IONOSPHERIC EFFECTS ON SPACEBORNE MEASUREMENTS OF L-BAND EMISSIVITY

The efficiency of the operational use of an L-band radiometer to retrieve surface parameters directly depends on its sensitivity to potential noise sources. Some objectives, such as ocean salinity retrieval, require a very high accuracy in the measurement of the emissivity. Noise sources such as ionospheric perturbations may consequently hinder the retrieval.

The main problem coming from some ionospheric effects is their relative temporal / spatial stability with respect to the temporal / spatial scales of the measurements. As a result, the perturbations must be considered more as a bias than as a random noise and often cannot be reduced by simple averaging.

The purpose of this note is to provide a rough estimation of the perturbation caused by the ionosphere on brightness temperature measurements made for an observation configuration similar to that of SMOS.

Faraday rotation

A linearly polarised wave propagating in a plasma will suffer a rotation of its plane of polarisation due to the anisotropy of the medium. The magnitude of this "Faraday Rotation" for the propagation of a monochromatic wave within a homogeneous medium depends on the wavelength, on the strength of the magnetic field and on the electron density of the medium. The relative directions of the wave propagation vector and of the magnetic field must also be taken into account.

Roughly, we have:

$$d\phi = \frac{K\rho(l)}{f^2}\vec{B}(l)\cdot\frac{\vec{k}}{\|\vec{k}\|}\,dl = \phi(l)dl \qquad (1)$$

Where:

- $d\phi$ is the Faraday rotation angle corresponding to the propagation along a distance dl
- ρ is the electron density
- f is the frequency of the propagating wave, $\vec{k}$ is the wave vector
- $\vec{B}$ is the magnetic flux density (Wb/m^2)
- K=2.36 10^4

The total Faraday rotation over a propagation path is obtained through:

$$\phi_{Faraday} = \int_{ray\ path}\phi(l)dl \qquad (2)$$

Consequently, assuming that the brightness temperature is measured over an extended target and that the complex directional functions (equivalent to the complex scattering coefficients for passive measurements) fh and fv are uncorrelated, the resulting brightness temperatures measured from space can be written:

$$T_H^{space} \cong T_H^{ground} \cos^2\phi + T_V^{ground} \sin^2\phi$$
$$T_V^{space} \cong T_V^{ground} \cos^2\phi + T_H^{ground} \sin^2\phi \quad (3)$$

Similar expressions may be obtained for the emissivities.

Generation of error maps

Faraday rotation effects may have an impact on the measurement of L-band emissivities from space. This effect will be equivalent to some kind of polarisation mixing (a part of the energy emitted in H pol will be measured on the V antenna and vice versa). To assess these effects, it is necessary to compute the amount of rotation over a given path across the atmosphere, corresponding to a LEO earth observation satellite. However, as the variables used for the computation of the rotation vary with space and time, the effective Faraday rotation of a given wave will strongly depend on the geographical location, as well as of the time of the year/day and of the sun activity. Subsequently, models are needed to predict the variations of the time/space dependant parameters, i.e. the electronic density within the ionosphere and the Earth magnetic field.

The NeQuick[i] model provides an estimation of the electronic density for any point in space (altitude from 0 to 20000 km) and for any date/time of the day. The values proposed are monthly mean values (present simulations will use March month). On the other hand, the Earth magnetic field can be computed in 3D through various models, such as the International Geomagnetic Reference Field[ii]. By combining these two models, it is possible to produce maps of the Faraday rotation angle that affects an electromagnetic wave propagating from the ground to the sensor. Given this angle, it is then possible to compute the biases on the emissivity measurements.

Total electron content

Figure 1 presents the results of a global NeQuick simulation (resolution: 0.5 degrees) of the integrated electron content of the ray path joining the ground to the sensor. The sensor is orbiting at an altitude of 800 km, looking at the Earth with an incidence angle of 45 degrees (across-track, or west-east orientation). On the figure, the latitudes are developed along the y-axis (from -80 to +80 deg), the longitudes along the x-axis (from -180 to +180 deg). The local time for each cell is 6AM.

