Regularized image reconstruction for the SMOS space mission

Eric Anterrieu and Ali Khazaal
Observatoire Midi-Pyrénées
Laboratoire d’Astrophysique de Toulouse-Tarbes (UMR 5572)
14 avenue Edouard Belin - 31400 Toulouse - France
E-mail: Eric.Anterrieu@ast.obs-mip.fr

Abstract. Synthetic Aperture Imaging Radiometers (SAIR) are powerful sensors for high-resolution observations of the Earth at low microwaves frequencies. Within this context, the European Space Agency is currently developing the SMOS mission devoted to the monitoring of Soil Moisture and Ocean Salinity at global scale from L-band space borne radiometric observations obtained with a two-dimensional interferometer. This contribution is concerned with the reconstruction of radiometric brightness temperature maps from dual-polarimetric interferometric measurements.

1. Introduction
The two-dimensional L-band interferometer MIRAS [1] (Microwave Imaging Radiometer by Aperture Synthesis) is the single payload of the SMOS [2] (Soil Moisture and Ocean Salinity) space mission led by the European Space Agency. The problem of retrieving the radiometric temperature distribution of a scene under observation from interferometric data has been widely addressed [3] and the errors that may affect the reconstructed maps have been identified and studied in depth [4][5]. A linear algebra framework has been given to this problem [6] showing that it is ill-posed and has to be regularized in order to provide a unique and stable solution [6][7]. This contribution extends the band-limited regularization approach to the case of the processing of dual-polarimetric data (namely, horizontal and vertical polarizations).

The modelling of the instrument and the regularized reconstruction procedure are recalled in section 2. Section 3 is devoted to the dual-polarimetric extension. The modelling equations prove to be coupled and the level of coupling depends on the ratio between the intensity level of the cross-polar voltage patterns and the intensity level of the co-polar ones. It is shown that the band-limited approach could be extended thoroughly to the processing of dual-polarimetric data. However it leads to the (pseudo-)inversion of a larger regularized matrix which exhibits a 2 × 2 blocks structure. The eventuality for this matrix to be block-diagonal dominant is addressed in section 4 where the impact of the coupling on the reconstruction process is examined with the aid of numerical simulations conducted within the frame of the SMOS project.

2. Theoretical framework
SAIRs devoted to Earth observation measure the correlation between the signals collected by pairs of spatially separated antennas which have overlapping fields of view, yielding samples
of the visibility function $V$ (also termed complex visibilities) of the brightness temperature distribution $T_b$ of the observed scene.

### 2.1. Direct problem

The relationship between $V$ and $T_b$ has been recently revisited in order to take into account mutual effects of close antennas [8]. Without polarimetric considerations it is now given by:

$$V_{kl} = \frac{1}{\sqrt{T_{kl}}} \int \int F_k(\xi) \tilde{T}_l(\xi)(T_b(\xi) - T_{\text{rec}}) \tilde{r}_{kl}(t) \frac{e^{-2j\pi u_{kl}\xi}}{\sqrt{1 - \|\xi\|^2}},$$

where $u_{kl}$ is the spatial frequency associated with the two antennas $A_k$ and $A_l$ (namely, the spacing $d_{kl}$ between $A_k$ and $A_l$ normalized to the central wavelength of observation $\lambda_0$), the components $\xi_1 = \sin \theta \cos \phi$ and $\xi_2 = \sin \theta \sin \phi$ of the angular position variable $\xi$ are direction cosines in the SAIR reference frame ($\theta$ and $\phi$ are the traditional spherical coordinates), $T_{\text{rec}}$ is the physical temperature of the receivers (assumed to be the same for all the receivers), $F_k$ and $F_l$ are the normalized voltage patterns of the two antennas $A_k$ and $A_l$ with equivalent solid angles $\Omega_k$ and $\Omega_l$, $\tilde{r}_{kl}$ is the fringe-wash function which accounts for spatial decorrelation effects, $t = u_{kl} \xi / f_o$ is the spatial delay and $f_o = c/\lambda_0$ is the central frequency of observation.

