated SMOS L1c products, obtained from an enhanced version of SEPSv4.0.1, that allows to make use of input data sets at high resolution (in this case, the underlying land classification is ECOCLIMAP, at 1km resolution). Figure 1 shows an example of snapshot extracted from this data set. X polarisation has been selected for this purpose.

To assess the sensitivity of the method, simulations have been done with various levels of attitude bias. Figure 2 shows impact on brightness temperatures related to a bias on roll angle of 0.05° (left) and 0.1° (right).

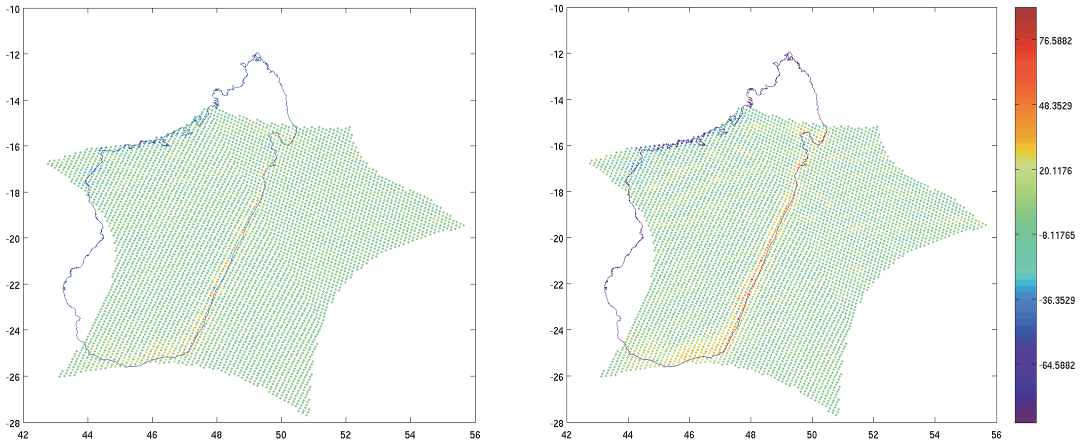

Figure 2 - Brightness temperature error due to a constant bias on roll.

The comparison of data points with theoretical landscape and model can be seen on figure 3. It shows data points acquired over the coastal region, with incidence angle between 32.5° and 37.5°, along with the theoretical landscape and the retrieved model. Both have been shifted by the retrieved across coast distance.

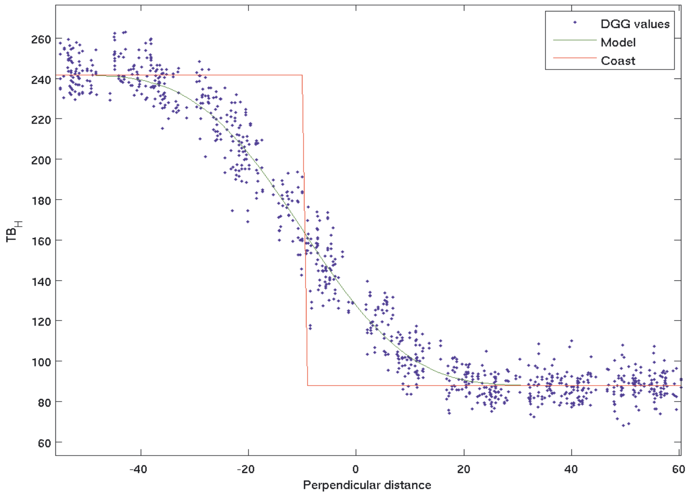

Figure 3 - Brightness temperature as a function of perpendicular distance to the coast.

For each set of data points, selected in a given range of incidence angles, a minimization is done to retrieve the shift across coastline, both temperatures and weighting function width. From these, only the first does not depend on incidence angle, the other three do not depend on roll bias. This can be seen on figure 3, that shows all retrieved parameters for the three cases: i) no bias to measure the constant shift between SEPS input data sets and the selected coastline reference (DCW), ii) 0.05° bias on roll and iii) 0.1° bias on roll. In the last case, the retrieved shift exhibit a slight dependence with incidence angle that is still under investigation.