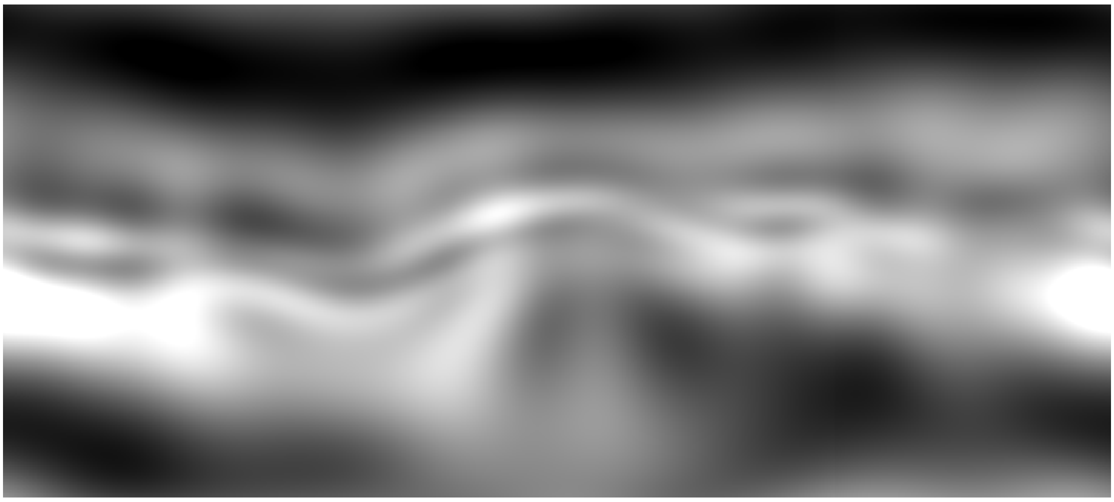


Figure 1: NeQuick computed TEC map (45 degrees of incidence) for a 6:00 local time and an average sun activity (latitude between -80 and +80 degrees, longitude between -180 and +180 degrees). Values range from 6TECU (black) to 17TECU (white) (1% and 99% cumulative respectively)

Rotation angle

To compute the Faraday rotation along a given path, it is possible to discretise this path and to compute the electron density (NeQuick) and the magnetic field (the International Geomagnetic Reference Field) for each of its elementary segments. Then, after a change of reference base (usually, the magnetic field is provided in an Earth centred base, and the propagation vector in a local base attached to the sensor), the application of equations (1) and (2) provides the total Faraday rotation angle along the path. Figure 2 presents the Faraday rotation angles corresponding to the TEC displayed on Figure 1. The rotation is maximum when (1) the TEC along the path is high and (2) when the distribution of the magnetic field along the path maximises the scalar product in equation (1). At 6AM, Faraday rotation angles may range from 0^o to more than 10^o in absolute value, depending on solar conditions. They may be positive or negative.

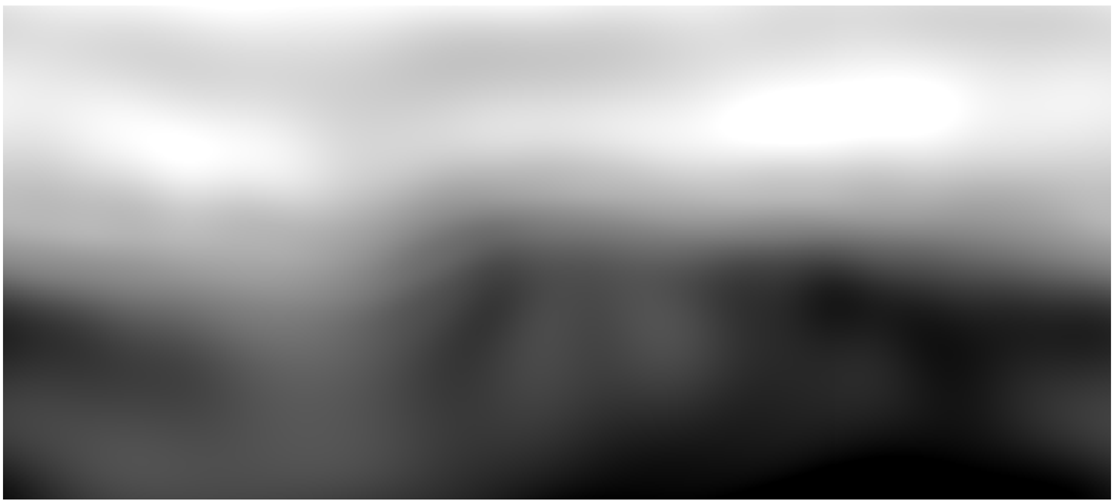


Figure 2: Corresponding Faraday rotation angles (6:00 AM, 45 degrees of incidence, looking across track). They range from -3 degrees (black) to +2 degrees (white)

Emissivity / Brightness temperature errors

By applying equation (3), it is possible to derive the corresponding variations of the brightness temperature measurement due to Faraday rotation (Figure 3 shows the horizontal polarisation case). It can be seen on Figure 3 that the resulting error varies quite a lot over the Earth surface. The high TEC around the equator is compensated by the nearly null scalar product between the Earth magnetic field and the direction of observation (across track).

