# Phase Correction for Accurate DOA Angle and Position Estimation of Ground Moving Targets using Multi-Channel Airborne Radar 

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#### Abstract

Accurate position estimation of ground moving targets is a crucial requirement for any radar-based surveillance system. For multi-channel airborne radar, the target position on the ground can be accurately obtained by estimating the direction-of-arrival (DOA) angle of the moving targets. However, in practice the aircraft motion caused by atmospheric turbulence tilts the antenna array and introduces undesired phase differences among the multiple receive channels. As a result, the accuracy of the estimated DOA angles can be severely affected. This letter presents a robust and efficient algorithm that corrects the undesired phase differences among the multiple receive channels. By doing this, accurate DOA angles and, therefore, accurate target positions on the ground can be estimated. Important inputs of the proposed algorithm are the precise absolute positions of the receive channels and the elevation of the terrain. The performance of the proposed algorithm is validated using simulated data as well as radar data acquired with the DLR's multi-channel airborne system DBFSAR.


Index Terms-Ground moving target indication (GMTI), radar signal processing, calibration, synthetic aperture radar (SAR), radar applications, airborne radar, maritime safety.

## I. Introduction

AIRBORNE radars are very attractive for surveillance applications due to their weather independent and daynight acquisition capabilities. One essential requirement for airbased surveillance systems is the accurate target position estimation on the ground. When the aircraft has an antenna array with multiple receive ( Rx ) channels, the target position on the ground can be obtained by estimating the direction-ofarrival (DOA) angle [1].

For this task, the DOA angle must be measured with respect to the azimuth or flight direction (cf. blue axis in Fig. 1). However, in practice, atmospheric turbulence causes variations in the aircraft's attitude angles (yaw, pitch and roll) and these variations tilt (or squint) the antenna array axis with respect to the azimuth direction (cf. red axis in Fig. 1). The tilted antenna array introduces undesired phase differences among the multiple Rx channels. For instance, yaw and pitch angles introduce an additional across-track baseline that causes rangedependent phases and DOA angle variations. These undesired phases need to be compensated in order to obtain accurate DOA angle estimates and thus, accurate target position estimates.

[^0]

Fig. 1. Acquisition geometry showing the problem of a tilted antenna array on the target's DOA angle estimation. The radar coordinate system projected on the ground is denoted by $\left[x_{\mathrm{r}}, y_{\mathrm{r}}, z_{\mathrm{r}}\right]$.

For doing this, a calibration framework was proposed in [2] for moving target indication (MTI) applications. One of the steps in the proposed calibration framework is the estimation of interferometric phase offsets among the Rx channels. Although the calibration is accurate, the phase offsets are not adaptively estimated and, therefore, this algorithm is robust only for low squint angle acquisitions and for moderately flat terrains.

Another algorithm was proposed in [3] for compensating the undesired phases among the Rx channels. This method handles effectively the high squint angle acquisitions and terrain's high topographic variations. Even though it gives reliable detection results, the achieved target position accuracy is poor since only two Rx channels are used. Moreover, it requires high computational power since it works only with fully focused SAR images, making it unsuitable for real-time applications.

This letter presents a robust and efficient phase correction algorithm that is applicable for high squint angle acquisitions and high topographic variations. For compensating the phases, the algorithm requires: 1) the precise geographical positions of all bistatic phase centers of the $R x$ antennas, which are generally provided by the aircraft's navigation system and the known lever arms; and 2) the terrain's elevation, which is obtained from a digital elevation model (DEM). The algorithm operates on range-compressed radar data and does not require complex and time-consuming SAR processing. For this reason, it is principally suitable for real-time applications. The performance of the proposed algorithm is validated using both simulated and X-band radar data sets acquired with the DLR's multi-channel airborne system DBFSAR [4].

