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A new technique for direction of arrival estimation for ionospheric multipath channels

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Abstract

A novel array signal processing technique is proposed to estimate HF channel parameters including number of paths, their respective direction of arrivals (DOA), delays, Doppler shifts and amplitudes. The proposed technique utilizes the Cross Ambiguity Function (CAF), hence, called as the CAF-DF technique. The CAF-DF technique iteratively processes the array output data and provides reliable estimates for DOA, delay, Doppler shift and amplitude corresponding to each impinging HF propagated wave onto an antenna array. Obtained results for both real and simulated data at different signal to noise ratio (SNR) values indicate the superior performance of the proposed technique over the well known MUltiple SIgnal Classification (MUSIC) technique.

Keywords: Ionosphere; Array signal processing; Direction of arrival (DOA); MUSIC; Time delay; Doppler shift; Cross Ambiguity Function (CAF)

1. Introduction

Today, HF technology provides reliable, secure and ever available communication over many thousands of miles (Tavares et al., 2005; Erhel et al., 2007). However, ionosphere is a dispersive channel which varies temporally and spatially (Goodman, 1992). This kind of channel behavior degrades the quality of the received signal and produces severe multipath effects. Therefore, accurate channel characterization and parameter estimation of the multipaths is crucial for reliable communication at higher rates. To estimate the HF channel properties, typically a sensor array is utilized. Coherent processing of the array output signals can provide estimates to the channel parameters. For this purpose various array signal processing techniques have been proposed (Pillai, 1989). Among them due to their relatively low computational cost and reliable performance, eigen-structure based methods such as MUltiple SIgnal Classification (MUSIC) (Schmidth, 1986), CLOSEST (Buckley and Xu, 1990) and Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) (Roy and Kailath, 1989) have found wide spread use in applications. These methods exploit the eigen-structure of the covariance matrix to distinguish the signal and noise subspaces. Although, given methods are computationally efficient, in correlated signal scenarios which is the case especially in high-latitude ionosphere (Warrington, 1998), they do not provide enough accuracy (Krim and Viberg, 1996; Pillai, 1989; Godora, 1997). The maximum likelihood (ML) optimal techniques overcome this difficulty, but their high computational complexity has limited their use in practice (Stoica and Sharman, 1990; Jaffer, 1988). However, recently there are various efforts in the literature where powerful optimization algorithms such as particle swarm optimization (PSO) are used for obtaining the global optimal solution of ML DOA estimation in an efficient way (Bratton and Kennedy, 2007; Jiankui et al., 2006; Li and Lu, 2007). Moreover, in modeling a reliable communication channel, in addition to the DOA of each path, accurate estimation of their delays and Doppler shifts

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is very important to be able to implement optimal reception based on Doppler compensated rake receiver techniques (Proakis, 1995). Although, there are some proposed techniques to estimate the delay and Doppler shifts of the individual propagation paths, the decoupled estimation of delay and Doppler shifts limits their overall performance (Helstrom, 1968; Habboosh et al., 1997; Jakobsson et al., 1998). Lastly, scattering function is widely used HF channel characterization (Warrington et al., 2000). However, it is very difficult to identify the delay-Doppler centers of the scattering function when the peak locations of the correlation or Doppler shift of the layers vary. Moreover, the reflectivity alternations of the layers can be mistakenly thought as Doppler spreads when the layers are not actually moving (Arikan, 1999).

In this paper, a novel array signal processing technique called Cross Ambiguity Function-Direction Finding (CAF-DF) is introduced for reliable estimation of HF channel parameters including their DOAs, delays and Doppler shifts. CAF-DF iteratively estimates DOA, time delay, Doppler shift and amplitude of each impinging signal onto an antenna array. Unlike the other alternatives, the proposed CAF-DF technique provides joint delay and Doppler shift estimates on the cross ambiguity function surface. The CAF-DF technique can resolve highly correlated signals with closely spaced signal parameters even in poor SNR conditions. Performances of the MUSIC and CAF-DF are compared using both synthetic and real signals for various SNR values. For this purpose, real HF channel sounding data set provided by Dr. E.M. Warrington and Dr. Alan Stocker from University of Leicester, UK is used. More details on the acquisition of the real data is provided in Section 5 and in Guldogan (2006).

This paper is organized as follows. In Section 2, the CAF-DF technique is introduced in detail. In Section 3, brief review of a MUSIC based alternative technique is given. Section 4 presents the simulation results on synthetic signals which enable us to conduct a comparative study where channel parameters and SNR can be varied in a wide range. Finally, in Section 5, we demonstrate the superior performance of the proposed CAF-DF technique on real ionospheric data.

2. The Cross Ambiguity Function based Direction Finding (CAF-DF) technique

In this section, we will introduce the details of the CAF-DF technique to estimate DOA of a known transmitted signal impinging on an antenna array through multiple paths with unknown delay, Doppler shift and attenuation. To illustrate the discussion, we will focus on a HF–DF application where propagation channel has slowly varying delay and Doppler shifts due to the dynamic nature of the ionosphere. As shown in Fig. 1, in an HF communication or Direction Finding (DF) application, a receiver array antenna is utilized to intercept the reflected waves of a transmitter from the ionosphere. In channel sounding applications, the transmitter transmits training sequences that are known to the receiver. Received signal at each antenna output is delayed, Doppler shifted and highly attenuated version of the transmitted training signal. Therefore, for a multipath environment the antenna array output can be modeled as follows:

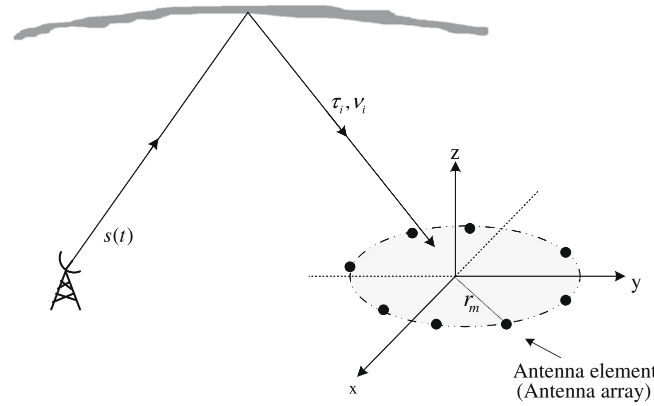

Fig. 1. In HF channel sounding experiments and Direction Finding (DF), a receiver antenna array is used to intercept the ionospheric reflections of a transmitted signal.