Denoting by $\ell$ the number of antennas, the number of complex visibilities $V_{kl}$ provided by the SAIR is equal to $\ell(\ell - 1)/2$ when accounting for the hermitian property of (1). However, some spatial frequencies $u_{kl}$ may be redundant since different pairs of antennas may lead to the same baseline. Since SAIR have limited physical dimensions, the spatial frequencies $u_{kl}$ sampled by an interferometer are confined to a limited region of the Fourier domain: the experimental frequency coverage $H$. In the case of MIRAS, a Y-shaped array fitted with $\ell = 69$ equally spaced antennas has been selected. Consequently, the visibility samples are obtained from raw data inside a star-shaped window over an hexagonally sampled grid $G_u$ in the Fourier domain [1]. Finally, for computational purposes, numerical integration is used to represent integral (1) as a discrete summation over $n^2$ integrand samples, here the $n^2$ pixels of the spatial grid $G_\xi$ which is the dual grid of $G_u$.

### 2.2. Regularized inverse problem

The inverse problem aims at retrieving $T = T_b - T_{\text{rec}}$ from $V$ by solving the linear system

$$GT = V,$$  

where $G$ is the discrete linear operator from the object space $E$ into the data space $F$ describing relation (1). Of course, the constant $T_{\text{rec}}$ will be added back to the final solution, whatever the method used to obtain it.

Since the direct problem is stated via an integral equation, (2) does not usually have a straightforward solution. Moreover, since the dimension of $E$ (the $n^2$ pixels used to sample $T$) is often larger than the dimension of $F$ (the $\ell(\ell - 1)/2$ samples of $V$), (2) is an underconstrained linear system with multiple solutions for $T$. As a consequence, the minimum of the least-square criterion

$$\min_{T \in E} ||V - GT||_F^2,$$

which is also the solution of the normal equation $G^*GT = G^*V$, is therefore not unique because the square matrix $G^*G$ is not invertible ($G^*$ being the Hilbert adjoint of $G$, namely the transposed complex conjugate). Thus, the inverse problem is ill-posed and has to be regularized in order to provide a unique and stable solution for $T$.  


A new regularized approach has been recently proposed to the European Space Agency and selected for implementation in the ground segment prototype [6]. This approach provides the best estimate $T_r$ of $T$ inasmuch as all the available information concerning the modelling of the instrument is taken into account in the (regularized) inversion [7]. Referring to a physical concept, namely the limited resolution of the SAIR, this approach finds the temperature map $T_r$ which has its Fourier transform confined to the experimental frequency coverage $H$. This band-limited solution realizes the minimum of the constrained problem

\[
\begin{cases}
\min_{T \in E} \| V - GT \|^2_F \\
(I - P_H)T = 0
\end{cases}
\]

where $P_H$ is the projector onto the subspace $E$ (of $E$) of the $H$-band limited functions. The unique solution of (4) is:

\[
T_r = U^* Z A^+ V,
\]

where $A^+$ is the Moore-Penrose pseudo-inverse of the rectangular matrix $A = G U^* Z$, $U$ is the Fourier transform operator, $Z$ is the zero-padding operator beyond $H$.

In order to reduce the systematic reconstruction error which has been recently analyzed [9], it has been proposed to subtract, from the complex visibilities $V$, the contribution $\tilde{V}$ of a brightness temperature distribution $\tilde{T}$ which is “as close as possible” to the observed scene $T_b$. More precisely, the differential system $\delta V = G \delta T$ is solved for $\delta T$ with $\delta V = V - \tilde{V}$ and $\tilde{V} = G \tilde{T}$ and the temperature map $\tilde{T}$ is added back to the solution $\delta T_r$ thus obtained, so that (5) becomes

\[
T_r = U^* Z A^+ (V - G \tilde{T}) + \tilde{T}.
\]

Finally, $T_r$ is damped by an appropriate apodization function $W$ [10] for filtering out the Gibbs effects due to the sharp frequency cut-off of the experimental frequency coverage $H$ and the constant $T_{rec}$ is added back to the solution thus obtained:

\[
T_r = U^* \tilde{W} U T_r + T_{rec},
\]

where $\tilde{W}$ is the diagonal matrix whose non-zero elements are the values of $\tilde{W}$ in $H$. As shown in [6], $T_r$ has to be compared to $T_w = U^* \tilde{W} U T_b$ (which is apodized with the same window $W$) and not to $T_b$ (which is at a higher spatial resolution).