## II. DOA Angle and Position Estimation

The multi-channel signal model is expressed by [5]

$$
\begin{align*}
& \boldsymbol{s}(t)= \\
& a_{\mathrm{s}} e^{-j \frac{4 \pi}{\lambda} R_{\mathrm{t}}(t)}\left[\begin{array}{c}
D_{\mathrm{Tx}}\left[u_{\text {array }}(t)\right] D_{\mathrm{Rx}, 1}\left[u_{\text {array }}(t)\right] e^{j \frac{2 \pi}{\lambda} u_{\text {array }}(t) x_{1}} \\
\vdots \\
\left.D_{\mathrm{Tx}}\left[u_{\text {array }}(t)\right] D_{\mathrm{Rx}, \mathrm{M}}\left[u_{\text {array }}(t)\right] e^{j \frac{2 \pi}{\lambda} u_{\text {array }}(t) x_{\mathrm{M}}}\right]
\end{array}\right.  \tag{1}\\
& \quad=a_{\mathrm{s}} e^{-j \frac{4 \pi}{\lambda} R_{\mathrm{t}}(t)} \boldsymbol{d}\left[u_{\text {array }}(t)\right]
\end{align*}
$$

where $a_{\mathrm{s}}$ is the complex reflectivity of the scatterer, $\lambda$ is the radar wavelength, M is the number of Rx channels, $R_{\mathrm{t}}$ is the target's slant range, $D_{\mathrm{Tx}}$ and $D_{\mathrm{Rx}, \mathrm{m}}$ are the complex transmit and receive azimuth antenna characteristics of the m-th Rx channel, and $x_{\mathrm{m}}$ are the antenna phase center positions [5]. The term $\boldsymbol{d}$ is the beamforming vector and $u_{\text {array }}$ is the directional cosine with respect to the antenna array axis and $t$ is the azimuth time.

The beamforming vector $\boldsymbol{d}$ is generally used for estimating the target's directional cosine, e.g., via the maximum likelihood estimator [6]:
$\hat{u}_{\text {array }}=\underset{u_{\text {array }}}{\operatorname{argmax}}\left\{\left|\boldsymbol{d}^{H}\left(u_{\text {array }}, f_{\mathrm{a}}\right) \cdot \widehat{\boldsymbol{R}}_{\mathrm{W}}^{-1}\left(f_{\mathrm{a}}\right) \cdot \boldsymbol{Z}\left(r_{\mathrm{k}}, f_{\mathrm{a}}\right)\right|^{2}\right\}$
where $[\cdot]^{H}$ denotes the Hermitian operator (complex conjugate transposition), $f_{\mathrm{a}}$ is the Doppler bin, $r_{\mathrm{k}}$ is the slant range to bin $k$ and $\boldsymbol{Z}$ is the multi-channel data vector in the range-Doppler domain. The term $\widehat{\boldsymbol{R}}_{\mathrm{W}}$ is the clutter covariance matrix (CCM), which can be estimated adaptively from the measured data for clutter suppression purposes (cf. [7] for more details).

For applications where high signal-to-clutter plus noise ratios (SCNR) are expected, the moving targets can be detected in the range-Doppler domain without any clutter suppression. In this case, the CCM can be omitted in (2) and the estimator becomes

$$
\begin{equation*}
\hat{u}_{\text {array }}=\underset{u_{\text {array }}}{\operatorname{argmax}}\left\{\left|\boldsymbol{d}^{H}\left(u_{\text {array }}, f_{\mathrm{a}}\right) \cdot \boldsymbol{Z}\left(r_{\mathrm{k}}, f_{\mathrm{a}}\right)\right|^{2}\right\} . \tag{3}
\end{equation*}
$$

The DOA angle of the target with respect to the antenna array axis is estimated according to $\widehat{\Psi}_{\text {DOA, array }}=\cos ^{-1}\left(\hat{u}_{\text {array }}\right)$.