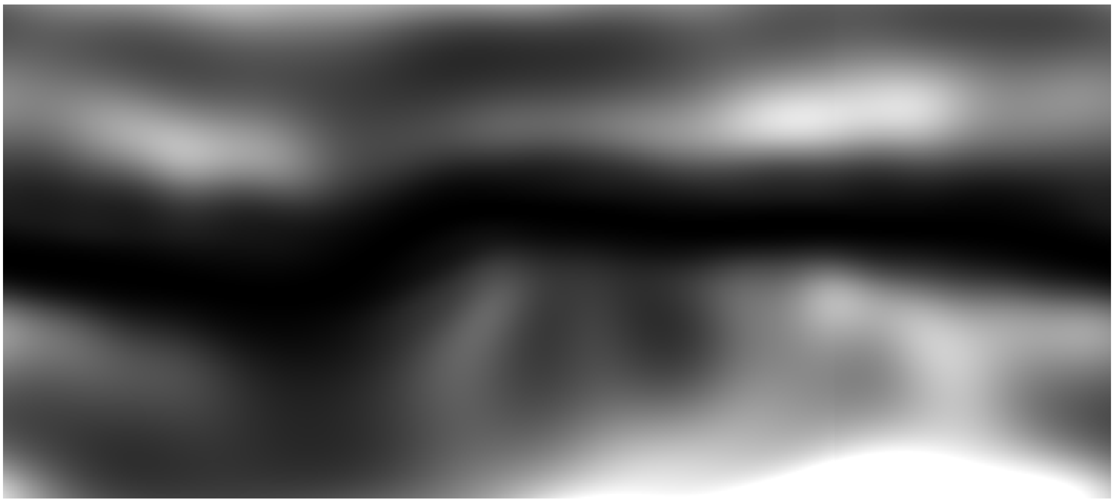


Figure 3: Map of the errors on the measurements of H-pol (6:00 AM, 45 degrees of incidence, looking across track). They range from 0 (black) to 0.00035 (white). Corresponding brightness temperatures errors may range from 0 to 0.11K for a 300K surface.

Some global results are presented on Table 1. The brightness temperatures assumed here are typical of the sea environment for these incidence angles / sea temperature (27^{o}C). The presented figures correspond to the maximum brightness temperature deviations for 90% of the Earth surface (the ground-based emissivities are here assumed to be constant). Even in a favourable case (morning orbit, as presented here), the error on the brightness temperature can still reach 0.1K. This bias needs to be corrected to achieve a high accuracy on the salinity retrieval (0.05K corresponds to slightly more than 0.05psu). Periods of high sun activity are particularly critical. Fast variations of the electronic content of the ionosphere at this time of the day need also to be taken into account (exact local sun time for the acquisition, position of the terminator).

		Maximum Faraday rotation angle and corresponding error on T_H (for a 300K surface) 90% of the measurements are lower than the displayed value			
Local Time	***Geometry of observation***	**Solar Flux F10.7=100 (sunspot number # 50)**			
		(nominal monthly TEC)		**(50% over monthly value)**	
		Angle(°)	**ΔT_B(K)**	***Angle(°)***	**ΔT_B(K)**
05:30	Inc **15** deg, **across** track	*1.71*	0.008	*2.42*	0.016
	Inc **15** deg, **along** track	*1.72*	0.008	*2.46*	0.017
	Inc **45** deg, **across** track	*1.71*	0.035	*2.40*	0.068
	Inc **45** deg, **along** track	*2.14*	0.055	*3.17*	0.119
06:00	Inc **15** deg, **across** track	*1.93*	0.010	*2.71*	0.020
	Inc **15** deg, **along** track	*1.92*	0.010	*2.76*	0.021
	Inc **45** deg, **across** track	*1.92*	0.044	*2.69*	0.086
	Inc **45** deg, **along** track	*2.53*	0.076	*3.73*	0.165
06:30	Inc **15** deg, **across** track	*2.32*	0.015	*3.26*	0.029
	Inc **15** deg, **along** track	*2.33*	0.015	*3.35*	0.031
	Inc **45** deg, **across** track	*2.36*	0.066	*3.27*	0.127
	Inc **45** deg, **along** track	*3.29*	0.129	*4.85*	0.279

Table 1: Errors on the measurements of Th for various time/sun activity configurations Tsea=300K, Th(45)=75K, Tv(45)=115K, Th(15)=90K, Tv(15)=100K, local time around 6AM, simulated conditions for 03/2004

The errors presented in Table 1 are applicable when no correction is proposed for ionospheric activity. They are only indicative as errors can easily reach several 10%. The errors may be too large for specific applications (e.g. salinity retrieval with high accuracy) but have to be considered, not as a stand alone, but as a basis of comparison with other sources of errors. Moreover, as the acquisition time drifts away from the early morning, the errors grow up quickly (e.g. the 45 deg, across track, solar flux=100, case reaches 0.044K at 6:00AM, 0.066K at 6:30AM, 0.086K at 7AM and 0.219K at 10 AM). This can be important if the time of acquisition of a given pixel varies with respect to sunrise.

In the case illustrated in Table 1, emissivities (ground based) at 15° and at 45° are provided through a two-scale model of sea emission (Yueh). Maps of Faraday rotation angle for incidence angles of 15 and 45 degrees and for an along-track (azimuth=0) and across-track (azimuth=90) look are presented on Figure 4.

