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Promising Techniques for Future Maritime Surveillance Demonstrated With DLR's Airborne Radar Sensors F-SAR and DBFSAR

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ABSTRACT

The Microwaves and Radar Institute of DLR operates the airborne synthetic aperture (SAR) radar sensors F-SAR and DBFSAR [1]. These sensors are used for investigating and demonstrating novel radar and signal processing techniques for a number of different applications. In the paper promising techniques for future *Maritime Surveillance with High-Altitude Platforms* (HAP) are discussed and demonstrated by using L- and X- band radar data acquired with F-SAR. A potential onboard processing concept is proposed which doesn't require conventional and time consuming SAR processing. The used techniques include automatic constant false alarm rate (CFAR) ship detection, tracking over long observation times, fusion with simultaneously acquired automatic identification system (AIS) data, and high-resolution inverse SAR (ISAR) imaging.

INTRODUCTION

Ship monitoring has evolved as an important topic for maritime security. Nowadays reliable air- and spaceborne SAR sensors are available for detecting and imaging ships at coastal areas as well as on open sea. One advantage of airborne SAR systems is, in contrast to spaceborne systems, that arbitrary (non-linear) flight tracks can be flown. This paves the way for following coastal lines, land borders or even for following arbitrarily moving ships of interest. A spatially limited region of interest can be monitored continuously over longer times limited principally only by the endurance of the aircraft.

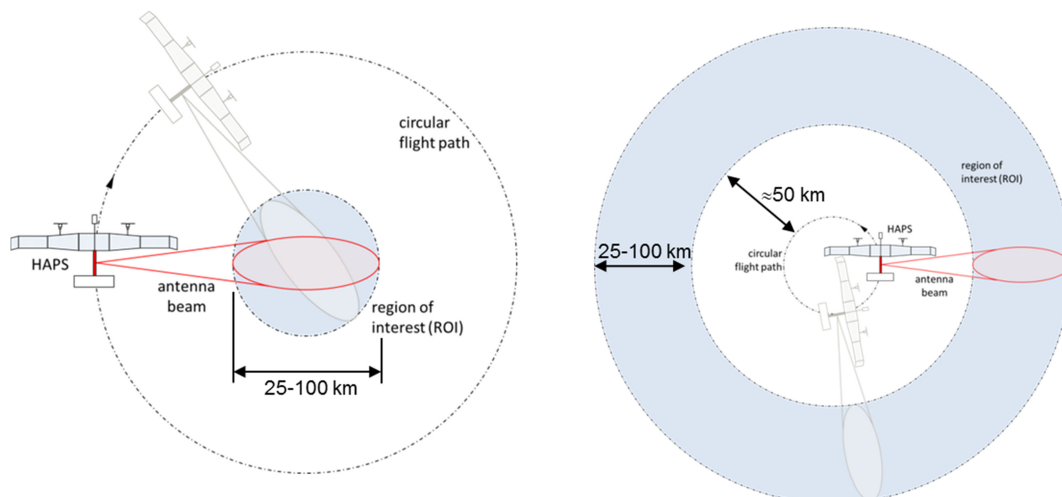


Fig. 1. Observation of a region of interest using circular flight tracks (left: the scene center is continuously illuminated by the antenna beam over the full aspect angle range of 360°; right: an annulus is periodically monitored).

Future high-altitude platforms (HAP) or high-altitude pseudo satellites (HAPS) flying in the stratosphere are expected to have a much longer endurance than conventional aircrafts. Missions lasting for several days, weeks, months or even years seem to be possible. With radars integrated in such platforms, a continuous monitoring of hotspots and larger regions of interest ranging in size from several hundred to several thousand square kilometers will become possible. In 2015, we have carried out a study for Airbus Defence and Space to investigate if it is feasible to bring and operate a light-weight radar sensor on their solar-powered Zephyr HAPS platform. In the study we found that the two main

platform restrictions, the limited payload weight and the limited available electrical power, can be overcome. For instance, with a well-designed radar and antenna as well as with suitable radar operation modes already a peak transmit power in the order of 50 W at a duty cycle of 20 % is sufficient for obtaining high-quality SAR images with resolutions <1 m at X-band and a swath width of 25 km, acquired from a flight altitude of 20 km. For detecting ships with a radar cross section (RCS) of at least 22 dB, the swath width can even be extended to 100 km [2].