For calculating the target's position on the ground, consider the acquisition geometry in the local Cartesian coordinate system $[\tilde{x}, \tilde{y}, \tilde{z}]$ shown in Fig. 2. In the figure, $\alpha_{\mathrm{p}}$ is the platform course angle with respect to the $\tilde{x}$ (Easting) axis. The terms $\Delta x_{\mathrm{r}}$ and $\Delta y_{\mathrm{r}}$ (in red) are the distances on the ground (in radar coordinates) between the platform and the target positions, which are obtained as:

$$
\begin{gather*}
\Delta x_{\mathrm{r}}=R_{\mathrm{t}} \cdot \cos \left(\widehat{\Psi}_{\mathrm{DOA}, \mathrm{az}}\right)  \tag{4}\\
\Delta y_{\mathrm{r}}=\sqrt{\left(R_{\mathrm{t}} \cdot \sin \left(\widehat{\Psi}_{\mathrm{DOA}, \mathrm{az}}\right)\right)^{2}-\left(\tilde{z}_{\mathrm{p} 1}-\tilde{z}_{t}\right)^{2}} \tag{5}
\end{gather*}
$$

where $\widehat{\Psi}_{\text {DOA, az }}$ is the target's DOA angle with respect to the azimuth or the flight direction. It is important to mention that after applying the proposed phase correction algorithm (cf. Section III), the antenna array axis is perfectly aligned with the azimuth direction, so that $\widehat{\Psi}_{\text {DOA }, \mathrm{az}}=\widehat{\Psi}_{\text {DOA, array }} \cdot \operatorname{In}(5)$, the term
$\tilde{z}_{\mathrm{p} 1}$ is the flight altitude from the reference channel Rx 1 and $\tilde{z}_{\mathrm{t}}$ is the terrain's elevation obtained from a DEM.

The target's position on the ground in local coordinates $\widetilde{\boldsymbol{x}}_{\mathrm{t}}$ is then calculated as (cf. Fig. 2):

$$
\begin{equation*}
\tilde{\boldsymbol{x}}_{\mathrm{t}}=\widetilde{\boldsymbol{p}}_{1}+\Delta x_{\mathrm{r}} \cdot \vec{e}_{\tilde{x}}+\Delta y_{\mathrm{r}} \cdot \vec{e}_{\tilde{y}}-h_{\mathrm{t}} \cdot \vec{e}_{\tilde{z}} \tag{6}
\end{equation*}
$$

where $\widetilde{\boldsymbol{p}}_{1}$ is the platform's position in the local coordinates obtained from the reference channel Rx1 and $h_{\mathrm{t}}=\tilde{z}_{\mathrm{p} 1}-\tilde{z}_{t}$ is the height difference between the first antenna element and the target. The unit vectors in (6) are defined as:

$$
\begin{gather*}
\vec{e}_{\tilde{x}}=\left[\cos \left(\alpha_{\mathrm{p}}\right), \sin \left(\alpha_{\mathrm{p}}\right), 0\right]^{\mathrm{T}}  \tag{7}\\
\vec{e}_{\tilde{y}}=\left[A \cdot \sin \left(\alpha_{\mathrm{p}}\right),-A \cdot \cos \left(\alpha_{\mathrm{p}}\right), 0\right]^{\mathrm{T}}  \tag{8}\\
\vec{e}_{\tilde{z}}=[0,0,1]^{\mathrm{T}} \tag{9}
\end{gather*}
$$

where $[\cdot]^{\mathrm{T}}$ denotes the transpose operator. Note in (8) that $A=$ 1 for a right-looking antenna (as for the DBFSAR system) and $A=-1$ for a left-looking antenna. As can be seen from (4)-(6), the estimated DOA angle $\widehat{\Psi}_{\text {DOA, az }}$ impacts directly the ground position estimation of the target.


Fig. 2. Top-view acquisition geometry used for the calculation of the target's position on the ground in local coordinates $[\tilde{x}, \tilde{y}, \tilde{z}]$. The terms $\widehat{\Psi}_{\mathrm{DOA}, \mathrm{az}, \mathrm{g}}$ and $R_{\mathrm{t}, \mathrm{g}}$ are the projections on the ground of the terms $\widehat{\Psi}_{\mathrm{DOA}, \mathrm{az}}$ and $R_{\mathrm{t}}$, respectively.