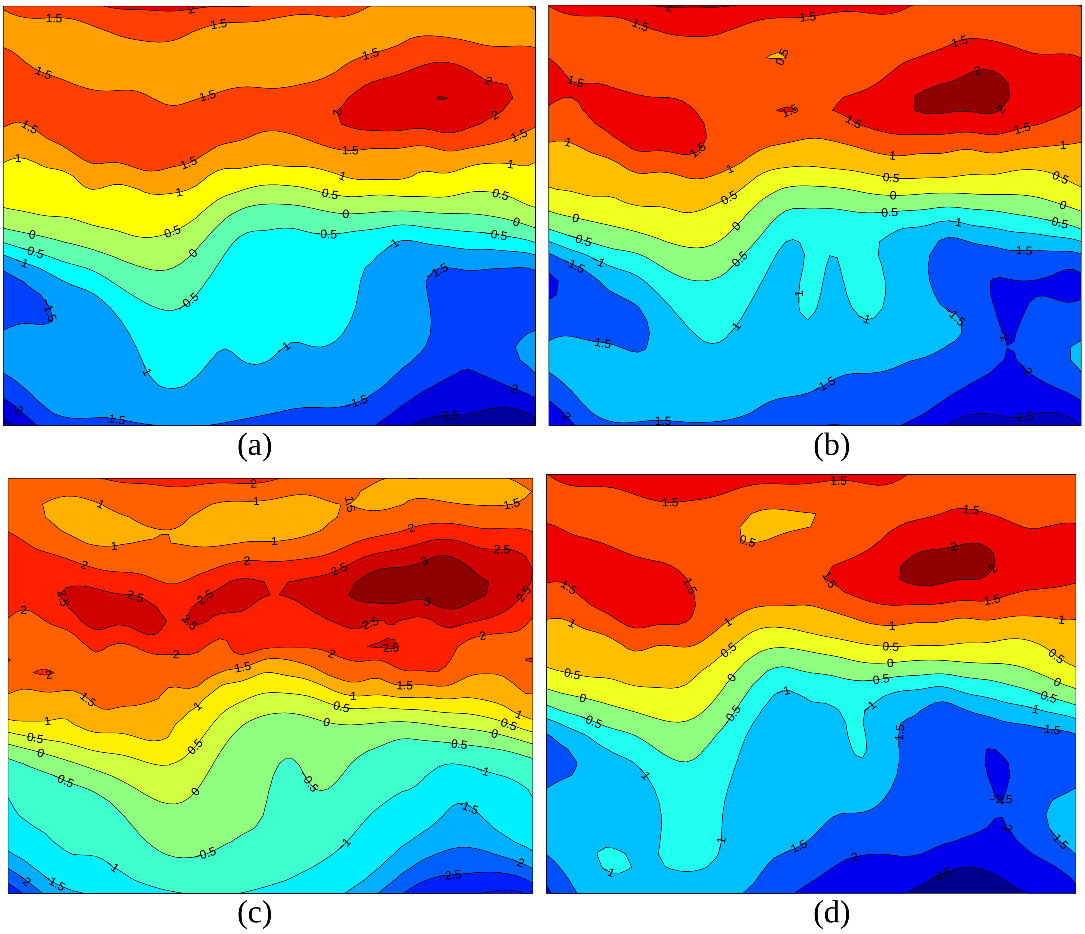


Figure 4: Maps of Faraday rotation angles (in degrees, 6AM, March, F10.7=100) for different geometries of acquisition (θ: incidence, ϕ :azimuth) (a) θ=15° ϕ=0° (b) θ=15° ϕ=90° (c) θ=45° ϕ=0° (d) θ=45° ϕ=90°

Temporal variability

The parameters characterising the sun radiation (solar flux, sunspot number) can exhibit a strong daily variation. As an example, Figure 5 presents the daily variations of the sunspot number for year 1993 (which behaviour should be close to year 2004, taken as a "worst" case for SMOS with respect to ionospheric perturbations, see the predictions on Figure 6). Variations of +100% / -50% with respect to the annual mean value are common. Table 1 includes simulations of the resulting error on T_B for cases were the sunspot number is 100% over the mean one (# F10.7 around 150 for a yearly mean value of 100).