3. Extension to the dual-polarization

In dual-polarimetric mode, MIRAS measures the brightness temperature in horizontal and vertical polarizations.

3.1. Direct problem

Denoting by $x$ and $y$ the polarizations (in the SAIR reference frame) that are selected in each of the two receivers $R_k$ and $R_l$ involved in the particular baseline $d_{kl}$, the dual-polarimetric version of (1) derived from [11] is given by the set of equations:

\[
V_{kl}^x = \frac{1}{\sqrt{\Omega_k \Omega_l}} \int_\Xi \left[ C_k^x(\xi) C_l^x(\xi) (T_b^x(\xi) - T_{rec}) + X_k^x(\xi) X_l^x(\xi) (T_b^y(\xi) - T_{rec}) \right] \tilde{r}_{kl}(t) \frac{e^{-2j\pi u_{kl} \xi}}{\sqrt{1 - \| \xi \|^2}} d\xi
\]

\[
V_{kl}^y = \frac{1}{\sqrt{\Omega_k \Omega_l}} \int_\Xi \left[ X_k^y(\xi) X_l^y(\xi) (T_b^y(\xi) - T_{rec}) + C_k^y(\xi) C_l^y(\xi) (T_b^x(\xi) - T_{rec}) \right] \tilde{r}_{kl}(t) \frac{e^{-2j\pi u_{kl} \xi}}{\sqrt{1 - \| \xi \|^2}} d\xi
\]
where $T^x_b$ and $T^y_b$ are the brightness temperature distributions of the observed scene in $x$ and $y$ polarizations. As demonstrated in [12], these brightness temperatures at antennas level are linear combinations of horizontal and vertical polarizations $T^h_b$ and $T^v_b$ at Earth level. Since $V^x$ and $V^y$ samples depend on both $T^x_b$ and $T^y_b$ temperatures, the two previous equations are said to be coupled. Here, the level of coupling depends in both polarizations on the intensity level of the cross-polar voltage patterns $X^x$ (resp. $X^y$) compared with the intensity level of the co-polar ones $C^x$ (resp. $C^y$). For antenna $A_k$ it could be defined by the ratios:

$$
\rho^x_k = 20 \log_{10} \frac{\max_{\|\xi\| \leq 1} \left| X^x_k(\xi) \right|}{\max_{\|\xi\| \leq 1} \left| C^x_k(\xi) \right|} \quad \text{and} \quad \rho^y_k = 20 \log_{10} \frac{\max_{\|\xi\| \leq 1} \left| X^y_k(\xi) \right|}{\max_{\|\xi\| \leq 1} \left| C^y_k(\xi) \right|}
$$

(9)

As shown in Fig. 1 for the $l = 69$ antennas of MIRAS whose co-polar and cross-polar voltage patterns have been measured in $x$ and $y$ polarizations in a radio anechoic chamber [13], this level of coupling varies from one antenna to another and from one polarization to the other. More exactly, $\rho^x$ varies between $-17.0$ dB and $-24.5$ dB and $\rho^y$ varies between $-18.9$ dB and $-26.7$ dB. The average level of coupling $\bar{\rho}$ is about $-21.9$ dB for $\rho^x$ and about $-22.7$ dB for $\rho^y$, in both polarizations the spread around these values is of the order of 2 dB.