## III. Proposed Algorithm

For explaining the proposed method, a simplified acquisition geometry is shown in Fig. 3, where multiple Rx channels are considered and the antenna array axis is tilted due to the platform motion. The phase correction is carried out in three main steps. At first, the original Rx channel positions $\widetilde{\boldsymbol{p}}_{m}$ are mapped onto the linearized reference track of channel Rx1 via vector orthogonal projection (cf. Section III-A and the detail box in Fig. 3). In the second step, reference points on the ground $\widetilde{\boldsymbol{g}}_{m}$ are calculated for each Rx channel $m$ using the coordinates of the relocated Rx channel positions $\widetilde{\boldsymbol{p}}_{m}^{\prime}$ (cf. Section III-B). In the third step, the range displacements $R_{m}-R_{\mathrm{t}}$ are calculated. These range displacements relate directly to the phase shifts to be compensated for each Rx channel $m$ (cf. Section III-C).

The aforementioned steps are presented in detail in Sections III-A to III-C. It is pointed out here that no phase correction is required for the reference channel Rx1, as shown in Fig. 3.

## A. Relocated Positions of Receive Channels

The following main steps are needed for mapping the original Rx channel positions $\widetilde{\boldsymbol{p}}_{m}$ onto the reference track of Rx1:


Fig. 3. Acquisition geometry showing the main steps of the proposed phase correction algorithm. The figure is shown for one specific transmitted pulse $n$ and slant range bin $k$. For simplicity, $\alpha_{p}=0^{\circ}$ is considered (cf. also Fig. 2).
i. Obtain the original positions (bistatic antenna phase center positions) of all Rx channels at the $n$-th transmitted pulse: $\widetilde{\boldsymbol{p}}_{m}[n]$. Also, obtain the original position of the reference channel Rx1 at a subsequent transmitted pulse: $\widetilde{\boldsymbol{p}}_{1}[n+1]$.
ii. Calculate the reference vector (in the flight direction) using the reference channel Rx 1 (cf. black vector in Fig. 3):

$$
\begin{equation*}
\widetilde{\boldsymbol{b}}_{\mathrm{az}}=\widetilde{\boldsymbol{p}}_{1}[n+1]-\widetilde{\boldsymbol{p}}_{1}[n] \tag{10}
\end{equation*}
$$

iii. Obtain the vectors corresponding to all original Rx channel positions (cf. orange vector in Fig. 3):

$$
\begin{equation*}
\widetilde{\boldsymbol{a}}_{m}=\widetilde{\boldsymbol{p}}_{m}[n]-\widetilde{\boldsymbol{p}}_{1}[n] \tag{11}
\end{equation*}
$$

iv. Perform the orthogonal projection of the vector $\widetilde{\boldsymbol{a}}_{m}$ onto the reference vector $\widetilde{\boldsymbol{b}}_{\mathrm{az}}$ (cf. green vector in Fig.3):

$$
\begin{equation*}
\operatorname{proj}_{\widetilde{b}_{\mathrm{az}}} \widetilde{\boldsymbol{a}}_{m}=\left(\frac{\widetilde{\boldsymbol{a}}_{m} \odot \widetilde{\boldsymbol{b}}_{\mathrm{az}}}{\widetilde{\boldsymbol{b}}_{\mathrm{az}} \odot \widetilde{\boldsymbol{b}}_{\mathrm{az}}}\right) \widetilde{\boldsymbol{b}}_{\mathrm{az}} \tag{12}
\end{equation*}
$$

where $\odot$ denotes the dot product operator.
v. Obtain the relocated Rx channel positions $\widetilde{\boldsymbol{p}}_{m}^{\prime}$ onto the reference track of channel Rx1 according to:

$$
\begin{equation*}
\widetilde{\boldsymbol{p}}_{m}^{\prime}[n]=\widetilde{\boldsymbol{p}}_{1}[n]+\operatorname{proj}_{\widetilde{\boldsymbol{b}}_{\mathrm{az}}} \widetilde{\boldsymbol{a}}_{m} \tag{13}
\end{equation*}
$$

