SAR/ISAR Imaging In Passive Radars

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***Abstract*— This paper presents a study on the possibility of using Synthetic Aperture Radar (SAR) and Inverse SAR (ISAR) imaging techniques in passive radars, utilizing commercial continuous wave transmitters as illuminators of opportunity. In presenting potential applications of this novel technology, obtainable maximum ranges and resolutions in passive SAR/ISAR technology are discussed. In the paper the main stages of a signal processing chain for SAR/ISAR imaging in passive radar are presented and discussed, showing the challenges and limitations which have to be addressed in designing the passive SAR/ISAR system. Additionally, real SAR and ISAR images obtained by passive radar demonstrators utilizing Digital Video Broadcasting-Terrestrial (DVB-T) illuminators are presented as the proof of concept of the presented technology.**

Keywords—Synthetic Passive Radar, SAR, Inverse SAR, ISAR, passive SAR, passive ISAR, passive radar imaging

I. INTRODUCTION

In the last decade the number of research and development institutions working in the field of passive radar has increased significantly. Due to the relatively low costs of the hardware components used in passive radar the development of this technology has also begun to be attractive to academia, which usually has to stay within a modest budget. Consequently, many demonstrators have been developed worldwide over the last few years [1-6]. The resulting fast-paced progress in this technology's development has increasingly convinced potential users of its worth in both civilian and military applications [7, 8]. As a result industries all over the world have started to work on new passive radar products to introduce to the market [6, 8-10].

The main application of modern passive radars, known also as passive coherent location (PCL) systems, is air surveillance: the detection and tracking of air targets. The passive radar has one unique feature – all targets are illuminated continuously, so target echoes can be used not only for detection, but also for imaging. Recently researchers have turned their attention to this new area of application for passive radars, conducting research on passive synthetic aperture radar (SAR) and passive Inverse SAR techniques [13-19]. In the early stages theoretical studies on this topic were carried out and published in open literature [11, 12].In recent times several validations of these theoretical works have been carried out by researchers, showing the possibility of obtaining passive SAR images of ground targets by utilizing ground based DVB-T sources of illumination and passive radars mounted on airborne platforms [13, 14] and also showing capabilities of imaging air targets [15] and sea targets [16, 17] by using DVB-T signals and ground based PCL receivers. The ability to image ground targets by using GSM [18] and WiFi [19] illuminators of opportunity has also been shown. The real life results presented show great potential for the future applications of passive radar systems.

In this paper further study on the possibility of using passive radars in SAR/ISAR imaging is presented. In the next section the obtainable maximum ranges and resolutions for passive radar imaging purposes are discussed. Section III presents the signal processing techniques used for passive SAR and ISAR imaging, and the challenges and limitations of this technology are also discussed. As a validation of the presented technology, the recent results of passive SAR and ISAR imaging are presented in section IV. In the last section conclusions are reached and the potential future development of the passive imaging technology discussed.

II. PASSIVE SAR/ISAR IMAGING

A passive radar utilizes bistatic geometry [1]. This means that the transmitter which is used as an illuminator of opportunity is placed at a distance L from the passive radar receiver as depicted in Fig. 1a. The target can be detected and localized in bistatic range (R_b) and bistatic velocity (V_b) coordinates. The computation of the cross-ambiguity function (1) between a direct signal from the transmitter ($s_r(t)$) and a reflected echo from the target ($s_r(t)$)) is used for this purpose, defined by:

$$X(R_b, V_b) = \int_0^{t_i} s_r(t) \cdot s_m{}^*(t - \tfrac{R_b(t)}{c}) \cdot \exp\left(-j2\pi f_c \tfrac{V_b}{c} t\right) \mathrm{dt}, \qquad (1)$$

where f_c is a carrierfrequency of the transmitter, c is the speed of light, and t_i is the time of the integration. The coordinates of the correlation peak points on the target bistatic range $R_b(t)$equals $R_1(t) + R_2(t) - L$and bistatic velocity $V_b$defined as the time derivation of the bistatic range.

The resolution cell of the cross-ambiguity function given by (1) in the bistatic range $\delta R_b$is given by:

$$\delta R_b = c/(B \cdot (1 + \cos(\gamma/2)), \qquad (2)$$

where B is the signal bandwidth and γ is the bistatic angle depicted in Fig. 1.