![Figure 1. Levels of coupling of the 69 antennas of MIRAS in x (left) and y (right) polarizations.](image)

### 3.2. Regularized inverse problem

Denoting again by $G$ the modelling operator which now exhibits a $2 \times 2$ blocks structure describing the two relations in (8), the inverse problem $GT = V$ now reads with $T^x = T^x_b - T_{rec}$ and $T^y = T^y_b - T_{rec}$:

$$
\begin{pmatrix}
G_{xx} & G_{xy} \\
G_{yx} & G_{yy}
\end{pmatrix}
\begin{pmatrix}
T^x \\
T^y
\end{pmatrix}
= \begin{pmatrix}
V^x \\
V^y
\end{pmatrix},
$$

(10)

where $G_{xx}$, $G_{xy}$, $G_{yx}$ and $G_{yy}$ are the four blocks of $G$. According to (8), the diagonal blocks $G_{xx}$ and $G_{yy}$ only depend on the co-polar voltage patterns $C^x$ and $C^y$, respectively, whereas the off-diagonal ones, $G_{xy}$ and $G_{yx}$, only depend on the cross-polar voltage patterns $X^x$ and $X^y$, respectively, and are therefore responsible for the coupling.

Referring again to the limited resolution of the SAIR, the band-limited solution $T_r$ now reads:

$$
\begin{pmatrix}
T^x_r \\
T^y_r
\end{pmatrix}
= \begin{pmatrix}
U^*Z & 0 \\
0 & U^*Z
\end{pmatrix}
\begin{pmatrix}
A_{xx} & A_{xy} \\
A_{yx} & A_{yy}
\end{pmatrix}^+
\begin{pmatrix}
V^x \\
V^y
\end{pmatrix},
$$

(11)

where $A_{xx} = G_{xx}U^*Z$, $A_{xy} = G_{xy}U^*Z$, $A_{yx} = G_{yx}U^*Z$ and $A_{yy} = G_{yy}U^*Z$ are the four blocks of the new $2 \times 2$ blocks matrix $A$. Equations (10) and (11) are similar to former equations (2) and (5). However, from the numerical implementation point of view, the dimension of the problem to be solved, or the size of the matrix to be (pseudo-)inverted, is now 4 times larger.
3.3. Bias reduction

With regards to the reduction of the systematic reconstruction error, the same strategy could be applied for solving a differential system by introducing artificial scenes, now in both polarization, so that solutions (11) become

\[
\begin{pmatrix}
T_x^y \\
T_y^y
\end{pmatrix} = \begin{pmatrix}
U^*Z & 0 \\
0 & U^*Z
\end{pmatrix}
\begin{pmatrix}
A_{xx} & A_{xy} \\
A_{yx} & A_{yy}
\end{pmatrix}^+ \left[
\begin{pmatrix}
V_x \\
V_y
\end{pmatrix} - \begin{pmatrix}
G_{xx} & G_{xy} \\
G_{yx} & G_{yy}
\end{pmatrix}
\begin{pmatrix}
\tilde{T}_x \\
\tilde{T}_y
\end{pmatrix}
\right] + \begin{pmatrix}
\tilde{T}_x \\
\tilde{T}_y
\end{pmatrix}.
\]

(12)

Depending on the level of coupling between the cross-polar voltage patterns and the co-polar ones, the off-diagonal blocks of $G$ could be neglected. Consequently, the inverse problem (10) could be reduced to the regularization and the inversion of two independent problems of smaller size, namely those corresponding to the remaining diagonal blocks of $G$, i.e. $G_{xx}T_x^x = V_x^x$ and $G_{yy}T_y^y = V_y^y$. If this eventuality would happen, the off-diagonal blocks of $A$ could also be neglected and solutions (12) would reduce to:

\[
\begin{align*}
T_x^x &= U^*ЗA_{xx}^+(V_x^x - G_{xx}\tilde{T}_x^x) + \tilde{T}_x^x, \\
T_y^y &= U^*ЗA_{yy}^+(V_y^y - G_{yy}\tilde{T}_y^y) + \tilde{T}_y^y.
\end{align*}
\]

(13)

Indeed, in such a situation, the computation of the Moore-Penrose pseudo-inverse $A^+$ would reduce to the computation of $A_{xx}^+$ and $A_{yy}^+$.

