DOA Angle Estimation Methods for Ship Geolocation using DLR's Multichannel DBFSAR System

Sushil Kumar Joshi, Stefan V. Baumgartner, André Barros Cardoso da Silva, and Gerhard Krieger
German Aerospace Center (DLR), Oberpfaffenhofen, Germany

Abstract

Direction of arrival (DOA) angle estimation is essential for projecting the airborne radar-based target detections on ground. Most state-of-the art DOA angle estimation methods assume one detection per target. These methods cannot be used one-to-one for extended targets like ships, because individual ships in high resolution data are generally composed of several distinct radar detections. Therefore, in this paper different methods for estimating the DOA angle for extended targets are presented. The most suitable method is then selected for generating the geocoding results of real ships present in real multichannel airborne radar data acquired from DLR's DBFSAR airborne radar sensor.

1 Introduction

Ship detection and monitoring is imperative to ensure safety and security at sea. Prominent state-of-the art sensors which are used for this task are the AIS (automatic identification system), marine radars and coastal surveillance radars [1]. Not all ships, especially the smaller ones, are equipped with the AIS transponders and marine radars do not suffice the maritime surveillance due to their limited range. Coastal radars have longer ranges because of their installations at higher altitudes such as hills, but their surveillance area is generally restricted to coastal regions only. Therefore, ships that are further away from the coast cannot be detected by coastal radars. To deal with these limitations, air- or spaceborne radar sensors can be a desirable choice. Besides their all-weather and day-night acquisition capabilities, one distinguishing feature of airborne radars is their flexibility to acquire data with very high resolution and, unlike space-based radars, they also allow for shorter revisits and longer observation times.

Airborne radar data can be acquired with multiple receiving (RX) channels. When multichannel system is used, the direction-of-arrival (DOA) angle of the detected target can be computed. With the estimated DOA angle and the aircraft's navigation parameters, the detected target can directly be mapped to ground via a geocoding operation [2]. The computed geographical positions of the targets can be compared with the AIS-based ground truth data for validation purposes.

For computing the DOA angle most state of the art MTI (moving target indication) algorithms assume one detection per target. Such an assumption is certainly valid for smaller targets like road vehicles in low resolution data where each target of target in most cases lies within a single radar resolution cell. However, in high resolution data targets like ships generally appear as extended targets occupying more than one resolution cell per target.

An example is shown in **Figure 1** where ship HAM 316

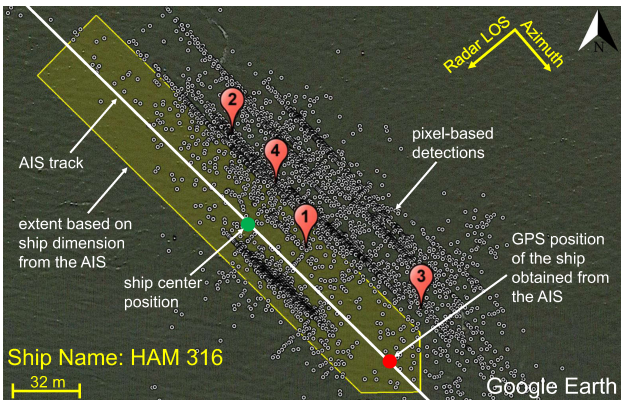

Figure 1 Geocoded radar-based detections obtained from ship HAM 316 at a specific time instant using real multichannel airborne radar data. Due to the side-looking acquisition geometry of the radar and the ship height, the detections are slightly displaced towards the radar in its line-of-sight (LOS) direction. Single ship positions 1, 2, 3 and 4 in the figure corresponds to methods ACA, MAA, NNCG and mean DOA, respectively. They are the proposed DOA estimation methods for extended targets and they are discussed in Section 4.

(cf. Table 2) has over 4000 radar-based detections at a single time instant. These detections are spatially distributed around the ship. This is because each geocoded detection has a unique DOA angle. The aim is to determine a single DOA angle so that a single position of the extended target on ground can be computed. By doing this, it is possible to initiate the tracks of the extended targets and also to maintain their tracks over time.

