High Angular Resolution RFI Localization in Synthetic Aperture Interferometric Radiometers Using Direction of Arrival Estimation

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Abstract

Radio Frequency Interferences (RFIs) seriously affect the retrieval of geophysical parameters from the measurements of microwave radiometers. An accurate geolocation of the RFIs is crucial to effectively switch off illegal transmitters. In this letter, a new RFI localization method is proposed to improve the achievable angular resolution by using beamforming and Direction Of Arrival (DOA) estimation techniques. The proposed RFI localization techniques can be employed in synthetic aperture interferometric radiometers, such as the European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) mission. Two DOA estimation techniques are tested for the RFI localization: Capon and MUSIC. The feasibility of these methods is demonstrated with SMOS data. In the test results, the MUSIC beamforming shows a better performance of RFI localization than the SMOS Fourier imaging and the Capon, in terms of accuracy and resolution.

Index Terms

Radio Frequency Interferences (RFIs), synthetic aperture radiometry, microwave radiometry, beamforming, direction of arrival (DOA) estimation, Soil Moisture and Ocean Salinity (SMOS) mission.

I. INTRODUCTION

Since the successful launch of the European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) mission [1], global maps of these two geophysical variables are routinely generated [2]. SMOS payload is the Synthetic Aperture Interferometric Radiometer (SAIR), called MIRAS from which two-dimensional L-band (1.4 GHz) Brightness Temperature (BT) maps are generated. Although this band is protected, there is still contamination

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from on-ground man-made sources of Radio-Frequency Interferences (RFIs), which operate close to this band or whose spurious signals fill in this band. The presence of RFIs in the measured data impacts the geophysical parameter retrieval, and therefore RFIs should be properly detected and mitigated to obtain the informative data from the SAIR measurements.

There are several methods to detect and mitigate the RFI, e.g., time, frequency, kurtosis, statistical, spectrogram (time-frequency), and wavelet methods [3]–[15]. However, MIRAS is a single frequency instrument with limited time and angular resolutions, and therefore it is difficult to apply the previous methods directly. The interferometric nature of SAIR imaging makes the RFI detection and mitigation more complicated. Actually, the ultimate method to fight against the RFI contamination is to enforce illegal transmitters to be switched off. In this case, providing accurate locations of the RFI sources is essential to eliminate the RFI impacts [8].

Because the SMOS spatial resolution is 35-55 km, it is quite a challenge to detect the RFI location precisely. In the worst case, multiple RFIs can be located closely, even within a single resolution pixel, and then it is impossible to resolve their locations [8]. The geolocation of RFI sources can be improved by statistical approaches such as the use of multiple snapshots [6], [8], [12]. In a single snapshot, however, it is restricted by the angular resolution of the instrument.

In this letter, a high spatial resolution method is proposed for the localization of RFI sources in the SAIR measurements. The main idea is to employ Direction Of Arrival (DOA) estimation schemes, used in array signal processing. In this case, RFI sources are considered as the signal source, and the brightness temperature of the scene is considered as the background noise. Then, DOA estimation can be applied to the localization of RFI sources.

In Section II, the SAIR observation is formulated for DOA estimation. Then, two DOA estimation techniques are applied to RFI source localization: the Capon and the MUSIC algorithms, in Section III. In Section IV, we demonstrate these techniques using real SMOS measurements, followed by the conclusion and outlook in Section V.

II. FORMULATION FOR RFI SOURCE DETECTION

The observables of a SAIR are samples of the visibility function, which are the cross-correlations of the signals collected by any two antenna-receiver chains (k th and l th). The SMOS visibility function is presented as [5], [16]:

$$\begin{aligned} V_{kl}^{pq} &= \langle y_k y_l^* \rangle \\ &= \frac{1}{\sqrt{\Omega_k \Omega_l}} \iint_{\xi^2 + \eta^2 \leq 1} \frac{T(\xi, \eta) - T_{rec} \delta_{pq}}{\sqrt{1 - \xi^2 - \eta^2}} F_{n,p_k}(\xi, \eta) F_{n,q_l}^*(\xi, \eta) \tilde{r}_{kl} \left(-\frac{u_{kl}\xi + v_{kl}\eta}{f_0} \right) \exp(-j2\pi(u_{kl}\xi + v_{kl}\eta)) d\xi d\eta \end{aligned} \quad (1)$$