Whatever the level of coupling, some surprising effects could also be expected from the bias reduction strategy. Indeed, the differential visibilities $\delta V_x^x = V_x^x - \tilde{V}_x^x$ and $\delta V_y^y = V_y^y - \tilde{V}_y^y$ between the brackets in (12) could be free from coupling, or less coupled than the visibilities themselves. Consequently, the reconstruction with a full matrix $A$ would not be justified and there is some room for an intermediate solution, between expressions (12) and (13), with a full modelling matrix $G$ for synthesizing the artificial visibilities $\tilde{V}_x^x$ and $\tilde{V}_y^y$ but a block diagonal matrix $A$ for the inversion of the differential visibilities thus obtained:

\[
\begin{pmatrix}
T_x^x \\
T_y^y
\end{pmatrix} = \begin{pmatrix}
U^*ЗA_{xx}^+ & 0 \\
0 & U^*ЗA_{yy}^+
\end{pmatrix} \left[
\begin{pmatrix}
V_x \\
V_y
\end{pmatrix} - \begin{pmatrix}
G_{xx} & G_{xy} \\
G_{yx} & G_{yy}
\end{pmatrix}
\begin{pmatrix}
\tilde{T}_x \\
\tilde{T}_y
\end{pmatrix}
\right] + \begin{pmatrix}
\tilde{T}_x \\
\tilde{T}_y
\end{pmatrix}.
\]

(14)

This intermediate solution would be less time consuming and would require less memory than the complete one. It should be more accurate than the approximated solution, but numerical investigations have to be conducted in order to compare its accuracy with the accuracy of the complete solution.

4. Numerical simulations

The results presented in this section are based on numerical simulations conducted within the frame of the SMOS project. All these simulations have been performed for a Y-shaped array equipped with $\ell = 69$ antennas. The number of available complex visibilities $V_{kl}$ is equal to $n_b = 2346$. However, some of the corresponding baselines $d_{kl}$ are redundant and consequently there are only $n_f = 1395$ spatial frequencies in the star-shaped frequency coverage $H$. Three reference radiometers have been added to the interferometric array in order to measure the visibility function for the zero spacing. The dimension of the sampling grids $G_u$ and $G_\xi$ has been fixed to $n^2 = 128 \times 128$.

Shown in Fig. 2 are the brightness temperature distributions in $x$ and $y$ polarizations of a test scene over the Iberian peninsula. Both maps are shown at their highest level of resolution as well as at the resolution level of the instrument and apodized with a Blackman window. The synthesized field of view of MIRAS being subject to Earth and sky aliasing because of the spacing between the antennas [2], the maps to be reconstructed $T_w^x$ and $T_w^y$ are shown in
that part of the synthesized field of view which is free from replica from the Earth whereas the
original maps $T_b^{x}$ and $T_b^{y}$ are shown in the whole space in front of the instrument. Two sets $V_1$ and $V_2$ of complex visibilities $V = (V^x, V^y)^t$ have been simulated from $T_b = (T_b^{x}, T_b^{y})^t$:

- $V_1$ has been simulated without cross-polar gains so that $V_1^x$ only depends on $T_b^{x}$ and $V_1^y$ only depends on $T_b^{y}$;
- $V_2$ has been simulated with both co-polar and cross-polar gains so that now $V_2^x$ and $V_2^y$ depend on both $T_b^{x}$ and $T_b^{y}$.

Then, four sets of maps $T_r = (T_r^{x}, T_r^{y})^t$ have been retrieved:

- $T_{1r}$ has been retrieved from $V_1$ with the corresponding independent reconstructions (13) since there is no coupling between $V_1^x$ and $V_1^y$;
- $T_{2r}$ has been retrieved from $V_2$ with the heavy reconstruction process (12) which involves the four blocks of matrices $G$ and $A$ for taking into account the coupling between $V_2^x$ and $V_2^y$ as well as between the differential visibilities $\delta V_2^x$ and $\delta V_2^y$;
- $T_{3r}$ has also been retrieved from $V_2$ but with the intermediate reconstructions (14) which takes into account an eventual coupling between $V_2^x$ and $V_2^y$ but which assumes that the differential visibilities $\delta V_2^x$ and $\delta V_2^y$ thus obtained are not coupled.
- $T_{4r}$ has also been retrieved from $V_2$ but with the light reconstructions (13) which do not take into account an eventual coupling between $V_2^x$ and $V_2^y$ as well as between the differential visibilities $\delta V_2^x$ and $\delta V_2^y$.