In this paper four methods for estimating the DOA angle of extended targets are presented. A suitable estimation method is then selected for mapping the radar-based target detections on ground. For this, real ships present in real multichannel airborne radar data acquired using DLR's

DBFSAR system [3] are used.

2 Basic Principle of Multichannel Data Processing

The algorithm operates on multichannel range-compressed airborne radar data. The fundamental steps of target's DOA angle and ground position estimation using multichannel radar data are outlined as:

- Partition of the multichannel radar data into smaller CPIs (coherent processing intervals) along the azimuth direction. We use 128 consecutive temporal azimuth samples within a single CPI. For the DBFSAR system which has a pulse repetition frequency of 3 kHz, single CPI corresponds to approximately 43 ms.
- Data calibration for correcting the phase and amplitude offsets among the RX channels in order to estimate the target positions on ground accurately [4].
- Transformation of individual CPIs to range-Doppler domain via azimuth fast Fourier transform (FFT).
- Target Detection in range-Doppler domain [5]. Detecting targets in Doppler domain has a benefit that targets even with low radar-cross-section moving with a certain LOS velocity appear out of the clutter region, thus improving their detectability.
- DOA angle estimation of the detected target via a beamforming operation.
- Target ground position estimation using the computed DOA angle, slant range of the target, the known terrain elevation, and the known geographical aircraft position and attitude angles.

3 State-of-the-Art DOA Estimation Methods for Point-like Targets

In this section for estimating the DOA angle using multiple RX channels a point-like target is assumed. **Figure 2** shows the multichannel radar data acquisition geometry with the target of interest.

As shown in **Figure 2**, the radar data are acquired using an antenna array that consists M number of RX channels. The receive channels are arranged in the along-track (or azimuth) direction of the aircraft. The multichannel signal model is given in [6].

For calculating the DOA angle, the directional cosine $\hat{u}$ of the target with respect to the antenna array is estimated by using a maximum likelihood operator as [2]

$$\hat{u} = \underset{u}{\operatorname{argmax}} |\boldsymbol{d}^H(u)\hat{\boldsymbol{R}}_{\mathbf{W}}^{-1}(f_{\mathrm{a}})\boldsymbol{Z}(r, f_{\mathrm{a}})|^2, \tag{1}$$

where $(\cdot)^H$ is the Hermitian operator (conjugate transpose), $\boldsymbol{d}(u)$ is the beamforming vector, steering vector or DOA angle vector and $\hat{\boldsymbol{R}}_{\mathbf{W}}(f_{\mathrm{a}})$ is the clutter covariance matrix. The term $\boldsymbol{Z}(r, f_{\mathrm{a}})$ denotes the multichannel data vector at slant range r and Doppler frequency f_{a} which is obtained after detecting the target in range-Doppler domain.

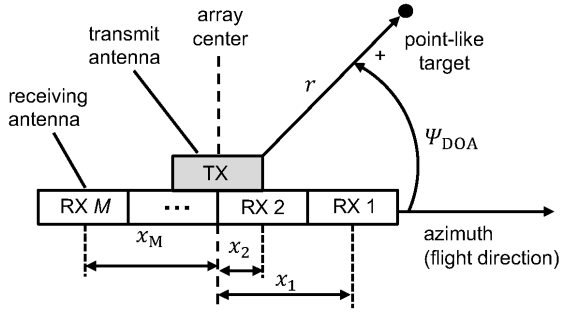

Figure 2 Multichannel data acquisition geometry with M RX channels. The terms $x_1, x_1, ...x_{\mathrm{M}}$ are the antenna center positions in azimuth direction with respect to the array origin. The target range r and its corresponding DOA angle ψ_{DOA} are shown in the figure.