where $\Omega_{k,l}$ is the equivalent solid angle of the antennas, $T(\xi, \eta)$ is the BT of the scene, T_{rec} is the Corbella term (physical temperature of the receivers), δ_{pq} is the Kronecker's delta function, $F_{n,p_k}(\xi, \eta)$ represents the k th antenna normalized voltage pattern at p polarization, the symbol $*$ denotes the complex conjugate, $\tilde{r}_{kl}$ is the fringe washing function (FWF) between k th and l th chains, f_0 is the central frequency of the receivers, and (ξ, η) are the direction

cosines with respect to the x- and y-axes. The baseline (i.e., spatial frequencies where the visibility function is sampled), (u_{kl}, v_{kl}) is computed from the antenna positions divided by wavelength:

$$(u_{kl}, v_{kl}) = \left(\frac{Px_k - Px_l}{\lambda}, \frac{Py_k - Py_l}{\lambda} \right) \quad (2)$$

where (Px_n, Py_n) denotes the n th antenna position, and λ is the wavelength.

In (1), the visibility samples are obtained by cross-correlating all the pairs of received signals in each antenna. These measurements can be understood as the elements of the covariance matrix $\mathbf{R}$ used in the beamforming for DOA estimation:

$$\mathbf{R} = \langle \mathbf{y}\mathbf{y}^H \rangle \quad (3)$$

where $\mathbf{y}$ is the vector of the receiver outputs, and the superscript H denotes the Hermitian transpose. The receiver outputs can be expressed as

$$\begin{aligned} \mathbf{y} &= [y_1, y_2, \dots, y_N]^T = \sum_{i=1}^M \mathbf{a}(\xi_i, \eta_i) s(\xi_i, \eta_i) + \mathbf{n} \\ &= [\mathbf{a}_1, \dots, \mathbf{a}_M] \mathbf{s} + \mathbf{n} = \mathbf{A}\mathbf{s} + \mathbf{n} \end{aligned} \quad (4)$$

where $\mathbf{s} = [s(\xi_1, \eta_1), \dots, s(\xi_M, \eta_M)]^T$ denotes the vector of the impinging signals from the (ξ, η) direction, $\mathbf{n} = [n_1, n_2, \dots, n_N]^T$ is the receiver noise vector, $\mathbf{a}(\xi_i, \eta_i)$ is the steering vector for the signal from (ξ_i, η_i) , and $\mathbf{A}$ is the steering matrix formed by piling up the different steering vectors. The size of the steering matrix is equal to the number of receivers (N rows), and the number of signal sources (M columns). The steering vector for the m th signal is given by

$$\mathbf{a}_m = \left[e^{-j\frac{2\pi}{\lambda}(Px_1\xi_m + Py_1\eta_m)}, \dots, e^{-j\frac{2\pi}{\lambda}(Px_n\xi_m + Py_n\eta_m)}, \dots, e^{-j\frac{2\pi}{\lambda}(Px_N\xi_m + Py_N\eta_m)} \right]^T. \quad (5)$$

Then, the covariance matrix can be written as

$$\mathbf{R} = \mathbf{A}\mathbf{s}\mathbf{s}^H\mathbf{A}^H + \mathbf{n}\mathbf{n}^H = \mathbf{A}\boldsymbol{\sigma}_s^2\mathbf{A}^H + \boldsymbol{\sigma}_n^2 \quad (6)$$

where $\boldsymbol{\sigma}_s^2$ denotes the signal power matrix ($M \times M$) of which diagonal is the power of each signal, $\boldsymbol{\sigma}_n^2$ denotes the noise power matrix of which diagonal is the variance of the noise in each visibility samples.

The k - l element of the covariance matrix R_{kl} is

$$\begin{aligned} R_{kl} &= \sum_{i=1}^M \exp \left\{ -j\frac{2\pi}{\lambda}(Px_k\xi_i + Py_k\eta_i) \right\} \exp \left\{ j\frac{2\pi}{\lambda}(Px_l\xi_i + Py_l\eta_i) \right\} \sigma_s^2(\xi_i, \eta_i) + \sigma_n^2 \\ &= \sum_{i=1}^M \sigma_s^2(\xi_i, \eta_i) \exp \{ -j2\pi(u_{kl}\xi_i + v_{kl}\eta_i) \} + \sigma_n^2, \end{aligned} \quad (7)$$

since the baselines (u_{kl}, v_{kl}) are the antenna spacing divided by the wavelength λ . Thus, the covariance matrix can be constructed by using the visibility samples themselves, and the beamforming for DOA estimation can be applied to RFI localization. The formulation of the SAIR observation in the sense of sensor array is described in more detail in [17] and [18].