$$x_m(t) = \sum_{i=1}^{d} \zeta_{m,i} s(t - \tau_{o,i}) e^{j2\pi v_i t} e^{-j2\pi v_c \xi_{m,i}(\theta,\varphi)} + n_m(t), \qquad (1)$$

where m is the antenna index, d is the number of different multipath signals, i is the signal source index, s represents the transmitted signal, $\zeta_{m,i}$ is a complex number including all the attenuations and phase rotations due to reflection of the ith path, $\tau_{o,i}$ is the ith path delay with respect to the origin, $v_{m,i}$ is the ith path Doppler shift, v_c is the carrier frequency, θ is the azimuth angle from x-axis to y-axis, φ is the elevation angle from x–y plane to z-axis and $\xi_{m,i}(\theta, \varphi)$ represents the phase difference of the mth antenna with respect to the phase reference center or the origin of the array due to ith signal source.

First goal of the CAF-DF technique is to estimate the DOA information which is hidden in the phase component, $e^{-j2\pi v_c \xi_{m,i}(\theta,\varphi)}$, as given in Eq. (1). For this purpose, delay and Doppler parameters of the impinging signals are estimated first. As used in radar signal processing applications, time delay of the Doppler shifted signals can be estimated by using CAF, which is first introduced by P.M. Woodward in 1953 and found wide variety of applications (Woodward, 1953; Levanon and Mozeson, 2004). Although, different representations for CAF are presented in the literature, we prefer to use the following symmetrical version.

$$\chi(\tau, v)_{x_m,s} = \int_{-\infty}^{\infty} x_m\left(t + \frac{\tau}{2}\right) s^*\left(t - \frac{\tau}{2}\right) e^{-j2\pi v t} dt. \qquad (2)$$

If $x_m(t)$ is delayed and Doppler shifted version of $s(t)$, the magnitude of the complex valued $\chi(\tau, v)_{x_m,s}$ has a peak at the corresponding delay and Doppler shift. Therefore, CAF provides us a detection surface in delay and Doppler shift plane. We will provide more detail how this surface can be used to detect the presence of multipath components and estimate their delays and Doppler shifts later in this section.

In the CAF-DF technique, we will use the CAF computation on each antenna output. Since the array antennas are located in close proximity relative to the transmitter–receiver distance, the individual receiver observes almost the same delay and Doppler shifts for each multipath. As will be clear later, the only measurable difference between array outputs is phase shift due to their relative spacing with respect to the array center. Hence, the magnitude of the CAFs computed on each array output is expected to have their peaks at the same location. Since, at the start of the CAF-DF iterations we do not have DOA estimates yet, we cannot correct the relative phases of each antenna output. Hence, as in Eq. (3), we perform an incoherent combination by adding the amplitudes of CAF surfaces at each antenna output.

$$\chi(\tau,\nu)_{incoh} = |\chi(\tau,\nu)_{x_1,s}| + |\chi(\tau,\nu)_{x_2,s}| + \cdots + |\chi(\tau,\nu)_{x_M,s}| \tag{3}$$

The combined detection surface $\chi(\tau,\nu)_{incoh}$ enables us to conduct detection and estimation of present multipath components better than the individual detection surfaces at the output of each antenna. Let (τ_p,ν_p) be the location of the maximum peak of $\chi(\tau,\nu)_{incoh}$. Then, we form the following vector by stacking up the CAF values of each antenna output at the (τ_p,ν_p) location:

$$\mathbf{P_p} = \begin{bmatrix} \chi_{\mathbf{x_1,s}}(\tau_p,\nu_p) \\ \chi_{\mathbf{x_2,s}}(\tau_p,\nu_p) \\ \vdots \\ \chi_{\mathbf{x_M,s}}(\tau_p,\nu_p) \end{bmatrix}_{\mathbf{M}\times 1} = \begin{bmatrix} |\chi_{\mathbf{x_1,s}}(\tau_p,\nu_p)|\mathbf{e^{j\Psi_1}} \\ |\chi_{\mathbf{x_2,s}}(\tau_p,\nu_p)|\mathbf{e^{j\Psi 2}} \\ \vdots \\ |\chi_{\mathbf{x_M,s}}(\tau_p,\nu_p)|\mathbf{e^{j\Psi_M}} \end{bmatrix}_{\mathbf{M}\times 1}. \tag{4}$$

where subscript p denotes the peak and Ψ_m is the phase of the peak point on the CAF surface calculated for mth antenna. For the path whose delay and Doppler shift is initially estimated as (τ_p,ν_p), we can obtain DOAs in azimuth, θ, and elevation, φ, as in the following equation:

$$(\hat{\theta},\hat{\varphi}) = \arg\max_{\theta,\varphi} \frac{1}{1-\frac{|\mathbf{P}_p^H\mathbf{S}(\theta,\varphi)|}{\|\mathbf{P}_p\|}} \tag{5}$$

where

$$\mathbf{S}(\theta,\varphi) = \frac{1}{\sqrt{M}} \begin{bmatrix} e^{j\xi_{1,i}(\theta,\varphi)} \\ e^{j\xi_{2,i}(\theta,\varphi)} \\ \vdots \\ e^{j\xi_{M,i}(\theta,\varphi)} \end{bmatrix}_{M\times 1}. \tag{6}$$

The required search in (θ,φ) space can be conducted over a grid whose spacing is chosen as the resolution in azimuth and elevation.

Having estimated the DOA $(\hat{\theta},\hat{\varphi})$ of the first path detected on the $\chi(\tau,\nu)_{incoh}$ surface, an improved estimate for the delay and Doppler shift can be obtained by forming a coherent summation of the individual CAF surfaces of each antenna output. The coherent summation achieved as in Eq. (7):

$$\chi(\tau,\nu)_{coh} = \chi(\tau,\nu)_{x_1,s}\cdot e^{j2\pi\nu_c\xi_{1,i}(\hat{\theta},\hat{\varphi})} + \cdots + \chi(\tau,\nu)_{x_M,s}\cdot e^{j2\pi\nu_c\xi_{M,i}(\hat{\theta},\hat{\varphi})}, \tag{7}$$

where $\xi_{m,i}(\hat{\theta},\hat{\varphi})$ is defined as in Eq. (1). It can be shown that, accurate $\hat{\theta}$ and $\hat{\varphi}$ estimates enables to achieve a M fold increase in the SNR, justifying the use of coherent summation (Guldogan, 2006).