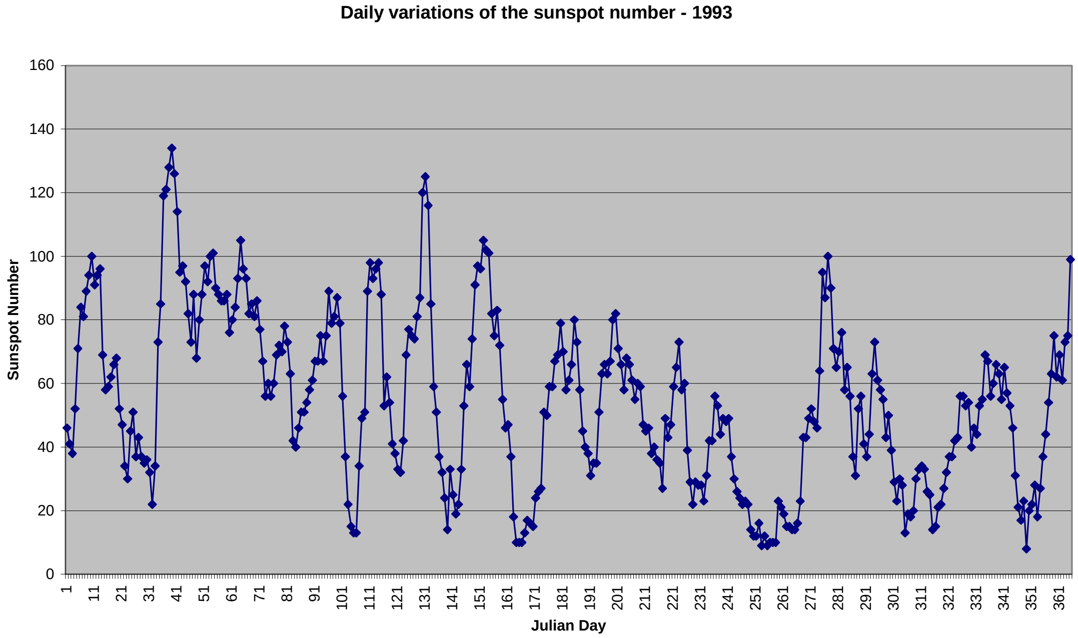


Figure 5: Daily variations of the sunspot number for year 1993 (mean value around 50)[iii]

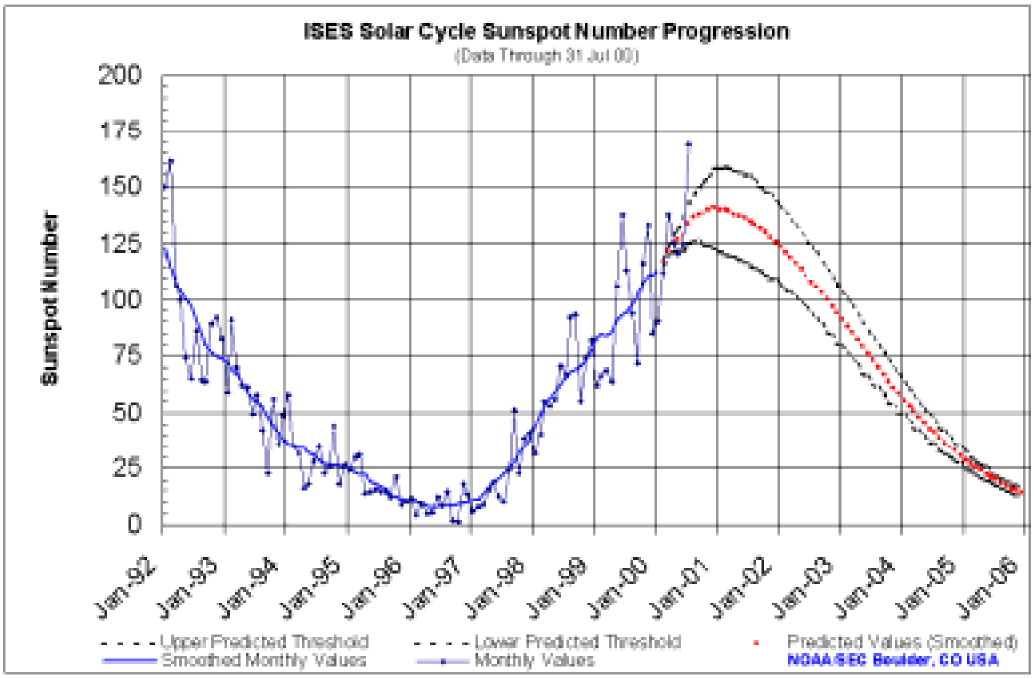
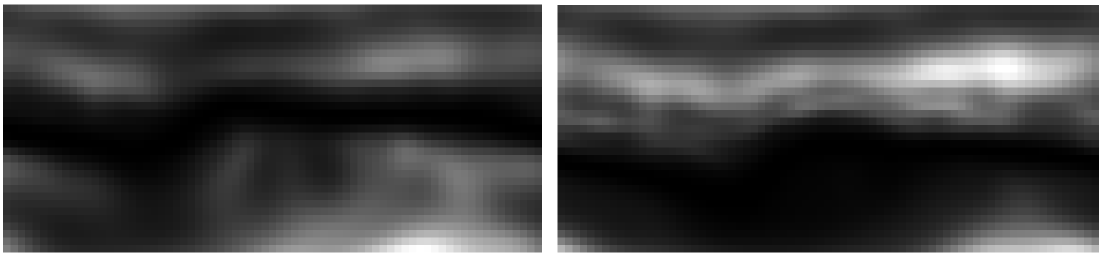


Figure 6: Measured and predicted variations of the monthly sunspot number (1992-2006)

Spatial heterogeneity in the errors distributions

The measurement errors due to Faraday rotation are not homogeneously spread over the Earth surface. This is due to the spatial structure of the magnetic field and of the electronic density. As a result, the error caused by Faraday rotation varies a lot all over the globe (a 1000 factor between min and max is not uncommon). This can have an effect on the retrieval; even if the mean value of the error is low, some regions of interest may display a strong bias, and these regions may differ depending on the geometry of observation (c.f. Figure 7), and on the time of the year. A superposition of the errors map with a land/sea mask could also be useful.