III. BEAMFORMING FOR RFI SOURCE DETECTION

Among the different beamforming techniques for DOA estimation, three classical methods are tested in this work, which are the conventional (Discrete Fourier Transform method), the Capon, and the MUSIC methods. The derivation and analysis of each method can be found in [19] and [20]. Only the DOA estimator, namely the spatial spectra of the three methods are presented here.

The spatial spectrum of the conventional beamforming is given by

$$P_{con}(\xi, \eta) = \frac{\mathbf{a}^H(\xi, \eta) \mathbf{R} \mathbf{a}(\xi, \eta)}{\mathbf{a}^H(\xi, \eta) \mathbf{a}(\xi, \eta)}. \quad (8)$$

Actually, the conventional beamforming is equivalent to the Discrete Fourier Transform (DFT) method used in SAIR image reconstruction [17], [21], [22], and therefore the angular resolution of RFI localization is the same as that of the reconstructed SAIR image.

The Capon method was proposed to improve the angular resolution associated with the conventional method. The Capon method is also known as Minimum Variance Distortionless Response (MVDR) method. The goal of Capon filter is to minimize the array output power (minimum variance) subject to a unity gain constraint (distortionless response) in the desired look direction [19], [20]. The Capon spectrum (unitless) is given by

$$P_{cap}(\xi, \eta) = \frac{1}{\mathbf{a}^H(\xi, \eta) \mathbf{R}^{-1} \mathbf{a}(\xi, \eta)}. \quad (9)$$

The MUSIC method is a parametric estimation, for which the number of signal sources should be an input parameter of the estimator. The MUSIC algorithm is a subspace method based on the fact that noise eigenvectors are orthogonal to the signal steering vectors. The spatial pseudo-spectrum (unitless) of MUSIC is given by

$$P_M(\xi, \eta) = \frac{1}{\mathbf{a}^H(\xi, \eta) \mathbf{E}_n \mathbf{E}_n^H \mathbf{a}(\xi, \eta)} \quad (10)$$

where $\mathbf{E}_n$ is the noise subspace, obtained by using the eigenvalue decomposition of the covariance matrix $\mathbf{R}$. The MUSIC estimator is a measure of the orthogonality between the steering vector $\mathbf{a}^H(\xi, \eta)$ and the noise subspace $\mathbf{E}_n$. Therefore, the MUSIC pseudo-spectrum produces peaks in the directions of the signal sources.

These beamforming methods are normally employed for DOA estimation in sensor array, e.g., smart antenna for communication, target detection of RADAR and SONAR, array seismology, and radio astronomy. In these applications, the arrived signals come from point-wise sources, while in the SAIR observations the signals come from continuous (or extended) sources. In the next section, the results of DOA estimation are illustrated using SMOS data to test the feasibility of techniques for RFI source localization.

IV. SMOS RFI LOCALIZATION USING DOA ESTIMATION

In this section, the RFI localization using DOA methods is demonstrated with SMOS data, the only available spaceborne SAIR instrument measurements. The payload of SMOS is MIRAS which has the Y-shaped array with 23 antennas per arm. Since the covariance matrix can be constructed by using the visibility samples, the SMOS L1A data are used for Capon and MUSIC DOA estimation. The BT snapshots in antenna frame (equivalent to conventional beamforming or DFT imaging results) are used for comparison. We have tested about 15 different snapshots. In this letter, three snapshots over Greece and Italy are shown as examples.

Fig. 1. Results of RFI localization using SMOS data. The first row (a, b, c, d) shows the results of Greece (Gr); the second row (e, f, g, h) results of Italy1 (It1); and the third row (i, j, k, l) results of Italy2 (It2). The first column (a, e, i) shows the SMOS geolocated images; the second column (b, f, j) SMOS DFT images in antenna frame, the third column (c, g, k) spatial spectra of Capon beamforming; and the fourth column (d, h, l) spatial spectra of MUSIC. The known RFI locations are marked with black circles in the geolocated images (a, e, i), and with white circles in the others. The color of geolocated images (a, e, i) are trimmed in the range of 0 to 350 K.

A snapshot over Greece is shown in Fig. 1(a). It was acquired at 2013-03-26T03:54:45. The other two were acquired over Italy, at 2011-03-06T04:30:37, and 2011-03-06T04:29:59, and are shown in Figs. 1(e) and (i), respectively. For convenience, three images are hereinafter called Greece (Gr), Italy1 (It1) and Italy2 (It2), respectively. The first column, Figs. 1(a), (e), and (i) show the corresponding SMOS calibrated and geolocated BTs reconstructed by DFT imaging. In these figures, the strong RFIs degrade the BT images, showing that the BTs of many pixels are higher than the highest natural emission level, i.e., $BT > 350$ K. This RFI contamination hampers the retrieval of soil moisture and ocean salinity from the BT images.