Of special interest for maritime surveillance may be circular flight tracks since they allow for observing ships or any other targets of interest over the full aspect angle range of 360° (cf. Fig. 1 left). In addition to the improved probability of detection, the data can be processed in a way so that an ISAR image sequence showing the ship under different aspect angles is obtained [3, 4]. This may aid later on for target classification and recognition. If the radar antenna is not pointing to the circle center but in opposite direction, an annulus on ground can be monitored periodically (cf. Fig 1 right). When the aircraft circles over an area or object to be protected, this acquisition geometry can be used for the detection and imaging of potential intruders.

For future maritime security applications a viable processing concept should cover the following requirements:

- *Detection of ships with low radar cross section:* For this requirement, generally a multi-channel radar system with at least two receiving (RX) channels for clutter suppression is necessary. This allows for detecting even ships with low RCS as long as they move with a sufficiently large line-of-sight velocity.
- *Accurate geographical position estimation:* In conventionally processed SAR images moving ships appear displaced from their actual positions (up to several hundreds of meters, depending on the line-of-sight velocity). To get additionally to the clutter suppression capability also an accurate position estimation performance, a third RX channel is mandatory.
- *Velocity and moving direction estimation:* For accurate velocity and moving direction estimation as well as for the prediction of future target positions, tracking is needed. The tracker should be powerful enough to handle multi-target scenarios, long observation times as well as observation gaps in the order of several seconds to minutes.
- *Ship classification:* To classify ships at least the length and width of the ship have to be estimated accurately. For this task it is principally necessary to generate high-resolution ISAR images of the detected ships. An ISAR image sequence acquired from different aspect angles may furthermore improve the classification result.
- *Ship recognition:* Robust ship recognition is still a current research topic which requires much more effort than classification. High-resolution range profiles (HRRPs), high-resolution ISAR images (or image sequences) and micro-Doppler signatures can, for instance, be used as input for ship recognition algorithms. A fusion with data from other sensors or sources may improve the recognition performance.
- *Simultaneous acquisition of AIS data:* International voyaging ships with 300 or more gross tonnage and passenger ships of any size have to be equipped with the automatic identification system (AIS). The ship data estimated from the radar-based ship detections can be fused with the simultaneously acquired AIS data. A comparison between AIS and radar data allows for anomaly detection. The simultaneous acquisition of AIS and airborne radar data generally requires an AIS receiver to be installed onboard the aircraft.
- *Real-time capability:* Depending on the particular application, all the processing steps needed for fulfilling the requirements listed above have to be executed in real-time or near-real time. Thus, processing onboard the aircraft is mandatory if the data link to ground has limited bandwidth.
- *Data transfer to ground:* If onboard processing is carried out, not all the acquired radar data need to be transferred to the ground. Only data of interest such as the ships' positions, velocities, moving directions, ISAR images, fused AIS data, and classification results need to be transferred. This kind of data reduction reduces the data transfer rate requirements significantly, especially if the radar system is operated with high pulse repetition frequencies (PRFs) and large chirp bandwidths for achieving high range resolution.

In the following sections the advantages of using range-compressed radar data and processing in range-Doppler domain are discussed, a potential onboard processing concept fulfilling most of the requirements listed above is introduced and experimental results obtained with fully polarimetric L- and X-band F-SAR data are presented.

ADVANTAGES OF RANGE-COMPRESSED DATA AND PROCESSING IN RANGE-DOPPLER DOMAIN

For ship detection, especially with spaceborne SAR sensors, nowadays in most cases fully focused SAR images are used. However, if the signal-to-noise ratio (SNR) is sufficiently large, as this is the case for many airborne radars and also for well-designed future HAPS and HAP radars, there is principally no need for the time-consuming generation of fully focused SAR images. Range-compressed data blocks containing only a small number of azimuth samples are successively transformed via azimuth fast Fourier transform (FFT) into the range-Doppler domain. Due to the short coherent processing interval (CPI) the signal phase can be considered as linear so that ships appear as focused peaks in Doppler domain. Signals from moving ships are additionally shifted in Doppler. If the line-of-sight velocity component is large enough, the signals appear in the exo-clutter region so that even ships with low RCS, not visible in time domain, can be detected in range-Doppler domain with a single-channel radar (cf. Fig. 2) [5,6].