(a) (b)

Figure 7: Errors on the brightness temperature measurements due to Faraday rotation. (a) across-track geometry (b) along-track geometry. Latitude ranges from -80 to +80 deg. Longitude ranges from -180 to +180 deg. The same colour scales are used.

Variability of Faraday error within the Field Of View of the instrument

Another issue is that the bias on the brightness temperature measurement strongly depends on the position of the resolution cell in the swath. Both the incidence and the azimuth angles have an influence on:

- the TEC (electronic densities) along the ray path
- the angle (more exactly the distribution of angles along the ray path) between the propagation vector and the Earth magnetic field
- the differences between the true (ground based) H and V emissivities

From Table 1 for example, it is easy to see that if Faraday rotation angle has a low impact for acquisitions with a small incidence angle (when brightness temperatures for H and V pol are quite similar), its effect drastically increases with the incidence angle.

Because of the complex structure of SMOS field of view, the Faraday rotation angle does vary within it. Moreover, its variation pattern depends on the geographical co-ordinates of the swath. Figure 8 presents the variations of the Faraday rotation angle within the FOV for two acquisitions at different latitudes.

These variations of Faraday angle within a FOV, combined with the variation of T_V-T_H within the FOV, may result in a noticeable variability of the measurement error. A simple example can be provided through the use of a perfectly smooth surface, where the emissivity depends only on the dielectric constant and the incidence angle. In that case, it is possible to simulate the brightness temperature of the surface for both polarisations, and to derive the consequent measurement errors due to Faraday rotation through equation (3). Results are presented in Figure 9. The measurement error can vary from 0 to 0.3 K depending on the position of the pixel in the FOV.

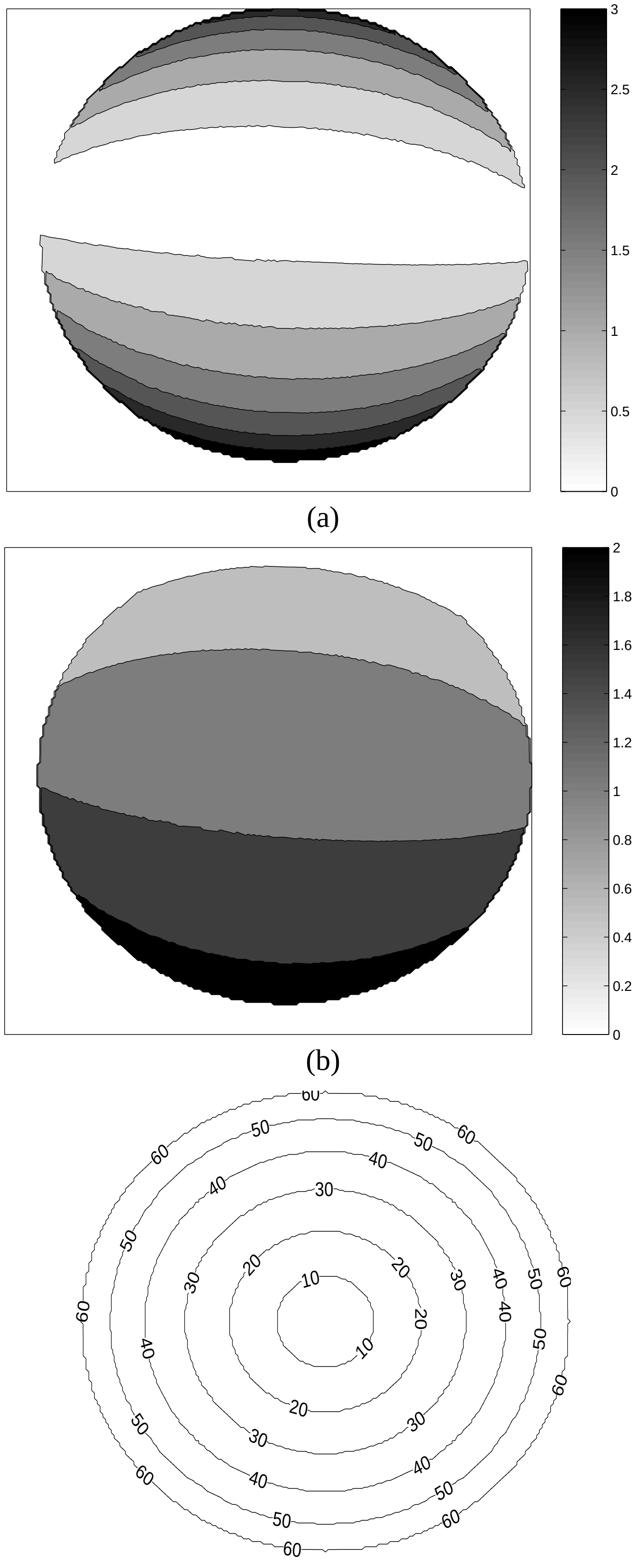
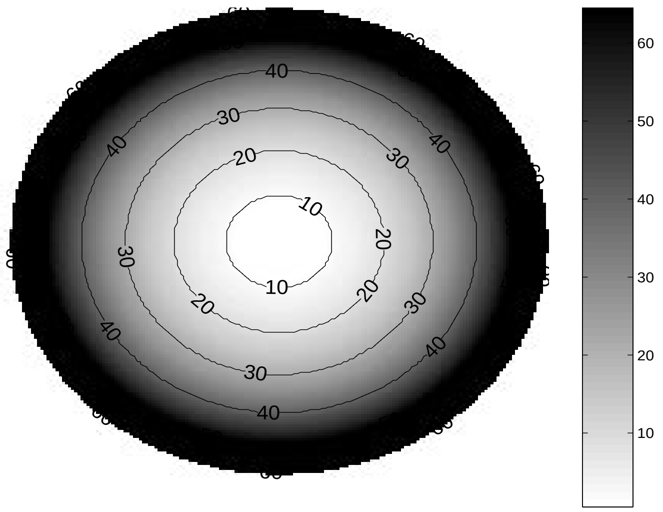
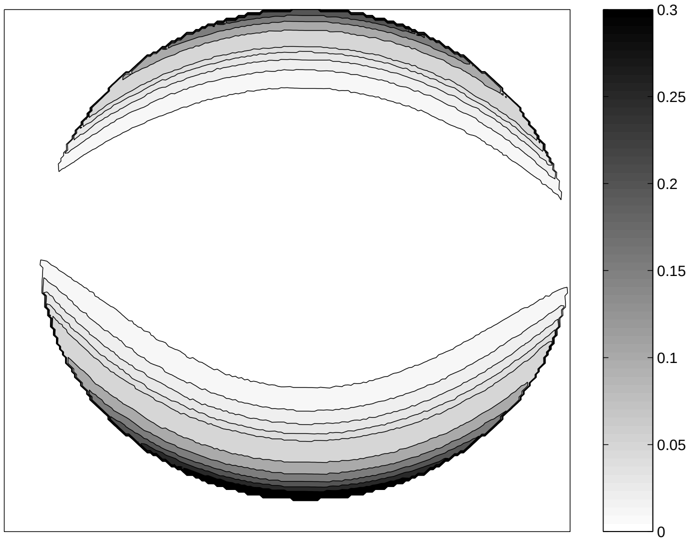