## B. Reference Point Positions on the Ground

The ground coordinates of the reference points at the slant range bin $k$ are given by:

$$
\begin{equation*}
\widetilde{\boldsymbol{g}}_{m}[k]=\widetilde{\boldsymbol{p}}_{m}^{\prime}+\Delta x_{\mathrm{r}}[k] \cdot \vec{e}_{\tilde{x}}+\Delta y_{\mathrm{r}}[k] \cdot \vec{e}_{\tilde{y}}-h \cdot \vec{e}_{\tilde{z}} . \tag{14}
\end{equation*}
$$

Note that in (14) the relocated Rx channel positions $\widetilde{\boldsymbol{p}}_{m}^{\prime}$ are used for calculating the reference point positions on the ground. The terms $\Delta x_{\mathrm{r}}$ and $\Delta y_{\mathrm{r}}$ are obtained with (4)-(5) by setting the DOA angle at the broadside direction (i.e., $\Psi_{\text {DOA }, \mathrm{az}}=90^{\circ}$ ) and by using the slant ranges $R_{\mathrm{t}}[k]$ (cf. Fig. 3).

## C. Range Differences Calculation and Phase Correction

The slant ranges $R_{m}$ between the original Rx positions $\widetilde{\boldsymbol{p}}_{m}$ and their respective reference points $\widetilde{\boldsymbol{g}}_{m}$ are obtained for each slant range bin $k$ by:

$$
\begin{equation*}
R_{m}[k]=\sqrt{\left(\tilde{x}_{\mathrm{p} m}-\tilde{x}_{\mathrm{g} m}\right)^{2}+\left(\tilde{y}_{\mathrm{p} m}-\tilde{y}_{\mathrm{g} m}\right)^{2}+\left(\tilde{z}_{\mathrm{p} m}-\tilde{z}_{\mathrm{t}}\right)^{2}}(1 . \tag{15}
\end{equation*}
$$

The slant range differences are computed by

$$
\begin{equation*}
\Delta R_{m}[k]=R_{m}[k]-R_{\mathrm{t}}[k] \tag{16}
\end{equation*}
$$

and the phases to be compensated for each Rx channel $m$ are:

$$
\begin{equation*}
\emptyset_{m}[k]=\exp \left\{j \frac{4 \pi}{\lambda} \cdot \Delta R_{m}[k]\right\} \tag{17}
\end{equation*}
$$

It is pointed out that the proposed phase correction algorithm is applied for all slant range bins. Nevertheless, if the moving targets are detected a priori, the phase correction could be directly applied only to the slant range bins of the detected targets, thus reducing even further the overall processing time.

## IV. Theoretical Evaluation

The performance of the proposed algorithm is evaluated by using simulated multi-channel data. The simplified flowchart of the simulation framework is shown in Fig. 4.

For generating the simulated multi-channel data, three inputs (cf. dashed green box in Fig. 4 top) are provided: 1) the target's true position on the ground, which is set by the user, 2) the radar and the acquisition geometry parameters, which are listed in Table I, and 3) the tracks of all Rx channels. The tracks include in their computation the platform's attitude angles as shown in Fig. 1. By using the tracks of the Rx channels and the target's ground position, the target's range histories and their corresponding azimuth signals are obtained for all Rx channels.


Fig. 4. Simplified flowchart for assessing the performance of the proposed algorithm using simulated multi-channel data.

The multi-channel data are initially segmented into $N$ small coherent processing intervals (CPIs) along the azimuth time direction. The phase correction is then applied to all the range samples of a CPI. Next, the CPIs are transformed into the rangeDoppler domain via azimuth FFT (fast Fourier transform).

The target is detected in the range-Doppler domain, where after detection, its slant range and its Doppler frequency are measured. The target's DOA angle is then estimated via beamforming using (3) and subsequently its position on the ground is computed by using (4)-(9). Finally, the target's absolute position error is obtained by calculating the absolute difference between its true and its estimated positions.