Having estimated the delay, Doppler, azimuth and elevation angles of the first multipath component, we can estimate its amplitude as the minimizer of a properly chosen cost function. The estimated multipath parameters can be used to express the arriving signal component at each antenna output as:

$$x_{m,i}(t) = \hat{\zeta}_{m,i}s(t-\hat{\tau}_{0,i})e^{j2\pi\hat{\nu}_i t}e^{-j2\pi\nu_c\xi_{m,i}}(\hat{\theta},\hat{\varphi}) \quad m = 1,2,\ldots M, \tag{8}$$

where $\hat{\zeta}_{m,i}$ is a complex number, whose magnitude is the desired multipath amplitude, observed at the m^{th} antenna. Depending on the accuracy of the calibration, $\hat{\zeta}_{m,i}$ value may be significantly different or almost the same for each antenna. Estimation of the $\hat{\zeta}_{m,i}$ can be performed by minimizer of the following cost function,

$$J_m(\zeta_{m,i}) = \int_0^T |x_m(t) - x_{m,i}(t)|^2 dt. \tag{9}$$

By using the derivative condition in Eq. (10), the minimizer $\hat{\zeta}_{m,i}$ of this quadratic cost function can be obtained as in Eq. (11).

$$\int_0^T \frac{\partial\left(|x_m(t) - x_{m,i}(t)|^2\right)}{\partial\zeta_{m,i}} = 0. \tag{10}$$

$$\hat{\zeta}_{m,i} = \frac{\int_0^T s^*(t-\hat{\tau}_{0,i})e^{-j2\pi\hat{\nu}_i t}e^{j2\pi\nu_c\xi_{m,i}(\hat{\theta},\hat{\varphi})}x_m(t)dt}{\int_0^T s^*(t-\hat{\tau}_{0,i})s(t-\hat{\tau}_{0,i})dt}. \tag{11}$$

For an accurately calibrated antenna array where ζ is assumed to be same for each antenna, we can obtain a more reliable estimate for ζ_i as:

$$\hat{\zeta}_i = \frac{\sum_{m=1}^{M}\int_0^T s^*(t-\hat{\tau}_{0,i})e^{-j2\pi\hat{\nu}_i t}e^{j2\pi\nu_c\xi_{m,i}(\hat{\theta},\hat{\varphi})}x_m(t)dt}{M\int_0^T s^*(t-\hat{\tau}_{0,i})s(t-\hat{\tau}_{0,i})dt}. \tag{12}$$

Once the amplitude of the multipath component is estimated, to eliminate it, we can form its synthetic copy by using Eq. (8) and subtract it from the corresponding antenna outputs. Then, we start our detection and estimation procedure again on the residual array outputs for other multipath components that might be present. Flowchart of the CAF-DF technique is given in Fig. 2.

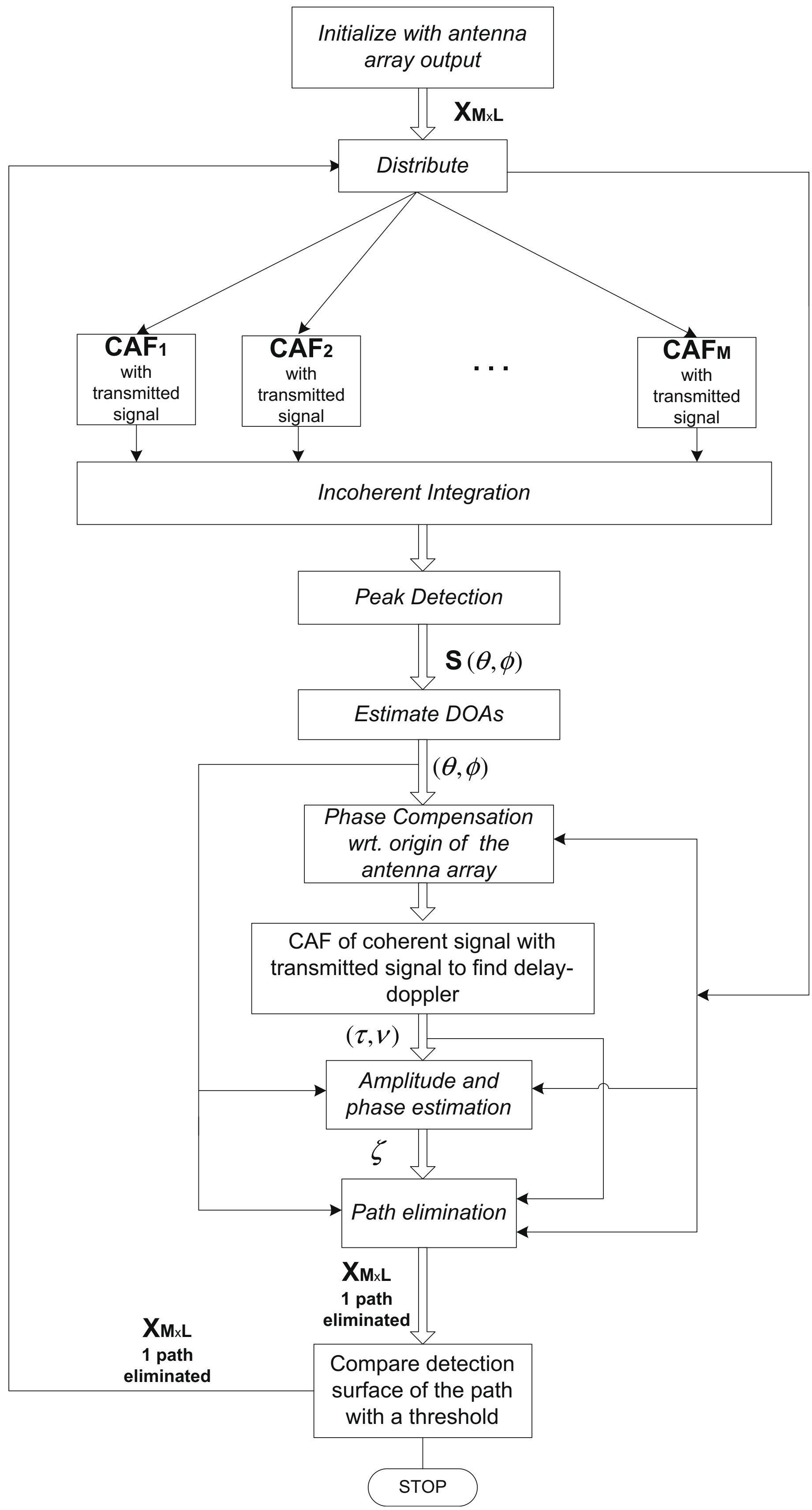

Fig. 2. The flowchart of the proposed CAF-DF technique. Following the initialization with the array output X_{ML}, the individual paths are identified and eliminated from the array outputs. Then, the next iteration starts working on the eliminated array output data.