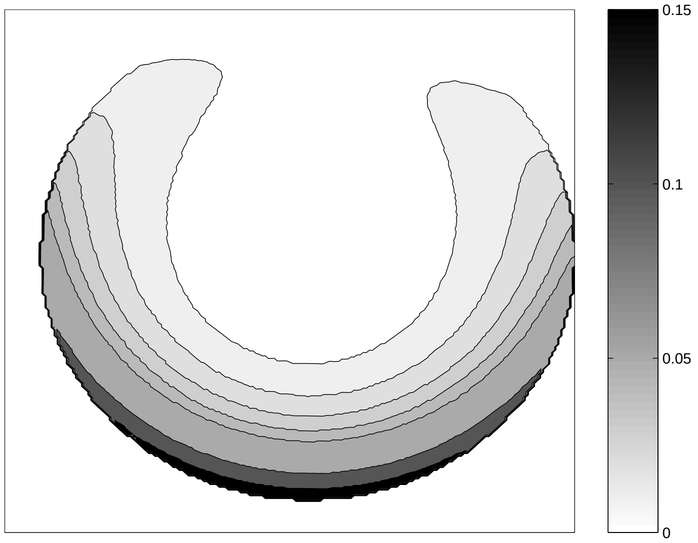
Figure 8: Variations of Faraday rotation angle (in degrees) within a simplified SMOS FOV. F10.7=100. Local time: 6AM. Longitude: 0^o. Latitude: (a) 15^o (b) 50^o. Incidence angle varies from 0 to 60^o (c). Sensor moves from bottom (S) to top (N).



(a)



(b)



(c)

Figure 9: (a) Brightness temperature difference between H and V for a perfectly smooth sea surface with T=27^o and salinity=35psu (in K as a function of incidence and azimuth angle). Errors on the brightness temperature measurements (in K) corresponding to the Faraday rotation angles of the previous figure. Latitude (b) 15^o, (c) 50^o.

Depending on their amplitude and on their frequency of occurence, it may be necessary to take these variations into account when applying a correction algorithm.

Small scale variations of the TEC

The model used so far does not reproduce the small scale variations of the electronic density, both for temporal variations and spatial ones. In a first step, these variations can be taken into account by introducing some noise distribution in the simulations.

Impact of Faraday rotation on retrieval algorithms

Ionosphere as a noise or bias source

Depending of the space/time resolutions needed for applications, the concept of the ionosphere as a noise source or a bias source has to be clearly defined. The large scale (spatial and temporal) variations should be considered as a bias with respect to the other error sources and should be corrected based on a model, on independent measurements, or through a index or multi-polarisation technique. On the other hand, the short scale/term fluctuations could be considered as random noise and be reduced by averaging (this depends on the spatial scale of the fluctuations).