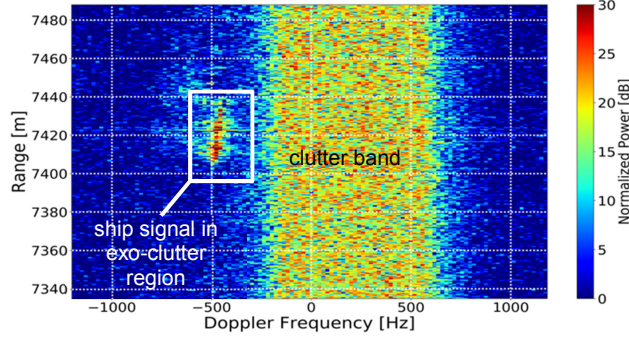


Fig. 2. Range-Doppler image containing a ship signal (left) and ocean clutter (center). The radar data were acquired with DLR's F-SAR sensor in X-band at an altitude of 5600 m above ground.

The minimum detectable line-of-sight velocity $v_{r,\min}$ for a single-channel radar can roughly be defined as the velocity which causes a Doppler shift of the signal so that at least 3 dB of the energy lies outside the *stationary* (= non-moving) clutter band B_c :

$$|v_{r,\min}| \approx \frac{\lambda}{4} \cdot B_c = 0.886 \cdot \frac{\lambda \cdot v_p}{2 \cdot L_a} \quad (1)$$

where L_a is the antenna length in azimuth direction, λ is the radar wavelength and v_p is the platform velocity. A HAPS is well suited for detecting slowly moving ships with low RCS since it can be operated with low platform velocities v_p in the order of 10 to 30 m/s. There is principally no strict restriction on the antenna length since it can be integrated into the aircraft structure, e.g., into the fuselage. The antenna length requires a trade-off: on one side it has to be large enough so that ships moving with a minimum line-of-sight velocity can be detected, but on the other side it has also to be small enough for achieving high azimuth resolution in stripmap mode if no azimuth beam steering and, thus, no spotlight mode is available. For an example, HAPS system with an azimuth antenna length of $L_a = 1.0$ m, a platform velocity of $v_p = 20$ m/s and X-band with $\lambda = 0.0312$ m, the minimum detectable line-of-sight velocity for a stationary clutter assumption is $v_{r,\min} = 0.276$ m/s ≈ 1 km/h. It is clear that this lower bound of the minimum detectable velocity may increase significantly in case of severe ocean surface currents or high sea states which increase the clutter bandwidth. In this case a more sophisticated performance analysis has to be carried out.

POTENTIAL RADAR PROCESSING CONCEPT AND PROMISING TECHNIQUES

A simplified representation of our proposed onboard processing concept for maritime surveillance using airborne and future HAPS radars is shown in Fig. 3. We have already implemented and tested most of the shown processing blocks with single- and multi-channel data acquired with DLR's F-SAR and DBFSAR sensors. The novel DBFSAR, which is installed onboard DLR's Dornier 228-212 research aircraft, is also equipped with a powerful onboard processor, a two-channel AIS receiver and a LTE router for transferring the processing results to a server on ground.

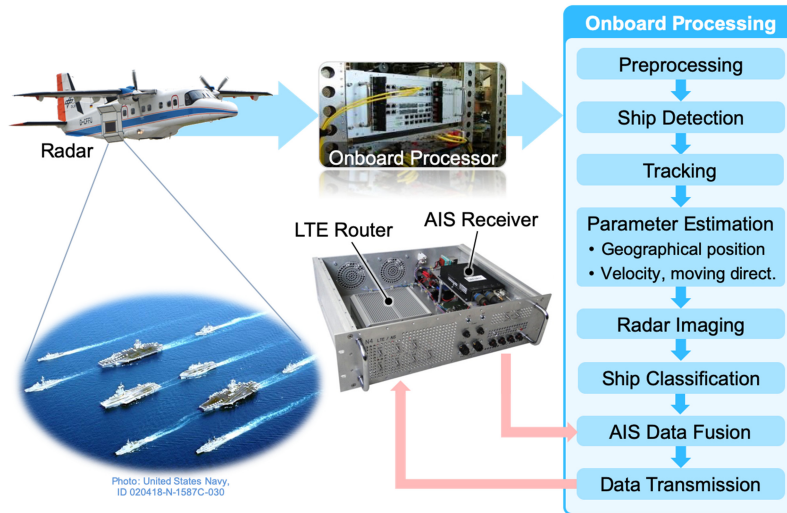


Fig. 3. Simplified representation of the proposed processing concept.

In the following section the processing blocks are discussed in more detail and results obtained with single-channel X- and L-band F-SAR data are shown.