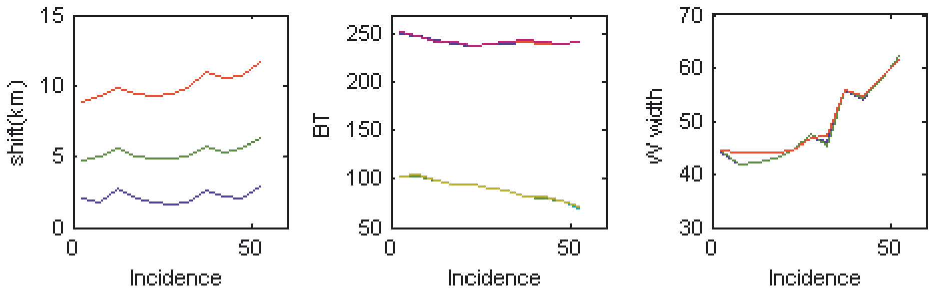

Figure 3 – Optimisation results for reference (blue), 0.05° bias (green) and 0.1° bias (red)

From these results, global statistics of accuracy can be assessed.

The following table summarizes the observed accuracy on shift retrieval when using ascending or descending orbits, as evaluated by comparison of our test cases:

	Descending	Ascending
Coastal shift accuracy (m)	489	462

These allow evaluating the bias on roll angle with an accuracy better than 0.02°, thus reducing the geolocation bias to be within the same accuracy.

The same analysis will be conducted using the earth horizon when it crosses the field of view during external calibration manoeuvres.

The present budget includes impact of residual geolocalisation errors of 489m, accounting for the expected accuracy on biases correction for an impact on brightness temperature of **1.22K**.

3.3 RADIOMETRIC INSTRUMENT PERFORMANCES

Extensive work has been conducted at UPC to provide a complete instrument performance assessment (AD2). It is based on SEPS simulations to evaluate the sensitivity of the instrument to various contributors. These sensitivities are then used to initialise a theoretical error propagation model. It is used here as a baseline for radiometric accuracy assessment at level 1.

It also accounts for calibration residual as they can be estimated based on the current state of IOCP (ref AD5). The results quoted here are representative of the system immediately after a calibration event.

The representative case for soil moisture is assessed with an antenna temperature of 220K and the ocean salinity case with a temperature of 150K.

Main findings of this work are the summarized in the following table (in K):

	Soil Moisture		Ocean Salinity	
Polarization	X	Y	X	Y
Sensitivity	2.43	2.43	1.99	1.99
Radiometric accuracy	**2.16**	**2.10**	**1.86**	**1.82**
Bias	0.99	0.86	0.78	0.69

Non compliant numbers quoted in red.

Here again a part of the budget is due to biases, here introduced mostly by gain error from NIR. These biases being mainly related to NIR receiver temperature, on-ground characterization and in-flight monitoring is expected to account accurately for them, they are not included in the following error budget, but they raise the open issue of on-ground calibration for thermal dependence and aging behaviour of this dependence. One important contribution to these biases appears to be the fact that the brightness temperature measured by the NIR and used for the reconstruction of the TB maps inside the AF-FOV is actually representative of the whole FOV. Important biases can therefore be expected if the TB outside AF-FOV is significantly different than the TB inside AF-FOV.

Only boresight results are quoted here, although results are also available in the 32° circle centred at boresight. But these results, including out of FoV contribution are deemed unrealistic.

On the other hand, these figures do not account for the following contributors:

External RFI:

Provided the emitters comply with ITU recommendations, the RFI level is not expected to exceed **0.02K**. Airborne experiments show strong evidence of non compliant emitters. Based on these campaign results, the levels of expected interference at satellite level has to be investigated.

Sun

Has to be analysed in at least two specific ways

Impact of direct sun in the antenna.

This impact and potential restoration has been specifically studied (Camps *et al.*, 2004). The expected performance of the proposed method is **2.42K**.