3. A MUSIC based delay-Doppler and DOA estimation technique

Well known MUSIC algorithm is a super-resolution method that is commonly used in array signal processing applications. An eigen-value analysis is required on the correlation matrix to form two disjoint subspaces: signal and noise subspaces, which are spanned by their corresponding eigenvector set (Schmidth, 1986). By using the orthogonal characteristics of eigenvectors in the signal and noise subspaces, the MUSIC spectrum P, can be written as:

$$P(\theta,\varphi)=\frac{\mathbf{a}^H(\theta,\varphi)\mathbf{a}(\theta,\varphi)}{\mathbf{a}^H(\theta,\varphi)\hat{\Pi}^{\perp}\mathbf{a}(\theta,\varphi)}, \tag{13}$$

where $\hat{\Pi}^{\perp}$ denotes the eigenvectors corresponding to the noise space and $\mathbf{a}$ represents the steering vector. (θ, φ) that maximizes equation above is the estimated DOA. In this work, a modified version of the MUSIC is used to estimate delay and Doppler shifts (Warrington, 1995). In the following section, we will detail its application on a channel sounding experiment.

4. Results of a comparative study between the CAF-DF and MUSIC techniques

In this section, performance of the CAF-DF is tested by computer simulations using synthetic signals and compared with a MUSIC based alternative technique (Warrington, 1995). A six-antenna circular array structure, which is also the actual array collecting the real data, is used in the simulations given in Fig. 3. To ensure that there is no spatial aliasing, the distances between array elements are smaller than the half-wavelength of the signal. We consider transmission of a pulse train consisting of 111 pulses, which are phase coded with Barker-13 code (Golomb and Scholtz, 1965). Duration of individual pulses is chosen as 18 ms and the duration of the pulse train is chosen as 2 s. The output signal at the mth antenna is modeled as

$$s_m(t)=\sum_{i=1}^{d} b_{13}(t-\tau_{0,i})e^{j(2\pi v_i t+\varphi_i)}e^{-j2\pi v_c \xi_{m,i}(\theta,\varphi)}+n_{m,i}(t), \tag{14}$$

where ϕ_i is a uniformly distributed random phase in $[0, 2\pi]$, $b_{13}(t)$ represents the Barker-13 coded sequence and $n_{m,i}(t)$ represents circularly symmetric Gaussian noise.

For a single path case, path parameters are chosen as follows: θ (azimuth) = 191.2, φ (elevation) = 31.3, τ (delay) = 0.4 ms, v (Doppler) = 0.67 Hz. The DOA, delay and Doppler estimates are calculated in the sense of root Mean Squared Error (rMSE) for each of the algorithm based on 300 Monte Carlo trials for various SNR values. Results are presented in Fig. 4. Moreover, Cramer-Rao lower bounds are included in the figure (Kay, 1993; Stoica et al., 2001). It can be observed that, especially for SNR values less than 15 dB, CAF-DF technique provides significant performance improvements over the MUSIC technique. Since, performance in the low SNR regions are of great interest in most of the applications, this improvement of CAF-DF technique is of critical importance.

In addition to single path case, we also conducted various simulations for two-path scenarios. For example, we studied paths with (1) closely spaced in Doppler shifts and DOAs, but differ in delays, (2) closely spaced in DOAs and delays, but differ in Doppler shifts, (3) closely spaced in DOAs, delays, and Doppler shifts. It is observed that for the chosen path parameters, although MUSIC cannot resolve the existing paths, the CAF-DF can provide reliable estimates for the path parameters (Guldogan and Arikan, 2008). In (Fig. 5), separation capability of two techniques is presented in the elevation–azimuth plane. Detailed comparison results for an extensive set of synthetic simulation scenarios are provided in (Guldogan, 2006).

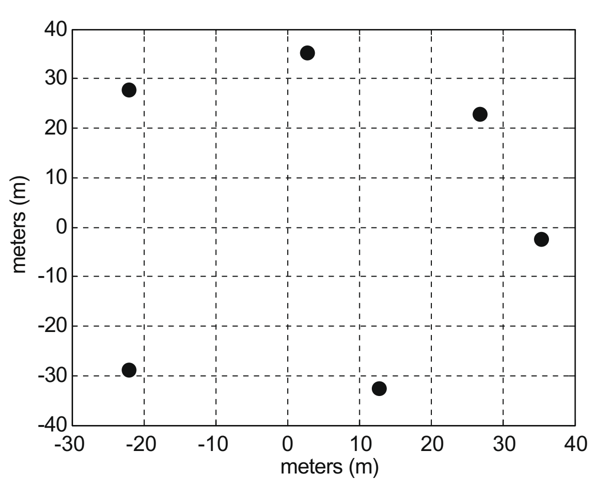

Fig. 3. The spatial distribution of the six-element circular antenna array used in the HF channel sounding experiment conducted between Uppsala and Kiruna in Sweden. The receiver array is located in Kiruna.