When the targets are expected to have high signal-to-clutter-plus-noise ratio (SCNR) in Doppler domain, they can be detected without performing any clutter suppression. Therefore, the term $\hat{\boldsymbol{R}}_{\mathbf{W}}(f_{\mathrm{a}})$ shown in (1) can be omitted and the directional cosine of the target can be rewritten as

$$\hat{u} = \underset{u}{\operatorname{argmax}} |\boldsymbol{d}^H(u)\boldsymbol{Z}(r, f_{\mathrm{a}})|^2. \tag{2}$$

This simpler equation is used for avoiding any biases on the performance assessment caused by clutter suppression. The DOA angle of the target is then computed as

$$\hat{\psi}_{\mathrm{DOA}} = \cos^{-1}(\hat{u}). \tag{3}$$

4 DOA Angle Estimation for Extended Targets

This section presents four different methods for estimating a single DOA angle of an extended target.

It was already mentioned in Section 1 that extended targets in high resolution data are composed of several pixel-based detections per target. Therefore, after detecting and clustering the target-originated pixels in range-Doppler domain in a single CPI, the single DOA angle of an extended target is computed based on:

1. The average complex amplitude (ACA)
2. The maximum of the absolute amplitude (MAA)
3. The complex amplitude at the nearest neighbor to the center of gravity (NNCG) of the cluster
4. The mean DOA angle of the target pixels

More details related to the aforementioned DOA estimation methods for extended targets, including the equations, will be presented in the final EUSAR paper.

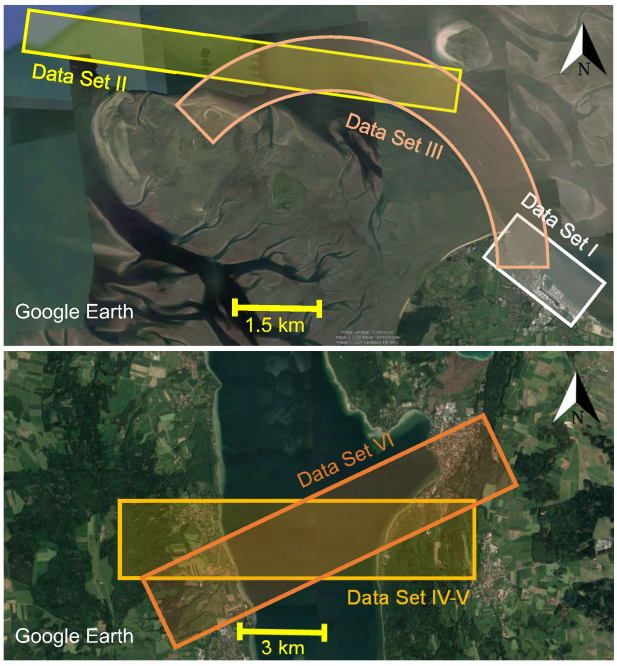

Figure 3 Google Earth image showing the test sites in North Sea near town Cuxhaven (top) and over Lake Ammersee (bottom) in Germany. The parameters of the acquired radar data are described in Table 1.

An example is shown in **Figure 1**, where these four methods are used for estimating the geographical positions of ship HAM 316 at a single CPI. It can be seen from the figure that the estimated ground positions of the ship are different. This is because for each method, the computed DOA angle is different. In Section 6 position accuracy and the geocoding results obtained using the best DOA estimation method are provided.

5 Multichannel Flight Campaigns and Radar Data

In November 2019 and October 2020, two different flight campaigns using DLR's multichannel airborne radar system DBFSAR [3] were carried out in North Sea near town Cuxhaven and over Lake Ammersee in Germany, respectively. **Figure 3** shows the Google Earth images of the test sites where the flight experiments were conducted. In the figure, data sets I-III were acquired in North sea (data set III were acquired circularly in order to observe a semi-annulus region), and data set IV-VI were acquired over the Lake Ammersee.

In the North Sea campaign several ships of opportunities were observed. The AIS receiver onboard the aircraft received the AIS signals from ships with distances up to 200 km away from the aircraft.

The goal of the Ammersee Flight Campaign was to detect, track and geolocate slowly moving small boats. For this reason, five electrical boats (size $\approx$ 3.5 m x 1.5 m) and a sail boat (size $\approx$ 5.0 m x 2.0 m) (in total six boats) were considered in this experiment.