Obviously the impact of the sun is in no way homogeneous throughout the FoV, and the cited study shows that local effects can be much more dramatic, but these areas are easy enough to discard at retrieval time, not to account for them in the overall error budget.

Impact of reflected sun glint on the surface.

As a continuation to the previous study, and accounting for all sun contributions (Camps *et al.*, 2005), direct and sun glint, comes out with an overall **3.4K** including the preceding effect. This contribution is expected to be of concern mainly for ocean observation.

Galactic noise:

A specific study has been dedicated to galactic background and sources reflexion at the surfaces (LeVine and Abraham, 2004). Its major findings are that the galactic contribution to the observed signal can range from 1K to 6.7K depending on the position, season and observed surface. This contribution needs to be corrected and the principal limitation to the accuracy of this correction will be the accuracy to which we can characterize the downwelling radiation. A typical accuracy for these maps is given in (Reich and Reich, 1986) at 0.5K, resulting in about **0.4K** after reflexion.

Additional marginal contributions from atmosphere, clouds and rain are also included for a total amount of 0.4K.

From all these figures, we sum up an overall radiometric accuracy at level 1 of:

Soil moisture	3.27 K
Ocean Salinity	3.08 K

This budget is obviously highly dominated by the sun contribution. Reducing this contribution must be thoroughly investigated, because it will actually make the compliance of the mission. The second important contribution being the bias introduced at NIR level.

3.4 RECONSTRUCTION

When concerned with radiometric accuracy, one should only consider the error propagation and amplification of a given reconstruction algorithm.

Many of the contributors that can be classified in this part are accounted for in the SMOS performance model provided by UPC, but closely linked to a specific reconstruction algorithm. If we want to keep this overall performance budget more general, we need to express reconstruction errors in less specific way.

An example is provided by CERFACS, who states an error amplification of 0.5 and a specific noise of **0.94K**. The resulting noise is estimated by the sum of specific and amplified input noise.

In the context of this report, however, the reconstruction added noise is assumed to be accounted for in the SEPS based error budget.

3.5 AUXILIARY DATA

At level 1, the following auxiliary data are required and have been accounted for in the present error budget, whenever their effect can be estimated:

	Source	accuracy	Resolution	Timely availability	sensitivity	Geo location
sky map	Reich et al.	0.5K			0.7K/K	NA
sun Tb	NGDC	10-22W/m²	1sec	1 day		
TEC	ESOC	2°	0.5°		0.1K/°	
Land mask	SRTM		1km/once			80m

4. LEVEL 2

4.1 INVERSION

4.1.1 SOIL MOISTURE

Based on inversion studies, we can estimate the error propagation as it has been done for reconstruction: by separating model specific errors and noise amplification.

A global inversion study (Pellarin *et al.*, 2003), based on global model regression show that the error can be separated in a specific noise of about 0.0197m3/m3 and a noise amplification term of 0.0055m3/m3/K. This results show both the effort to be done on the model, and the robustness of the regression with respect to noise in the input data.

Additional contributions to take into account are listed in the auxiliary data table below, along with expected sensitivity.

A global estimate of the overall accuracy expected for soil moisture from the above assumptions is **4.41%vol.**

This figure, out of specification, is again highly dependent on efficient sun correction and NIR bias removal. At this level, just as at level 1, these two contributions can make the mission compliant or not.

4.1.2 OCEAN SALINITY

Global studies based on simulated data sets show that the sensitivity of L2-OS products can be expressed in the same way as for SM, with following figures: specific noise around 0.04 and noise amplification of 0.5 psu/K. This error model is dominated by the influence of the knowledge of the surface of the ocean, as described in Boutin *et al.*, 2004.

From what precedes, we can estimate the overall salinity retrieval accuracy to **2.43psu.**

This is a direct estimate of what the given radiometric accuracy can allow to expect for a single snapshot retrieval. Although it can be expected to improve this accuracy by averaging retrievals along a dwell line, it should be remembered that a large part of the error budget is constituted by biases.