Preprocessing

In the *Preprocessing* block, the conventional radar calibration steps (e.g., delay compensation, I/Q balancing, etc.) and range compression are carried out. Furthermore, if multiple RX channels are used, the channels have to be equalized. For this task different state-of-the-art digital channel balancing methods can be used. So far we have good experience with a simple method where the average amplitudes are normalized to a reference channel and the along-track interferometric phase offsets are compensated [7,8].

Ship Detection

As already mentioned in previous sections, ship detection is carried out by transforming small azimuth blocks of range-compressed radar data via azimuth FFT to range-Doppler domain (cf. Fig. 4). In case of single-channel data, the Doppler spectrum has to be normalized before a Doppler frequency independent constant false alarm rate (CFAR) detection threshold can be applied [5,6]. In case of multi-channel data, the sum channel data can be used in the same way. If clutter suppression is needed, post-Doppler space-time adaptive processing (STAP) can be applied [8, 9]. In the implemented *Ship Detection* block between the three afore mentioned options *single-channel*, *sum channel* and *STAP* can be selected.

For computing a CFAR detection threshold in any case a suited sea clutter model has to be fitted to the data. For this purpose training data free of ship signals are needed. We have developed and implemented an automatic training data selection procedure which excludes potential ship signals from the data prior to the model fitting by using a novel pre-detector operating in time domain [5]. During our investigations with F-SAR data we found out, that the optimum clutter models need to be selected as a function of incidence angle. For near and mid range the most accurate model is the K-Rayleigh distribution. For far range with shallower incidence angles in the order of 50° and larger the 3MD (tri modal discrete texture) model is well suited [5]. It has to be pointed out that for our investigations only a limited amount of F-SAR data without changing sea states were available. Further investigations regarding optimum clutter model selection are necessary.

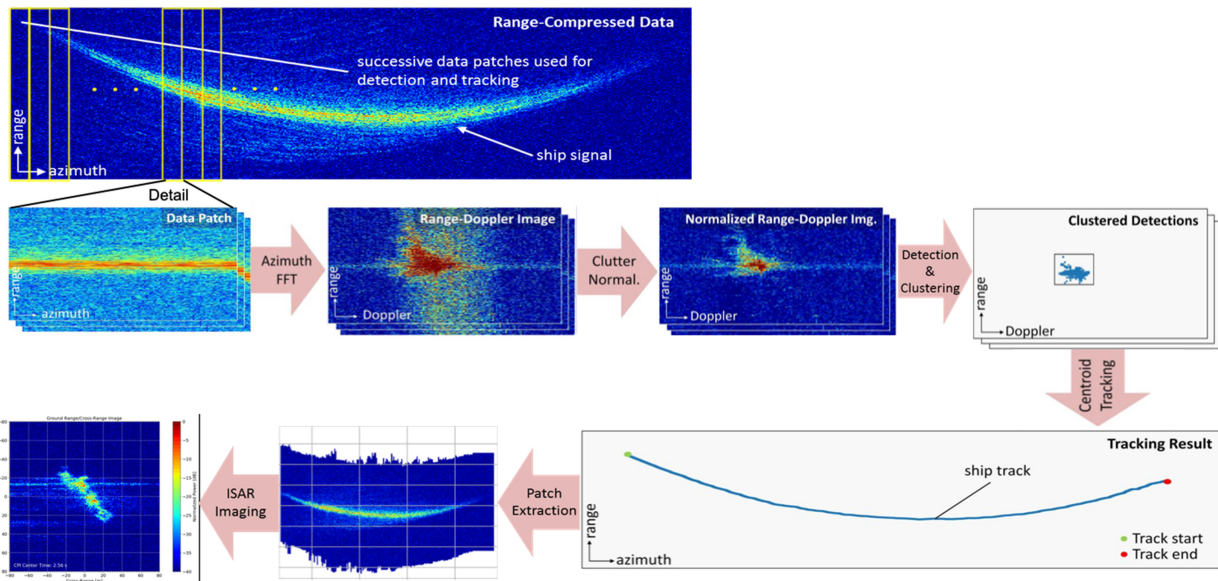


Fig. 4. Simplified processing steps showing the principle of the proposed detection in range-Doppler domain, the clustering of the pixel-based detections to a single object (middle right), the target track transferred from range-Doppler to time domain (bottom right), and the extracted range-compressed ship signals (bottom center) needed for generating a high-resolution ISAR image sequence (bottom left).