The real-valued $2 \times 2$ blocks matrix $A$ of MIRAS shown in Fig. 3 turns out to be block-diagonal dominant. Indeed, the off-diagonal blocks could be neglected since there is more than 2 orders of magnitude between the diagonal blocks and the off-diagonal ones. As a consequence, provided that the inversion process is still stable, both the approximate solutions (13) and the intermediate ones (14) should be very close to the complete solutions (12). This is exactly what is observed since the four error maps $\Delta T_r = T_r - T_w$ turns out to be almost identical. The bias $\Delta T_r$ and the standard deviation $\sigma_{\Delta T_r}$ are of the same order: 0.23 K and 0.56 K, resp., for the

Figure 2. A test scene in $x$ (left) and $y$ (right) polarizations at its highest level of resolution $T_b$ (top) and the corresponding maps to be reconstructed $T_w$ (bottom) in the frame attached to the instrument.
Figure 3. The regularized $2 \times 2$ blocks matrix $A$ of MIRAS.

$x$ polarization, 0.14 K and 0.50 K, resp., for the $y$ polarization. As a consequence, the following preliminary conclusions can be drawn:

- no size effects have affected the quality of the reconstructed maps in both polarizations otherwise $\Delta T_{2r}$ and $\Delta T_{1r}$ would differ;
- the coupling between the two polarizations could be neglected otherwise $\Delta T_{4r}$ and $\Delta T_{3r}$ would differ from $\Delta T_{2r}$.

In order to confirm the previous results and to ensure the stability of the overall regularized inversion of dual-polarimetric data, the level of coupling between the cross-polar voltage patterns and the co-polar ones has been artificially changed by multiplying the 69 cross-polar voltage patterns of MIRAS in both polarizations by the same factor so that the average antenna coupling $\bar{\rho}$ varies between $-31.9$ dB and $-11.9$ dB in $x$ polarization and between $-32.7$ dB and $-12.7$ dB in $y$ polarization, that is to say 10 dB on both sides of the actual values of MIRAS. For $\bar{\rho} < -20$ dB, both the bias and the standard deviation of the three solutions are constant and of the same order of magnitude of the values obtained in the absence of any coupling. In any case, the three solutions $T_{2r}$, $T_{3r}$ and $T_{4r}$ are almost identical to the solution $T_{1r}$ which means that the coupling could be neglected. On the contrary, when $\bar{\rho} > -20$ dB the approximate solution differs from the others: both the bias $\Delta T_{r}$ and the standard deviation $\sigma_{\Delta T_{r}}$ are increasing functions of the average coupling $\bar{\rho}$. This is not the case of the complete and (to a less extent) intermediate solutions. As a consequence, the following preliminary conclusions can also be drawn:

- the coupling between the two polarizations could not be neglected as soon as it is greater, on the average, than $-20$ dB since below this value $\Delta T_{4r}$ does not differ from $\Delta T_{1r}$ whereas above this value both the bias and the standard deviation of $\Delta T_{4r}$ are increasing functions of the average level of coupling;
- as expected, the bias reduction strategy has the nice property to reduce the coupling between the differential visibilities since $\Delta T_{3r}$ does not differ from $\Delta T_{2r}$, however the standard deviation is somewhat larger for the intermediate solution than for the complete one when the average coupling is above the previous limit;
- provided that the coupling is taken into account, it does not affect the quality of the reconstructed maps in both polarizations since $\Delta T_{2r}$ does not differ from $\Delta T_{1r}$.

Other simulations conducted with other test scenes have led to similar observations and conclusions.
5. Conclusions

This contribution was concerned with the reconstruction of brightness temperature maps from interferometric measurements provided by a SAIR. The band-limited regularisation selected by the European Space Agency for the SMOS mission has been extended to the case of the processing of dual-polarimetric data. Depending on the level of coupling between the co-polar and cross-polar voltage patterns of the antennas, the retrieved maps are obtained either at the cost of the resolution of a large coupled system, if needed, or with the resolution of two independent problems of smaller size, if this coupling is negligible. It has been shown that the quality of the reconstructed maps is not affected by some size effects.