Table 1 System and acquisition geometry parameters common for both North sea and Ammersee multichannel airborne data used for the investigations.

Acquisition Parameters	Typical Values
Average Platform Velocity [m/s]	90
Average Platform Altitude Above Ground [m]	2500
Number of TX/RX Channels	1/6
Physical Antenna Separation [m]	0.2
Chirp Bandwidth [MHz]	500
Range Resolution [m]	0.3
Pulse Repetition Frequency [Hz]	3004.8

Table 2 AIS-based specifications of the ships present in the multichannel radar data acquired using DBFSAR in North Sea, Germany.

Ship Name	Speed Over Ground [m/s]	Ship Length/Beam [m]	Ship Moving Direction w.r.t the Aircraft [°]
		Data Set I	
LANGELAND	2.72	82/12	-8.35
LONGDUIN	6.94	112/15	195.93
HAM 316	3.96	129/22	-1.23
		Data Set II	
CHARISMA	4.47	12/4	7.67
HOFFNUNG CUX10	1.64	15/5	-0.32
SAPHIR	1.85	17/6	1.59
GEO GRAPH	1.18	18/6	-150.48
UTHOERN	3.75	31/9	-182.02
WANGEROOGE	1.38	52/13	20.14
FAIR LADY	9.82	68/10	4.39
MT BLUE STAR	7.76	126/18	23.31
VEGA GRANAT	4.73	180/20	-169.94
		Dataset III	
GEO GRAPH	3.34	18/6	-11.81
TINA CUX-5	2.21	19/5	-173.52
AURORA	4.06	20/6	-104.68
PILOTVESSEL HANSE	4.83	49/21	-182.36
RMS RATINGEN	4.27	88/11	-185.16
LONGDUIN	6.07	112/15	-3.75

The acquisition geometry and the DBFSAR system parameters common for both North Sea and Ammersee flight campaigns are listed in Table 1.

6 Experimental Geocoding Results

In the North Sea campaign, according to the received AIS messages, there were in total three ships in data set I, nine ships in data set II and six ships in data set III, as shown in Table 2. The received AIS positions from the ships are used as ground truth for calculating their position accuracy. In the Ammersee campaign, there were six controlled boats, the GPS-based reference positions of these boats are used for calculating their ground position accuracy.

After having the ground truth information, the ACA-based DOA estimation method is chosen for geocoding the radar-based target detections on ground and for comparing the geocoded detections with the available ground truths. **The reason for selecting the ACA method will be explained in the final EUSAR paper.**

The geocoding results obtained using the ACA method are shown in **Figure 4** and **Figure 5** for multichannel radar dataset III (from North Sea campaign) and VI (from Am-