4.2 AUXILIARY DATA

At level 2, the following auxiliary data are required:

Common	source	accuracy	resolution	Timely availability	sensitivity
Land/sea, water bodies	ECOCLIMAP, DCW				

mask					
Pressure	ECMWF	10mbar	0.5°/6hours		0.0024K/mb
Air temperature	ECMWF	20K	0.5°/6hours		0.001K/K
Water vapour content	ECMWF		0.5°/6hours		0.002K/g/m2
land cover	ECOCLIMAP, MODIS				
Soil Moisture					
Biomass, vegetation type, optical depth, VWC	ECOCLIMAP, MODIS	1.15 LAI rms	1km/10days, 1km/8days		1.6K
topography	GTOPO30, SRTM		1km		
soil texture	ECOCLIMAP		1km/10days		
Land surface temperature	ECMWF	2K	50km/6hours, 1km		0.85K/K
Land cover	ECOCLIMAP, MODIS		1km/10days, 1km/3months		
Snow cover	ECMWF		50km/6hours		
frozen soils	ECMWF		50km/6hours		
Ocean Salinity					
sea state: roughness, foam	ECMWF, WAM				
sea surface temperature	ECMWF				

The sensitivities to the various contributors in this table still need to be evaluated in the process of the L2 processor development.

Localisation error with respect to auxiliary data:

From section 3.1, we can estimate the contribution from incorrect registration of brightness temperature with respect to auxiliary data at **1.22K**. This assumes a sensitivity of 2.5K/km, which is clearly a worst case, as can been found on coastal pixels.

4.3 RESAMPLING

The baseline of resampling process to the final geographic grid is achieved in two steps. First the brightness temperature maps are reconstructed in the antenna frame and then this frame is projected onto the selected geographical grid. Since at least one of these grids is equally spaced, the selected interpolation algorithm has to be spatially compact and thus introduces an additional noise.

Therefore we have to account for an additional error source due to the interpolation function that will be used at this step.

As a baseline, we can consider the error introduced by nearest neighbour, bilinear or bicubic interpolation which are 1.11%, 0.59% and 0.25%.

Obviously, this error contribution can be avoided by operating the reconstruction directly in the final geographic grid, since the selected reconstruction process allows it. Still, this error must be kept in mind because the final user will very likely need to resample SMOS products to a grid of his liking.

5. LEVEL 3 IMPACTS

There are no requirements at this level that can be addressed in this document.

G-4.7.2-005 The accuracy of the ocean salinity maps outside coastal areas, after averaging over 200 km x 200 km x 10 days space-time domain, shall be better than 0.1 PSU, after corrections by using vicarious calibration, namely by periodical imaging of one or more well-known reference sources.

G-4.7.2-006 The goal for the radiometric accuracy to retrieve ocean salinity through (multi-angle) data processing of observations acquired over a period of 10 days (TBC) is 0.03 K RMS.

G-4.7.2-007 In order to support vicarious calibration, the system shall ensure a stability of the systematic component of the radiometric error (including: bias, drift, periodic and other errors such as thermo-elastic effects) better than 0.02 K/day.

For soil moisture, the situation is not yet clear as how the independent measurements issued from level 2 will be used to derive level 3 products, if we assume an inversion process that allows to retrieve biomass and soil moisture for the narrow swath and then use the biomass on all acquisitions up to the next access in the narrow swath, we can evaluate the impact of biomass stability through time on the retrieved soil moisture that make use of this retrieval.

For ocean salinity, preliminary studies show that averaging does not reduce the noise as if all samples were independent. Presumably some correlation still exists in the data sets and error sources so that the resulting errors do not combine as gaussian independent error sources. Still, at this stage we can assume that the error is reduced according to a gaussian law. Based on this, we need a bit less than 200 views to any given zone to comply with level 3 salinity goal. This is deemed very optimistic since the more important contributions (NIR bias and sun effect) are clearly biases and will not be solved through averaging.

6. OPEN ISSUES

The following is a list of the issues, summarized from what precedes, that should be addressed in the current phase:

Sun:

Direct impact	Already identified as a major contributor to error budget
Sun glint over ocean	
Specular and sun glint over land	Needs assessment

Auxiliary data:

The presented tables must be completed for all missing information.