Figure 5a shows a comparison between the target's DOA angles obtained with and without the phase correction. From the
figure it can be seen that the estimated DOA angles without phase correction (red curve) not only fluctuate over time but also give a root mean square error (RMSE) of about $2.2^{\circ}$. This leads to a mean absolute position error of about 106 m , as shown in Fig. 5b (red curve). However, after applying the proposed phase correction algorithm the estimated DOA angles overlap quite well with the true DOA angles (orange line in Fig. 5 a ) and give a mean DOA and position errors of nearly $0^{\circ}$ and 0.3 m , respectively, as indicated in the blue curves in Fig. 5.


Fig. 5. Simulation results: (a) target's DOA angle; (b) target's absolute position error with and without phase correction.

## V. EXPERIMENTAL RESULTS

The proposed algorithm is validated using X-band VVpolarized airborne radar data sets. The flight campaign with DLR's new airborne system DBFSAR [4] was conducted in October 2020 over the Lake Ammersee, in Germany. Table I shows the main radar and acquisition geometry parameters.

Figure 6 shows the image of the test site, which is overlaid with fully focused SAR images for visualization purposes. Five small electrical boats \#1-5 (size $\approx 3.5 \mathrm{mx} 1.5 \mathrm{~m}$ ) and a sailboat \#6 (size $\approx 5.0 \mathrm{mx} 2.0 \mathrm{~m}$ ) were located in the region of interest (ROI). The tracks of the boats were recorded by handheld GPS devices. Note in Fig. 6 (bottom right) that the boats \#1-4 moved in different linear tracks, boat \#5 moved in circles and the sailboat \#6 moved freely within the ROI. Their absolute ground velocities were on the order of $1.5 \mathrm{~m} / \mathrm{s}$.

## A. DOA Angle Estimation Accuracy

The accuracy of the estimated DOA angles is evaluated with and without phase correction considering the data set 1 (cf. Fig. 6). Figure 7a shows that without phase correction a high DOA angle variation is obtained. An example is shown in Fig. 7c, where the red histogram shows the DOA angle variation within the ROI.

After correcting the unwanted phases, a great improvement of the DOA angle estimates can be noticed, as shown in Fig. 7b. It can also be observed in Fig. 7b that the DOA angle estimates change outside the ROI. This is due to the terrain's topographic variation, since the phase correction was carried out for the full data using for simplicity the mean terrain's elevation of the ROI (cf. Table I) instead of a DEM. Nevertheless, within the ROI the estimated DOA angles approach the reference value of $\Psi_{\text {DOA, array }}=90^{\circ}$. The blue histogram in Fig. 7c shows that

TABLE I
Main Radar and Acquisition Geometry Parameters: Data Sets 1-3

| Quantity | Value |
| :--- | :---: |
| Velocity of the platform | $90 \mathrm{~m} / \mathrm{s}$ |
| Number of Tx/Rx channels | $1 / 6$ |
| Pulse repetition frequency (PRF) | 3004 Hz |
| Slant range resolution | 0.3 m |
| Effective along-track baseline between adjacent channels | 0.1 m |
| Wavelength | 0.03155 m |
| Maximum squint angle | $5^{\circ}$ |
| Mean altitude of the platform (above ellipsoid) | 2498 m |
| Mean terrain's height of the ROI (above ellipsoid) | 579 m |