5. Results of CAF-DF technique on real HF channel sounding data

Performances of the two techniques CAF-DF and MUSIC are tested on two recorded data sets from a high latitude HF link. The data sets are provided by Dr. E.M. Warrington and Dr. Alan Stocker from University of Leicester, Engineering Department, UK. First part of the dataset is recorded in May 02, 2002. The signals were received on a six-element circular array as given in Fig. 3. However, due to some calibration problems, we discarded the third antenna and used the remaining five antennas. The individual array elements are connected to individual inputs of a multi-channel receiver via a calibration switch (Warrington, 1998). Transmitted pulse train consists of Barker-13 coded BPSK pulses modulated at 1667 baud with a repetition rate of 55 coded pulses per second. The total length of the sequence is 2 s. Delay and Doppler resolution is 0.1 ms and 0.0023 Hz in both techniques. The

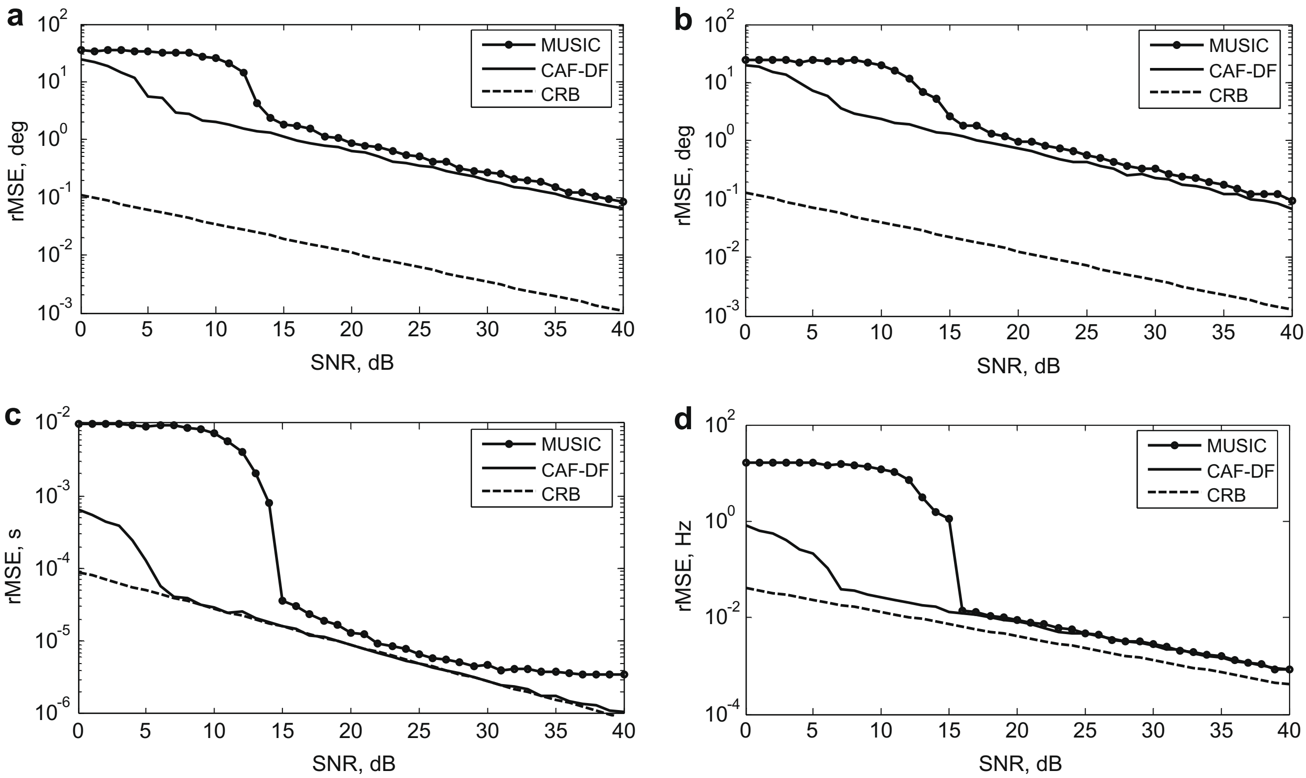

Fig. 4. The rMSE of estimates in (a) azimuth, (b) elevation, (c) delay and (d) Doppler shift of CAF-DF and MUSIC techniques as a function of SNR. Dashed line represents the unbiased Cramer-Rao lower bound. As shown in the figures, the CAF-DF technique provides significant improvements for SNR values less than 15 dB.

transmitter and the receiver are located in Uppsala, Sweden and Kiruna, Sweden, respectively. Estimation results obtained by CAF-DF and MUSIC for dataset recorded in 2002 are tabulated in Tables 1–4. Both techniques provide nearly the same azimuth estimates that are in accordance with the transmitter–receiver configuration. The observable difference is in elevation estimates. In Tables 1 and 2, it is seen that, CAF-DF used the Doppler difference between second and third paths and resolved the third path which is at the same delay with the second one. In Tables 3 and 4, Doppler estimates of each path are very close to each other with separated delay estimates. When compared to the previous case, CAF-DF used the delay difference between the second and the third paths and was able to resolve a third path which is at the same Doppler with the second path. However, the MUSIC technique could not separated these paths in elevation and provided almost the same elevation estimates for each of the three paths.

In addition to provide path estimates for a 2 s interval, we also analyzed a 1-h data recorded at between 23:00:49 and 23:48:49 at two different frequencies 4.63 MHz and 6.95 MHz, respectively. The obtained results for the CAF-DF technique are presented in Figs. 7–9. As seen from the figures, the CAF-DF technique separated three different multipath components most of the observed time interval. Azimuth estimates are consistent with the relative orientations of the transmitter and receiver. There are no sharp changes in the azimuth, elevation, delay and Doppler shift estimates of the strongest signal source for nearly one hour measurement period. For the second and third signal sources we observe noisy elevation and delay estimates. We also investigated the performance of the CAF-DF technique over a second set of data which is recorded in April 13, 2007. This data set is recorded by using an eight-element inhomogeneous circular array is used as given in Fig. 6. As in the first set, Barker-13 coded BPSK pulses are used. In this data set, the baud rate is raised to 2000. The HF transmitter is located at Uppsala, Sweden and the receiver is at Bruntingthorpe, UK. The distance between these two points is about 1417 km. In (Fig. 10), estimated azimuth, elevation, delay and Doppler of the recorded data by CAF-DF at between 11:00:09 and 11:58:09 are presented. Also for this data set, azimuth estimates are consistent with the relative orientations of the transmitter and receiver. It is seen that elevation estimates of the 6.95 MHz are noisier than the other frequencies and consistent with the corresponding changes in delay estimates. Maybe the response of ionosphere at 6.95 MHz during the measurement period is not stable. Note that, the significant but orderly variation of the Doppler shifts observed within one hour duration indicates a physical mechanism that should be of interest to ionospheric physicists.