The DFT results in antenna frame are shown in the second column, Fig. 1(b), (f), and (j). The RFI sources are presented as local peaks of $BT > 350$ K. The spatial spectra of the Capon and the MUSIC in antenna frame are shown in the third, and the fourth columns in Fig. 1, respectively. The peaks in DFT results are also present in the Capon and MUSIC results. Note that the DFT results represent directly the BT maps, so the colorbar units are Kelvin in Figs. 1(b), (f), and (g). The Capon and MUSIC produce pseudo-spectra, so the colorbars of their results in Fig. 1 (third and fourth columns) are unitless.

In Fig. 1, the MUSIC results seem to produce higher angular resolution of the RFI localization. In other words, the RFIs are presented as sharper peaks in MUSIC than in the others. In order to compare the RFI localization

Fig. 2. Zoom of a single source localization. The first row (a, b, c) shows the results in Greece; the second row (d, e, f) in Italy1, and the third row (g,h,i) in Italy2. The first, second, and third columns show the results of SMOS DFT, Capon, and MUSIC, respectively. The RFI directions identified on-ground are denoted by the white circles, and the local maxima by the black crosses.

performances of the three methods, the accuracy and the resolution are discussed one by one.

A. Accuracy of RFI Location

In the snapshots tested, there are two RFI sources which have been identified on ground. One is located around $(\text{long, lat}) = (\text{E } 25^\circ, \text{N } 35^\circ)$ ¹, which is marked with black circles in Fig.1(a) and with white circles in Figs.1(b), (c), and (d). The second one is located around $(\text{long, lat}) = (\text{E } 09^\circ, \text{N } 46^\circ)$, which are marked in the second and the third rows in Fig.1.

¹The exact locations of RFI sources are confidential, and the authors have received the instructions not making them publicly available.

The regions are zoomed in and shown in Fig. 2; the first row corresponds to the Gr data, the second row to the It1 data, and the third row shows the It2 data. The true RFI directions are denoted by white circles. Local maxima correspond to the estimated direction of the RFI sources, which are denoted by the black crosses in Fig. 2. For comparison purpose, the images are normalized, and contour plots are added. Table I shows the accuracy of a single RFI source localization. The distances between the maxima and the true RFI positions are used to assess the accuracy. As shown in Fig. 2 and Table I, the errors of the MUSIC method are smaller than the others. The Capon shows smaller errors than the SMOS image for strong RFI, e.g., Gr and It1 results. However, it becomes worse in weak RFI as in It2. All three methods show the degradation of accuracy as the BT is weak.

TABLE I
ACCURACY TEST RESULTS

		RFI Source direction	Distance to true	
		(ξ, η)	in (ξ, η)	km
Gr (BT = 2203 K)	TRUE	(0.0306, -0.4751)		
	SMOS	(0.0335, -0.4756)	0.0029	2.28
	CAPON	(0.0306, -0.4762)	0.0011	0.96
	MUSIC	(0.0306, -0.4761)	0.0010	0.87
It1 (BT = 1260 K)	TRUE	(0.3431, -0.1638)		
	SMOS	(0.3404, -0.1604)	0.0043	4.22
	CAPON	(0.3425, -0.1614)	0.0025	2.47
	MUSIC	(0.3425, -0.1625)	0.0014	1.41
It2 (BT = 537 K)	TRUE	(0.2973, 0.0597)		
	SMOS	(0.2950, 0.0633)	0.0043	5.11
	CAPON	(0.2899, 0.0663)	0.0099	10.95
	MUSIC	(0.2928, 0.0621)	0.0024	3.32

B. Angular / Spatial Resolution of RFI Location

As shown in Fig. 2, the MUSIC method detects the RFI sources as narrower peaks, namely, with high angular / spatial resolution. Table II shows more results of the resolution test. In each snapshot, three peaks are selected as examples. The half power width (approximate diameter of the 0.5 contour as in Fig. 2) is used to assess the resolution. Overall, the MUSIC method yields the best performance in the resolution, compared with the others. For the strong RFI sources, the half power widths of MUSIC are quite smaller than those of SMOS images. For example, the RFI source of BT=2203 K in Gr, the half power width of MUSIC is 38 % SMOS DFT results, in Table II. For the weak RFI sources, MUSIC shows comparable resolution, e.g., in the worst case, MUSIC half power width is 99% SMOS DFT, on BT=907 K in It2.