TABLE II
SCNR And Position Errors of the Detected Boats in Data Sets 1-3

| Data <br> Set | Boat <br> $(\#)$ | Absolute <br> Position Error [m] <br> Without Correction | Absolute <br> Position Error [m] <br> With Correction | SCNR <br> $[\mathrm{dB}]$ |
| :---: | :---: | :---: | :---: | :---: |
| 1 | 1 | 180.34 | 17.21 | 17.40 |
|  | 2 | 185.41 | 16.62 | 16.43 |
|  | 3 | 174.87 | 10.42 | 15.96 |
|  | 5 | 186.91 | 10.21 | 15.29 |
|  | 6 | 175.83 | 9.72 | 18.63 |
| 3 | 1 | 179.48 | 9.67 | 19.27 |
|  | 2 | 176.24 | 15.84 | 17.95 |
|  | 4 | 178.78 | 10.19 | 16.83 |
|  | 5 | 175.79 | 14.33 | 14.27 |
|  | 6 | 176.86 | 10.31 | 19.11 |
|  | 1 | 252.54 | 19.16 | 17.12 |
|  | 2 | 252.53 | 10.21 | 15.71 |
|  | 3 | 127.91 | 7.63 | 13.71 |
|  | 3 | 250.87 | 10.39 | 19.44 |
|  | 6 | 262.53 | 13.38 | 14.15 |

after phase correction the mean estimated DOA angle is $\bar{\Psi}_{\text {DOA, array }}=89.74^{\circ}$, which presents an offset of $\Psi_{\text {DOA }, \text { offset }}=$ $0.26^{\circ}$ with respect to the reference value (dashed green line). This offset is mainly caused by the surface velocity of the lake in the line-of-sight direction of the radar [8]. The lake's surface velocity can be estimated as a function of the $\Psi_{\text {DOA,offset }}$. However, this computation is out of the scope of this paper.


Fig. 6. Experiment with six controlled boats in the Lake Ammersee. The small boats moved in the ROI (orange box) and their tracks were recorded by handheld GPS devices. Data sets 1 and 2 were acquired with the same azimuth or flight direction.


Fig. 7. DOA angles estimated using data set 1: (a) without and (b) with phase correction. The histograms of the DOA angles for the ROI with and without phase correction are shown in (c).

## B. Position Estimation Accuracy

Before evaluating the target's position estimation accuracy, the moving boats need to be detected and tracked. The detection and tracking were carried out using the algorithms presented in [9]-[10]. For this experiment, no clutter suppression was performed and single-channel data were used for detecting the moving boats. Nevertheless, there is no restriction for using multi-channel data for detection, where either sum-channel data or clutter suppressed data can be used.

Figure 8 shows the geocoded radar detections (orange) and the GPS tracks (white) obtained from the boats in data set 1 . The GPS tracks are shown for the entire flight duration ( $\cong 85 \mathrm{~s}$ ) and the arrows indicate the direction of motion of the boats. In Fig. 8a it can be seen that without applying the phase correction algorithm the geocoded radar detections of the boats are significantly displaced from their GPS tracks. In contrast, after applying the phase correction algorithm the geocoded radar detections are found very close to their corresponding GPS tracks, as shown in Fig. 8b. Note that the boat \#4 could not be detected in data set 1 due to its low SCNR.


Fig. 8. Geocoded radar detections (orange) and GPS tracks (white) of the moving boats in the ROI of data set 1 (cf. Fig. 6): (a) without and (b) with phase correction.

Finally, the absolute position errors of the moving boats obtained with and without applying the proposed phase
correction algorithm are summarized in Table II for data sets 1 to 3. The table shows that without phase correction the absolute position errors were found higher than 175 m for data sets 1 and 2 , and they reached up to 262 m for data set 3 , which had the highest squint angle of about $5^{\circ}$. In contrast, after correcting the phases the absolute position errors of the boats have significantly decreased to less than 20 m . Such a position accuracy can be considered as very good for airborne radarbased moving target monitoring, especially when taking into account that this also applies to small boats and to strongly changing aircraft attitude angles.

## VI. CONCLUSION

This letter presents a robust phase correction algorithm for ground and maritime moving target monitoring applications using multi-channel airborne radar data. The algorithm is validated using simulated data as well as multi-channel X-band radar data acquired with DLR's new airborne system DBFSAR. The experimental results show that the proposed algorithm successfully corrects the undesired phases of the Rx channels giving an absolute position error of the boats better than 20 m . Such accuracy is considered impressive, since the detectability of the boats was very low due to their dimensions and the radar data were acquired with high squint angles on the order of $5^{\circ}$.

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