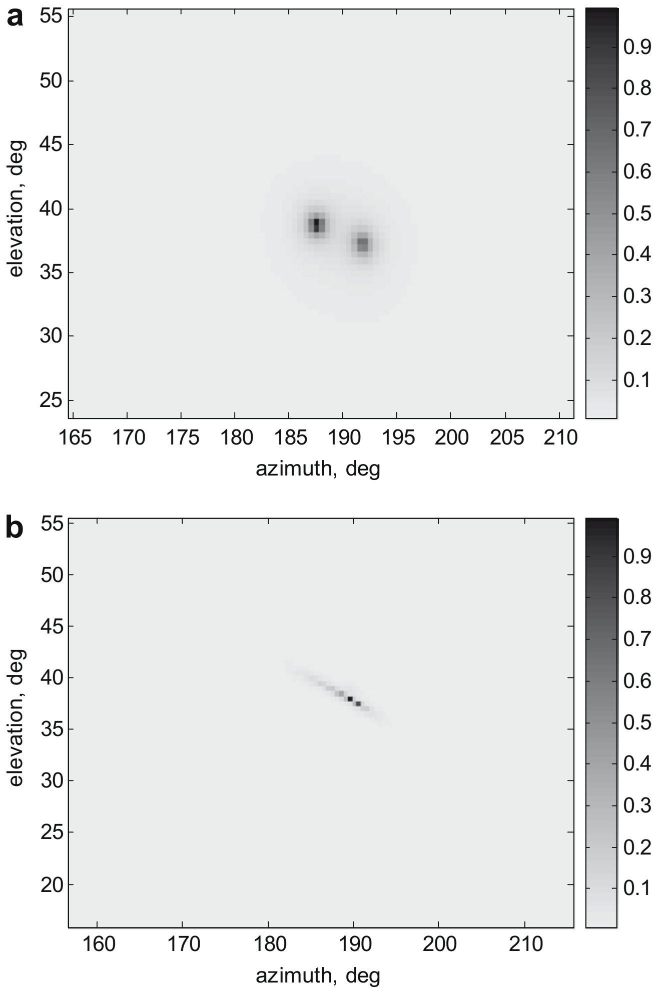

Fig. 5. For a two signal path scenario, the detection surface in the elevation–azimuth plane for (a) CAF-DF and (b) MUSIC techniques, respectively. The parameters of the first path are: (azimuth = 191.2°, elevation = 36.3°, delay = 0.4 ms, Doppler = 0.31 Hz). The parameters of the second path are: (azimuth = 187.3°, elevation = 38.2°, delay = 0.6 ms, Doppler = 0.93 Hz). It is seen that CAF-DF clearly separates two paths on the elevation–azimuth surface whereas MUSIC fails to separate them.

Table 1
Azimuth, elevation, delay and Doppler estimates of CAF-DF for three signal paths. Data is recorded in May 02, 2002 at 23: 15: 49. Note that the third signal path is resolved by CAF-DF.

	Azimuth, deg	Elevation, deg	Delay, ms	Doppler, Hz
1. Path	197.30	31.87	9.4	−0.5912
2. Path	198.48	54.79	11.5	−0.9417
3. Path	200.55	22.86	11.5	−0.5125

Table 2
Azimuth, elevation, delay and Doppler estimates of MUSIC for three signal paths. Data is recorded in May 02, 2002 at 23: 15: 49. MUSIC could not separate the third signal path.

	Azimuth, deg	Elevation, deg	Delay, ms	Doppler, Hz
1. Path	197.12	31.80	9.4	−0.5914
2. Path	198.41	57.49	11.5	−0.9586
3. Path	197.67	32.91	10.7	−0.5966

Table 3
Azimuth, elevation, delay and Doppler estimates of CAF-DF for three signal paths. Data is recorded in May 02, 2002 at 23: 06: 49. Note that, Doppler shifts of each path are very closely spaced. Using time–delay difference CAF-DF separates each path.

	Azimuth, deg	Elevation, deg	Delay, ms	Doppler, Hz
1. Path	195.82	31.73	9.4	−0.5078
2. Path	194.49	39.56	11.5	−0.5388
3. Path	197.74	18.42	8.7	−0.4291

Table 4
Azimuth, elevation, delay and Doppler estimates of MUSIC for three signal paths. Data is recorded in May 02, 2002 at 23: 06: 49. Since estimated Doppler shifts for each signal path are nearly same, MUSIC could not effectively resolve paths.

	Azimuth, deg	Elevation, deg	Delay, ms	Doppler, Hz
1. Path	195.45	29.58	9.4	−0.5080
2. Path	195.64	31.43	8.1	−0.5042
3. Path	195.64	33.46	10.7	−0.5195

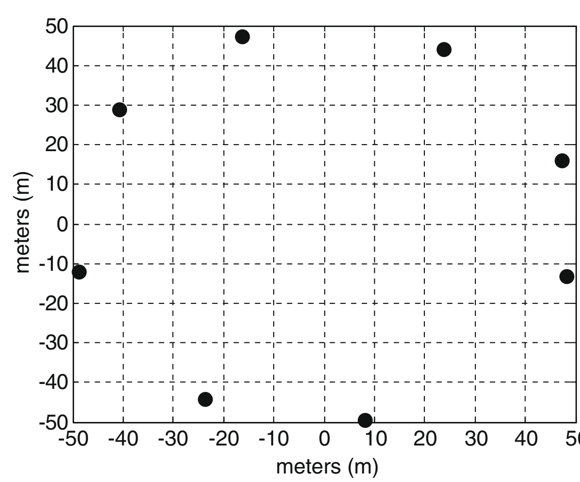

Fig. 6. The spatial distribution of the eight-element circular antenna array used in the HF channel sounding experiment conducted between Uppsala, Sweden and Bruntingthorpe, UK. The receiver array is located in Bruntingthorpe.