Tracking

Tracking is not only required for ship velocity estimation, moving direction estimation and for target position prediction, but also for extracting successive range-compressed ship signals over a longer period of time as needed for high-resolution ISAR imaging (cf. Fig 4 bottom). Since CFAR detection is pixel-based, multiple detections belonging to one and the same ship have to be clustered to a physical object prior to tracking. For this task we use a DBSCAN algorithm [5]. The positions of the center of gravity of the clusters in range-Doppler domain are tracked. Due to the short CPIs the center positions in range-Doppler domain can easily be transferred to range-time domain. We have implemented a tracking algorithm based on the Kalman filter. This tracker can also handle multi-target scenarios.

Parameter Estimation

For accurate position estimation of ships with low RCS at least 3 RX channels are required. The multiple channels allow for an accurate direction-of-arrival (DOA) angle estimation and, thus, for an accurate geographical position computation. If post-Doppler STAP is applied (with or without clutter suppression [8]) in the *Ship Detection* block, the directional cosine and the DOA angle are additionally obtained for each detected object. With the estimated DOA angle and the known aircraft position and Euler angles obtained from the aircraft's inertial measurement unit, the geographical position of the ship can be computed. However, in the single-channel case an accurate position estimation is generally not possible.

The velocities of the ships and the moving directions are obtained from the ship tracks provided by the *Tracker*. Target position prediction so far is carried out by fitting a linear function to the track and by performing extrapolation.

Radar Imaging

It has to be pointed out, that only the range-compressed data containing ship signals need to be ISAR processed (cf. Fig. 4 bottom center). This saves computation time, paves the way for real-time processing and saves data link bandwidth. For generating a radar image and HRRP sequence, the ISAR processor we have developed recently is used [3, 4]. This processor is capable of delivering high-resolution ISAR images and HRRPs, independent of the ship motion and the flight track of the aircraft. In Fig. 5 an ISAR image sequence acquired during a circular F-SAR flight track with the antenna pointing to the circle center where the controlled police ship Bad Bramstedt was moving is shown (cf. also Fig. 1 left). In total, the ship was observed over 400 s (cf. Fig. 6).

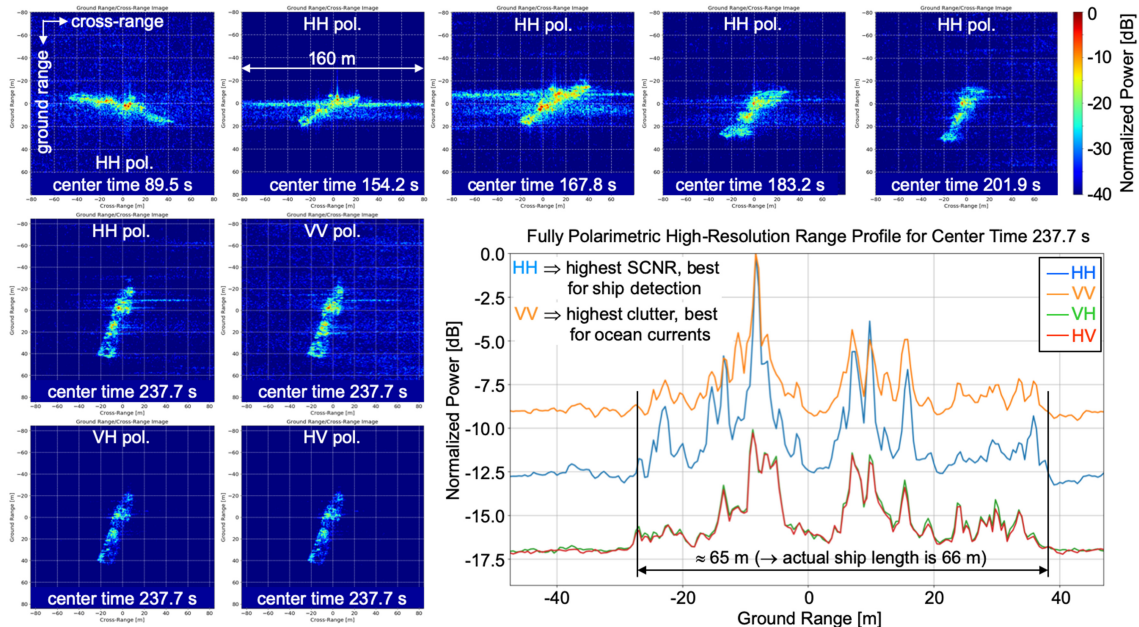


Fig. 5. Automatically obtained X-band ISAR image sequence of the police ship Bad Bramstedt (top and left) and the fully polarimetric high resolution range profiles (bottom right) corresponding to the images labelled with a center time of 237.7 s. The CPI per ISAR image was set to 1.7 s.