With regards to the three approaches for reducing the bias and retrieving the brightness temperature maps in both polarization, it has been shown that the bias reduction strategy has the nice property to provide differential visibilities which are free from coupling, or less coupled than the visibilities themselves. Numerical simulations have confirmed that the intermediate approach is of course more accurate than the approximated one (which assumes no coupling and solves two independent systems) and less time consuming than the complete one (which solves a large coupled system). They have also shown that this approach is nearly as accurate as the complete one for a wide range of coupling levels.

With regards to the actual voltage patterns of MIRAS, it turns out that the coupling could be neglected since it is actually below a limit which has been found to be $-20$ dB (this study therefore validates the $-25$ dB isolation requirement imposed by ESA to the MIRAS designer). Consequently, the retrieved dual maps could be obtained with the approximated approach at the cost of the resolution of the two independent problems of small size. However, if for any reason the level of coupling would increase above the value of $-20$ dB, it has been shown that the dual maps retrieved with the complete approach (and to a less extent with the intermediate one) are not affected by the coupling, provided that this coupling is properly taken into account.

References

[1] M. Martin-Neira, Y. Menard, J.-M. Goutoule and U. Kraft, *MIRAS, a two-dimensional aperture synthesis radiometer*, in proc. IGARSS’94, Pasadena (California, USA), vol. 3, pp. 1323-1325, 1994.

[2] Y.H. Kerr, P. Waldteufel, J.-P. Wigneron, J.-M. Martinuzzi, J. Font and M. Berger, *Soil moisture retrieval from space: The Soil Moisture and Ocean Salinity (SMOS) Mission*, IEEE Trans. Geosci. Remote Sens., 39(8), pp. 1729-1735, 2001.

[3] A. Lannes and E. Anterrieu, *Image reconstruction methods for remote sensing by aperture synthesis*, in proc. IGARSS’94, Pasadena (California, USA), vol. 4, pp. 2228-2230, 1994.

[4] A. Camps, J. Bara, F. Torres, I. Corbella and J. Romeu, *Impact of antenna errors on the radiometric accuracy of large aperture synthesis radiometers*, Radio Sci., 32(2), pp. 657-668, 1997.

[5] F. Torres, A. Camps, J. Bara and I. Corbella, *Impact of receiver errors on the radiometric resolution of large two-dimensional aperture synthesis radiometers*, Radio Sci., 32(2), pp. 629-641, 1997.

[6] E. Anterrieu, *A resolving matrix approach for synthetic aperture imaging radiometers*, IEEE Trans. Geosci. Remote Sens., 42(8), pp. 1649-1656, 2004.

[7] B. Picard and E. Anterrieu *Comparison of regularized inversion methods in synthetic aperture imaging radiometry*, IEEE Trans. Geosci. Remote Sens., 43(2), pp. 218-224, 2005.

[8] I. Corbella, N. Duffo, M. Vall-llossera, A. Camps and F. Torres, *The visibility function in interferometric aperture synthesis radiometry*, IEEE Trans. Geosci. Remote Sens., 42(8), pp. 1677-1682, 2004.

[9] E. Anterrieu, *On the reduction of the reconstruction bias in synthetic aperture imaging radiometry*, IEEE Trans. Geosci. Remote Sens., 45(3), pp. 592-601, 2007.

[10] E. Anterrieu, P. Waldteufel and A. Lannes, *Apodization functions for 2D hexagonally sampled synthetic aperture imaging radiometers*, IEEE Trans. Geosci. Remote Sens., 40(12), pp. 2531-2542, 2002.

[11] M. Martin-Neira, S. Ribó and A.J. Martin-Polegre, *Polarimetric mode of MIRAS*, IEEE Trans. Geosci. Remote Sens., 40(8), pp. 1755-1768, 2002.

[12] S. Ribó and M. Martin-Neira, *Faraday rotation correction in the polarimetric mode of MIRAS*, IEEE Trans. Geosci. Remote Sens., 42(7), pp. 1405-1410, 2004.

[13] N. Skou, *Aspects of the SMOS pre-launch calibration*, in proc. IGARSS’03, Toulouse (France), vol. 2, pp. 1222-1225, 2003.