6. Conclusions and future work

For the estimation of multipath channel parameters, a new array signal processing technique is proposed. In addition to provide DOAs, the new technique makes use of cross ambiguity function computation for joint and reliable estimation of delays and Doppler shifts of individual multipath channels. Hence, this new technique is called as the Cross Ambiguity Function-Direction Finding (CAF-DF) technique. Extensive set of simulation studies has shown that the CAF-DF technique provides significant performance improvements at low SNRs compared to commonly used MUSIC based techniques. Studies on the real HF channel sounding experiments clearly indicate the channel

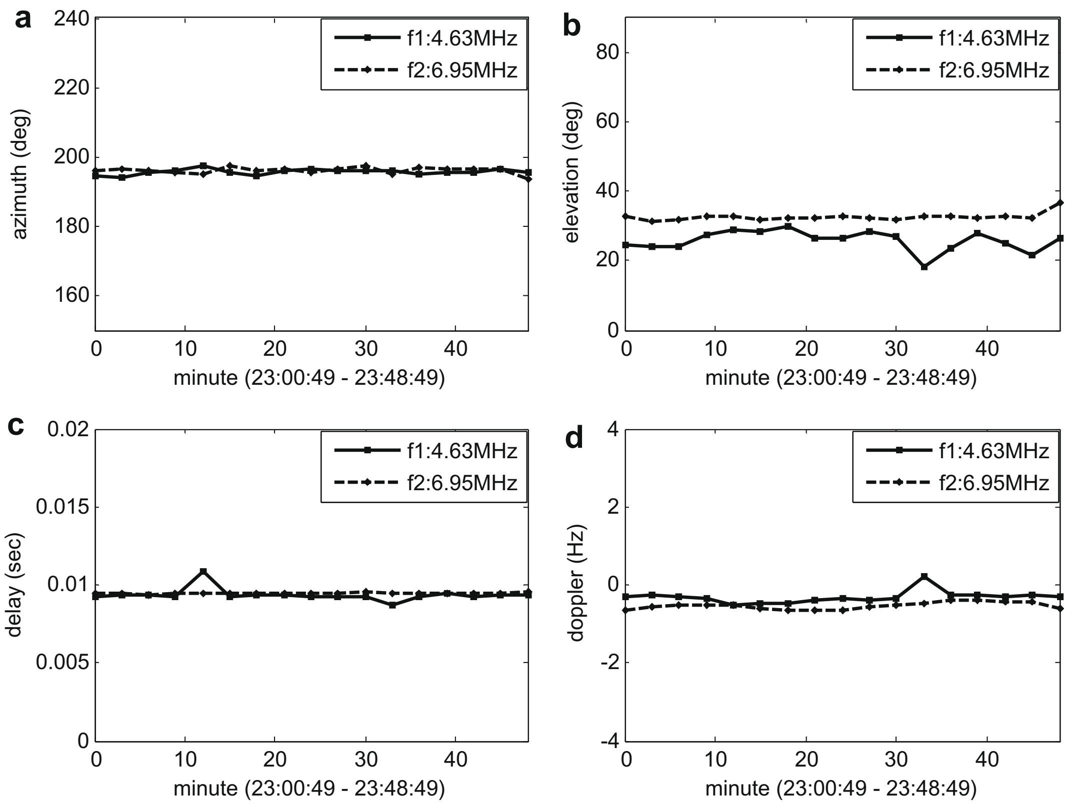

Fig. 7. (a) Azimuth, (b) elevation, (c) delay and (d) Doppler shift estimates of the first signal source by CAF-DF of the data recorded in May 02, 2002 at between 23: 00: 49 and ← ← ← ← ←23: 48: 49 for two frequencies. Note that, in (b) elevation estimates differ between two frequencies.

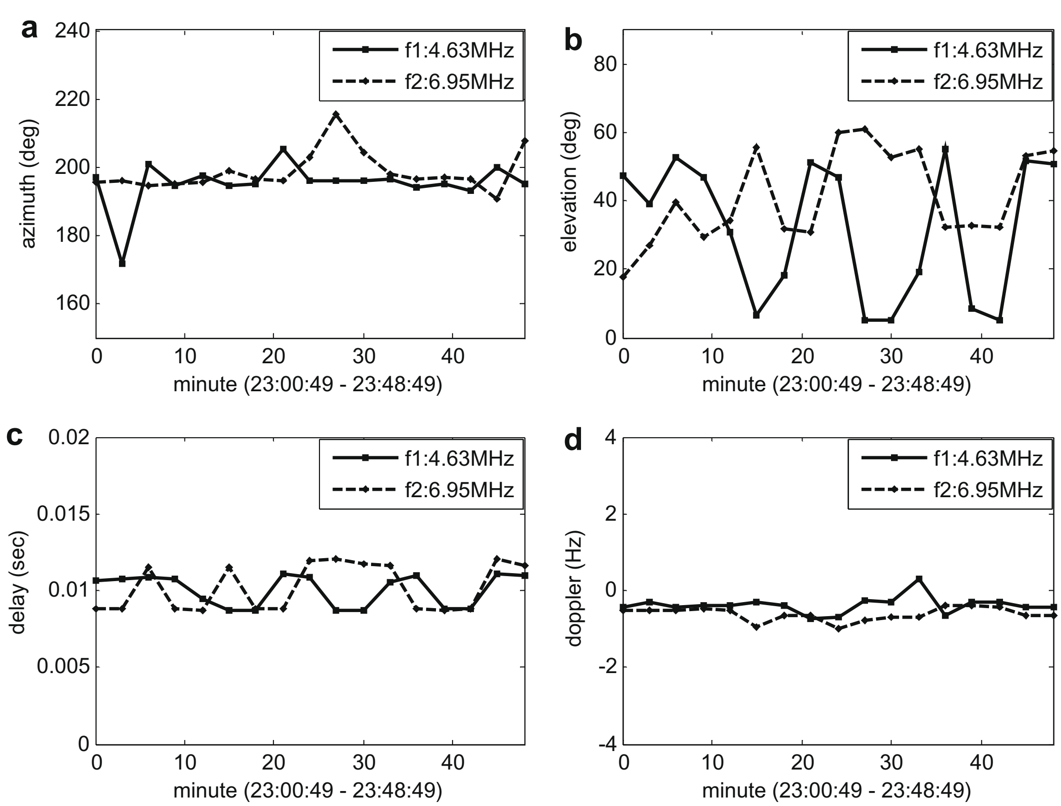

Fig. 8. (a) Azimuth, (b) elevation, (c) delay and (d) Doppler shift estimates of the second signal source by CAF-DF of the data recorded in May 02, 2002 at between 23: 00: 49 and ← ←23: 48: 49 for two frequencies.