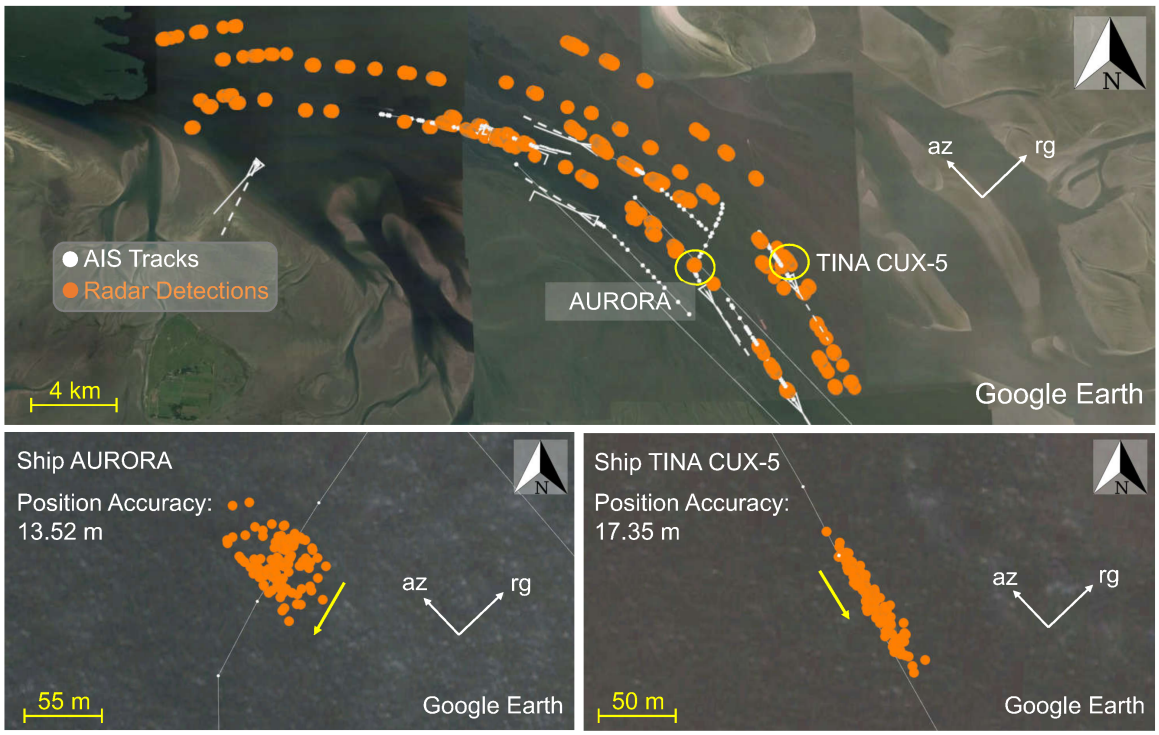

Figure 4 Top: Geocoding results obtained from multichannel data set III (circular flight). In the figure several targets of opportunity can be seen. Bottom: Details of ship AURORA and ship TINA CUX-5 using all CPIs (cf. data set III in Table 2). Yellow arrows in the figure indicate the ships' moving directions.