The main issue concerns the possibility of averaging independent samples to lower ionospheric noise. This possibility directly depends on the repeatability of the error patterns within different FOV. For example higher incidence angle will result, nearly in all cases, in an higher Faraday rotation error. Consequently, a bias will still be present after averaging (with respect to acquisitions at lower incidence angles). Incidentally, acquisitions with high incidence angles may be the most valuable for retrieval algorithms, as they maximise the difference between polarisations.

Finally, the impact of ionospheric perturbations on the retrieval will also depend on the algorithm used. They will be more annoying for an algorithm based on a comparison between of T_V and T_H at high incidence angles than for an algorithm using just one polarisation at low incidence angle.

Single channel inversion: requirements on TEC accuracy

In the case of a unique channel (one polarisation, or two polarisations at a low incidence angle), some ancillary data on the electronic content of the ionosphere is required. Let's assume that both the geometry of the acquisition and the magnetic field can be known with a perfect accuracy. In that case, there are only two sources of inaccuracy: instrument uncertainties and Faraday rotation. It is then possible to derive the uncertainties on the final measurement:

$$(\Delta T_H)^2 = (\Delta T_V)^2 = (\Delta T_{instrument})^2 + 4\sin^2\phi \cos^2\phi (\Delta\phi)^2 \left(T_H^2 + T_V^2\right)$$

Φ is the Faraday rotation angle (in radians).

If we now assume that the number of samples is large enough to make $\Delta T_{instrument}$ negligible, then it is possible to derive the accuracy ΔTEC needed to achieve a given ΔT_H.

$$\Delta TEC = \Delta T_H \left(\frac{f}{23600.B_{av}} \right) \frac{1}{2\sin\left(\frac{23600.B_{av}}{f^2} TEC \right) \cos\left(\frac{23600.B_{av}}{f^2} TEC \right)} \frac{1}{\sqrt{T_H^2 + T_V^2}}$$

Where B_{av} is the average characteristic magnetic flux density on the ray path.

Some comments:

- $\frac{\Delta TEC}{TEC}$ is not constant. The acceptable relative error on TEC diminishes quickly when TEC increases
- typical morning TECs for SMOS configurations are lower than 5e17 e/m2 (and most of the time lower than 1e17 e/m2). The required accuracy on TEC inputs is given by the following table (for T_V=110K and T_H=75K)

TEC(e/m2)	**ΔT (K)**	**Corresponding ΔTEC (e/m2)**	***Relative error on TEC***
5e17	0.01	1.8e15	*0.4%*
	0.05	9.2e15	*1.8%*
	0.10	1.8e16	*3.7%*
1e17	0.01	9.2e15	*9.2%*
	0.05	4.6e16	*45.9%*
	0.10	9.2e16	*91.8%*

Providing a correction through TEC maps (from models or measurements) can most of the time result in a sufficient accuracy on T. However, high TEC values may still be problematic as they require an higher accuracy on the ancillary data.

Multi-channel algorithms

When several channels (especially polarisations) are available, ancillary knowledge about the ionosphere may be unnecessary as the corresponding information is already present in the various channels. Several types of algorithms may take advantage of this:

- estimation / correction of Faraday rotation effect through the complementary information brought by the different channels (polarisations)[iv].
- integration of the TEC as a parameter to retrieve in the multi-channel approach[v].

In all cases, an accurate estimation of the final (after post-processing) errors affecting SSS measurements must be undertaken.

Summary

An estimation of the fluctuations of the brightness temperatures caused by Faraday rotation effect has been proposed. A post processing correction could be applied through ancillary measurements / modelling. The possibility of using multi-channel algorithms to bypass Faraday-based limitations is very promising and is dealt with in separate documents [iv,v].

To be done

- to study the small scale variations in the ionosphere
- concerning Faraday rotation: to assess the hypothesis on the ionosphere which are used in the multi-channel algorithms (e.g. spatial and temporal stability of the vertical TEC within the field of view). Validated multi-channel algorithms would enable the direct use of SMOS data without being bothered by Faraday rotation.
- to describe and quantify the other potential ionospheric effects which may limit SMOS measurements

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[i] "The 3D NeQuick Model of vertical and slant TEC and worst cases scenarios", S.M. Radicella, R. Leitinger, B. Nava, G. Hochegger, L. Chander and P. Spalla, Ionospheric assessment for EGNOS report by the IET, Toulouse, 21-23 June 1999

[ii] http://nssdc.gsfc.nasa.gov/space/model/models/igrf.html

[iii] SIDC, Belgium Royal Observatory, http://sidc.oma.be/

[iv] Faraday rotation and L-band oceanographic measurements (Niels Skou, SMOS SAG note)

[v] Increase of uncertainty on retrieved SSS when retrieving the Faraday angle (Philippe Waldteufel, SMOS SAG note)