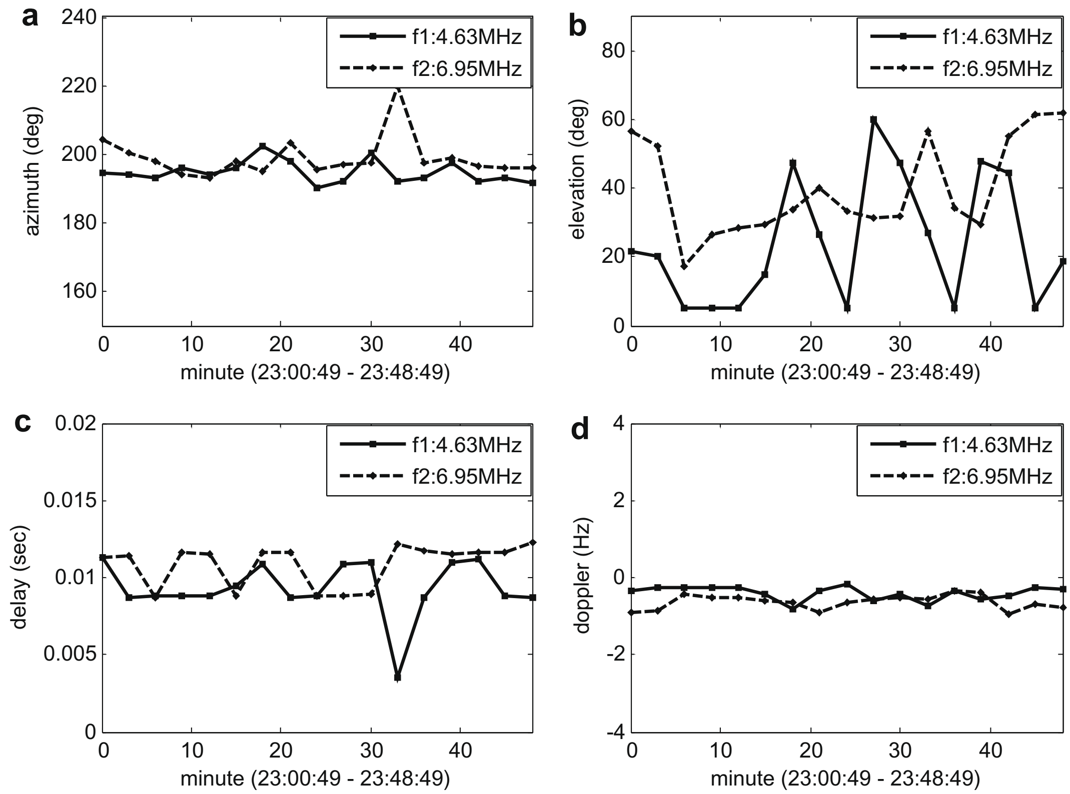

Fig. 9. (a) Azimuth, (b) elevation, (c) delay and (d) Doppler shift estimates of the third signal source by CAF-DF of the data recorded in May 02, 2002 at between 23: 00: 49 and ←23: 48: 49 for two frequencies.

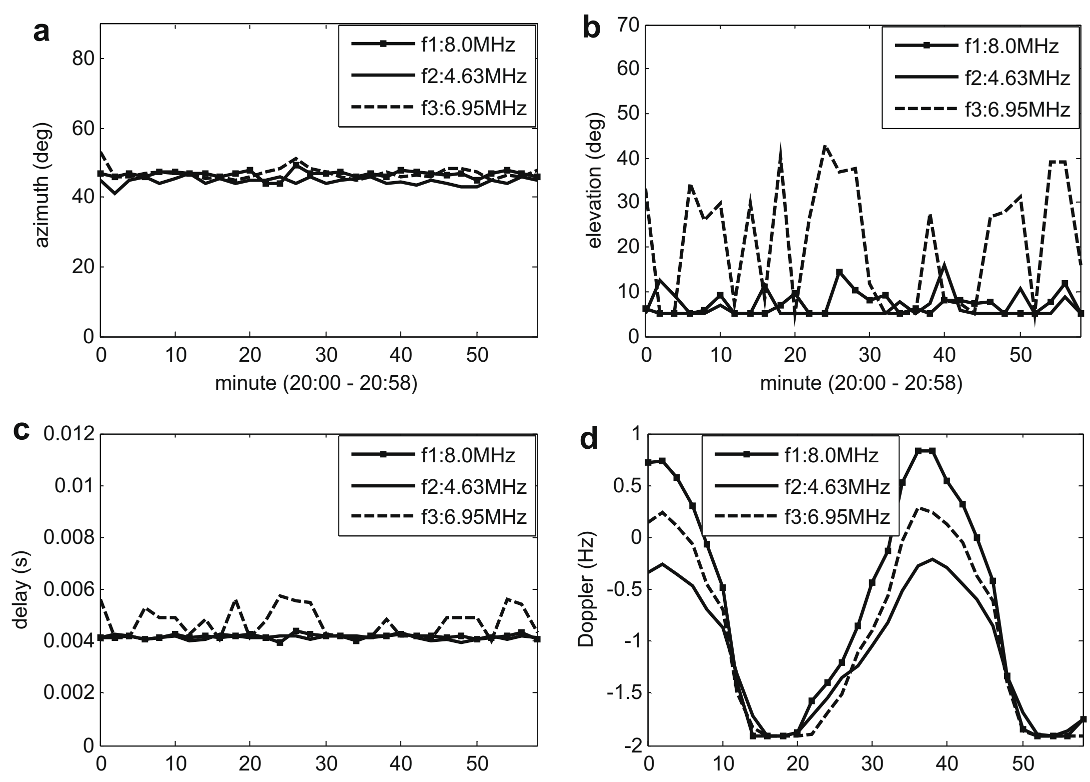

Fig. 10. (a) Azimuth, (b) elevation, (c) delay and (d) Doppler estimates by CAF-DF of the data recorded in April 13, 2007 at between 11: 00: 09 and ←11: 58: 09 for three different frequencies. Note that the significant but orderly variations of the Doppler shifts in (d) should be of interest.

resolution power of the CAF-DF over the MUSIC based alternatives. Furthermore, CAF-DF provides reliable Doppler shift estimates that can be monitored over time revealing interesting oscillatory phenomena that should be of interest for the atmospheric physics community.

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