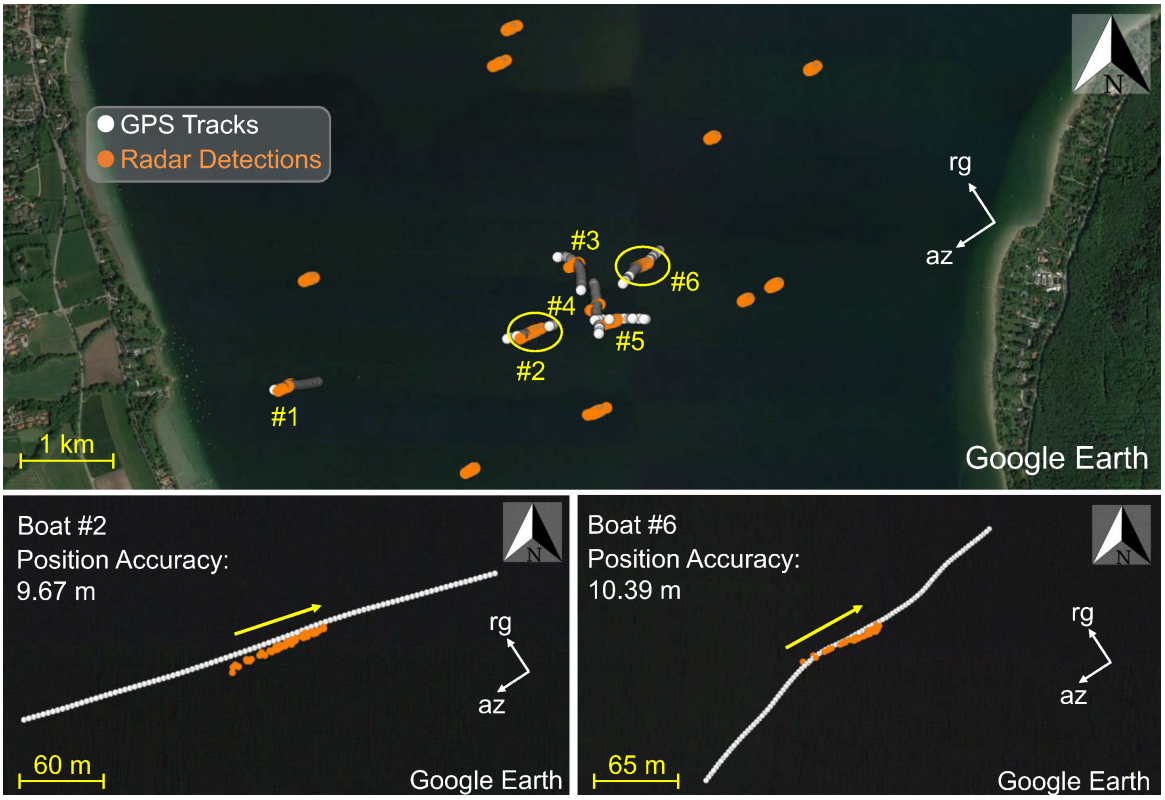

Figure 5 Top: Geocoding results obtained from multichannel data set VI. In the figure several targets of opportunity can be seen. Bottom: Details of Boat #2 and Boat #6 using all CPIs. Yellow arrows in the figure indicate the boats' moving directions.

mersee campaign), respectively (cf. **Figure 3** for both campaigns). From the figure it can be seen that the geocoded radar-based detections from the targets are found very close to their corresponding AIS and GPS tracks giving a

position estimation accuracy of less than 20 m for both the datasets. Such accuracy for an extended target can be considered very good for radar-based ship monitoring using an airborne radar sensor. **In the final EUSAR paper the ground position accuracy results for all the ships and boats present in the investigated multichannel radar datasets will be presented and discussed in detail.**

7 Conclusion

In this letter four methods for estimating the DOA angle of extended targets using high resolution range-compressed multichannel airborne radar data are presented. The methods are evaluated using real X-band VV polarized radar data sets acquired using DLR's DBFSAR multichannel airborne radar system. Based on the experimental results, we recommend using the average complex amplitude (ACA) method for estimating the DOA angles of extended targets. This method not only gives an acceptable position accuracy, but can also be considered computationally efficient and has real-time processing capability. **More details about the method will be given in the final EUSAR paper**.

8 Literature

[1] A. N. Ince, E. Topuz, E. Panayirci, and C. Isik, *Principles of integrated maritime surveillance systems*. Springer Science & Business Media, 2012, vol. 527.

[2] D. Cerutti-Maori, J. Klare, A. R. Brenner, and J. H. Ender, "Wide-area traffic monitoring with the SAR/GMTI system PAMIR," *IEEE Trans Geosci Remote Sens*, vol. 46, no. 10, pp. 3019–3030, 2008.

[3] Andreas Reigber, Rolf Scheiber, Marc Jäger, Pau Prats-Iraola, Irena Hajnsek, Thomas Jagdhuber, Konstantinos P. Papathanassiou, Matteo Nannini, Esteban Aguilera, Stefan Baumgartner, Ralf Horn, Anton Nottensteiner and Alberto Moreira, "Very-high-resolution airborne synthetic aperture radar imaging: Signal processing and applications," *Proceedings of the IEEE*, vol. 101, no. 3, pp. 759–783, 2013.

[4] A. Barros Cardoso da Silva, S. K. Joshi, S. V. Baumgartner, F. Q. de Almeida, and G. Krieger, "Phase correction for accurate DOA angle and position estimation of ground moving targets using multi-channel airborne radar (accepted)," *IEEE Geoscience and Remote Sensing Letters*, 2021.

[5] S. K. Joshi, S. V. Baumgartner, A. B. da Silva, and G. Krieger, "Range-Doppler based CFAR ship detection with automatic training data selection," *Remote Sensing*, vol. 11, no. 11, p. 1270, 2019.

[6] J. H. Ender, C. H. Gierull, and D. Cerutti-Maori, "Improved space-based moving target indication via alternate transmission and receiver switching," *IEEE Trans Geosci Remote Sens*, vol. 46, no. 12, pp. 3960–3974, 2008.