The RFI location resolution of SMOS DFT is roughly constant, ($\Delta\xi_{-3dB} \approx 0.04$). It is related to the angular resolution of the SMOS MIRAS, which is defined by the maximum baseline of the antenna array [23]. However, the Capon and MUSIC methods have different resolutions with respect to the observed scene, specifically dominated by

the source power, i.e., Signal-to-Noise Ratio [19]. Accordingly, the MUSIC and Capon methods show the resolution performance with respect to the RFI source BT, see Table II.

Capon results improve in the strong source case, e.g., the case of BT=17097 K in Table II. However, the Capon can be worse than the SMOS DFT in weak RFI cases. Comparing Figs. 2(g) and (h), the SMOS DFT has a smaller half power width than the Capon result. In the worst case, the Capon results could not make the closed ellipse of half power contour, which are denoted by “N” in Table II.

TABLE II
RESOLUTION TEST RESULTS

RFI Location in SMOS Image			Half Power Width		
(ξ,η)		BT (K)	SMOS	CAPON	MUSIC
			in (ξ,η) (km)		
Gr	(0.0335, -0.4756)	2203	0.0423	0.0336	0.0162
			19.76	15.69	7.56
	(-0.2545, -0.2659)	589	0.045	N ^a	0.0308
			22.8		15.73
	(-0.2752, 0.0243)	3170	0.0424	0.0286	0.0103
			28.28	18.96	6.82
It1	(0.3404, -0.1604)	1260	0.0366	N	0.0279
			24.06		18.35
	(-0.3606, -0.3622)	17097	0.0372	0.0259	0.0152
			19.61	13.63	7.99
	(0.0148, -0.2346)	656	0.0411	N	0.0373
			20.47		18.66
It2	(0.2950, 0.0633)	537	0.0381	N	0.037
			27.00		26.25
	(-0.1089, -0.6172)	5079	0.0324	0.0347	0.0188
			14.46	15.45	8.39
	(-0.3239, -0.1017)	907	0.0328	0.0445	0.0324
			20.23	27.51	20.08

^aContour of 0.5 is too large to calculate the half power width.

C. RFI Cluster Location

In the first row of Fig. 1, there is a cluster of RFI sources around (-0.35,-0.15), zoomed in Fig. 3 and normalized for comparison purpose. This result clearly shows the higher resolving performance of the MUSIC beamforming over the other methods. If the threshold to flag the RFI location is selected as the half of the local maximum (contour of 0.5), neither the SMOS image nor the Capon method resolve the multiple RFI sources. In order to separate the local peaks, the threshold should be selected higher than 0.6 in the SMOS image, and 0.8 in the Capon results. In the MUSIC results, multiple sources are clearly differentiated in the 0.5 contour.

Fig. 3. Zoom of multiple source localization in Greece: (a) SMOS DFT, (b) Capon, and (c) MUSIC results.

The two RFI sources located at $(-0.3741, -0.1783)$ and at $(-0.3654, -0.2170)$ can be detected separately only in the MUSIC results. In the other methods, these two sources are merged in a single wide spot, due to their lower angular resolution.

V. CONCLUSION

In this work, MUSIC and Capon DOA estimation techniques have been applied to improve the performance of RFI localization in SAIR imaging. The visibility samples of SAIR are interpreted as the elements of the covariance matrix of the sensor array, and then high resolution DOA estimation methods can be directly applied for RFI localization. Using SMOS data, the feasibility of DOA estimation method for RFI localization has been demonstrated. In the test results, the MUSIC method shows promising performance over the Capon and the DFT images. In terms of accuracy, the error of MUSIC RFI location is about 36% of the SMOS DFT for strong RFI sources, and 67% for the weak ones. For the angular resolution, the half power width of MUSIC can decrease down to 25% of SMOS DFT results, for strong RFI sources. The performance of MUSIC algorithm declines with the power of sources. In the tests, the MUSIC localizes the RFI sources with comparable performance to the DFT, down to $BT=537$ K.

The feasibility study of MUSIC algorithm in this letter implies the prospect of improving the SMOS RFI source detection. The detection in a single snapshot level will be enhanced in terms of accuracy and efficiency. The spatial resolution of RFI sources detection will also improve, and therefore the sources located close to each other can be detected separately.

As future work, the RFI detection method for MUSIC algorithm will be addressed. It includes RFI detection algorithms, e.g., an adaptive threshold and false alarm avoidance. The systematic RFI detection process chain with multiple snapshots are also required to improve the performance of the MUSIC RFI detection method. Additionally, a larger set of SMOS data will be tested and analyzed for the concrete performance evaluation.

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