Ship Classification

So far we only consider the length and width of the ship estimated from the ISAR image. This allows just for a rough classification, but may be accurate enough for anomaly detection using the fused AIS data. We have not yet implemented any recognition algorithm. For estimating the dimensions of the ship a method based on the Radon transform is used.

AIS Data Fusion and Data Transmission

A dual-channel AIS receiver is integrated in the navigation track of DBFSAR so that AIS signals can be acquired simultaneously with the multi-channel radar signals. For fusing the AIS data with the radar-based detections, the inter- and extrapolated geographical position differences over time are compared. If the position difference is smaller than a certain threshold, it is assumed that the data belongs to one and the same ship. By doing this an anomaly detection is

possible. For transmitting the processed data to ground, a consumer LTE (Long Term Evolution) router is integrated in the same 19 inch slot as the AIS receiver (cf. Fig. 3). We have successfully demonstrated data transmission from DLR's research aircraft DO 228-212 via LTE in 2015 [10]. As long as the aircraft flies near the coast and not over open sea, the data transmission capability of LTE is sufficient for our research purposes. For operational open sea surveillance, a microwave data link or even a satellite connection is necessary. Both options are more expensive than LTE.

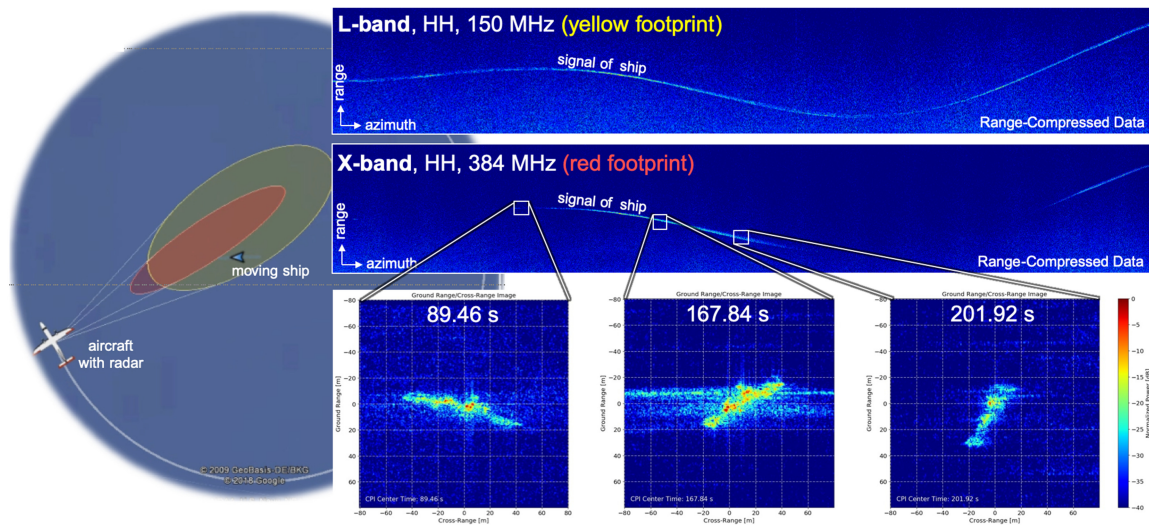


Fig. 6. Range-compressed HH polarized L-band (top right) and X-band data (middle right) of the police ship Bad Bramstedt acquired during a circular F-SAR flight track (left). The azimuth axis covers an observation time of approx. 7 minutes. At the bottom an ISAR image sequence generated from the range-compressed X-band data is shown.

CONCLUSION

In the paper a potential onboard processing concept including promising techniques for maritime surveillance with airborne radar and future HAP and HAPS radar was introduced. The concept uses single- or multi-channel range-compressed radar data as input. No conventional and time consuming SAR processing is required. Most blocks of the processing concept we have already implemented and tested with radar data acquired with DLR's airborne sensor F-SAR. The obtained results are promising and we are convinced that the proposed concept is well-suited for future HAP and HAPS.

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