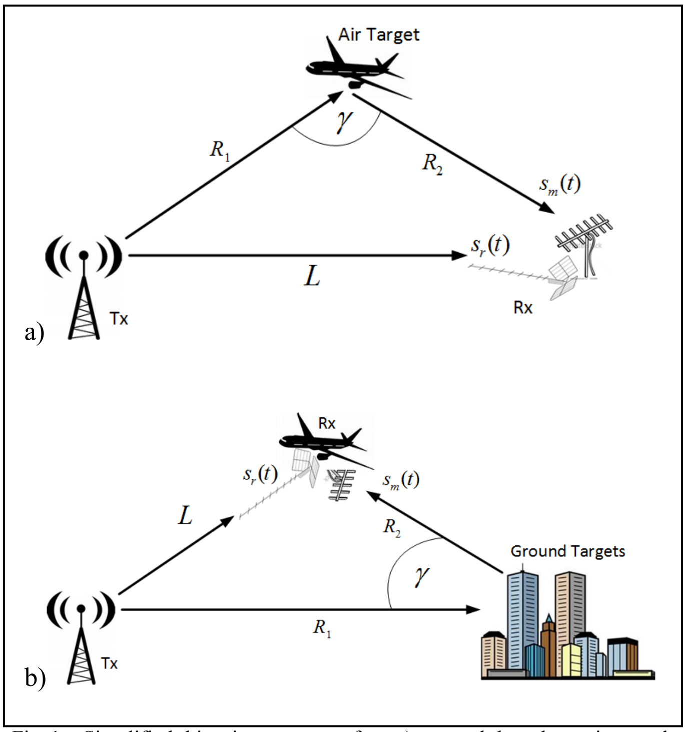

Fig. 1. Simplified bistatic geometry for: a) ground based passiver radar (passive ISAR case), b) airborne passive radar (airborne passive SAR case).

The resolution cell in bistatic velocity δV_bcan be determined from the following formula:

$$\delta V_b = c/(f_c \cdot t_i), \tag{3}$$

From the SAR/ISAR radar imaging point of view range resolution is a crucial parameter. For modern high resolution active SAR/ISAR radars the range resolutions can achieve a level of a few centimeters utilizing the bandwidth of the transmitted signal at the level of a few GHz. In passive radars, which are fully dependent on commercial sources of illumination, the range resolutions currently achievable are several orders smaller. The highest bistatic range resolution (for bistatic angle γ equals zero degrees – quasi monostatic geometry) can be achieved using a wideband telecommunications transmission such as Wi-Fi with a 40MHz bandwidth (δR_b =3.25m) LTE with 20MHz bandwidth (δR_b =7.5m) of the transmitted signal. Unfortunately, this type of transmission is characterized by a low maximum detection range due to the low transmitted power of the illuminators and this limits its application to a very short range. The detection range for bistatic radars is given by the following formula:

$$R_1 R_2 < \sqrt{\frac{P_T G_T G_R S_0 \left(\frac{c}{f_c}\right)^2 t_i}{(4\pi)^3 k T_R L_s D_0}}, \tag{4}$$

where $P_T$is the power transmitted by the illuminator of opportunity, $G_T$is the transmitterantenna gain in the direction of the receiver, $G_R$is thereceiver antenna gain in the direction of the transmitter, S_0 is the target radar cross-section (RCS), $k$is the Boltzmann constant, $T_R$the equivalent noise temperature of the receiver, $L_s$stands for the propagation and the system losses, andD_0 is a detection factor depending on the assumed probability of a false alarm. The detection range given by formula (2) is the second most important parameter, which could limit the application of the passive radar sensors for imaging purposes. The longest detection ranges are achievable nowadays with FM-radio illumination, which uses powerful transmitters with a transmitted power typically up to 100kW [4], allowing the detection of targets at distances of several hundred kilometers. Unfortunately, the maximum range resolution for FM illumination is at the level of 1.5km related to a 200kHz bandwidth of a single FM channel. Such a resolution is not acceptable for imaging purposes. A compromising arrangement regarding the range resolution and detection range can be found through using passive radars utilizing DVB-T based illumination, which allows a target to be detected at a distance of up to 100km with arrange resolution of 20m when utilizing a single DVB-T channel of the 7.6MHz bandwidth. Comparison of the detection ranges and achievable resolution has been depicted in Fig. 2.

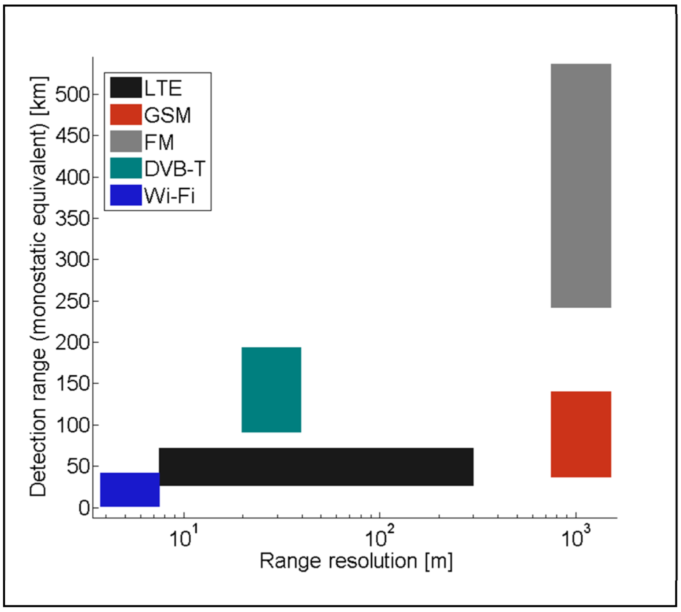

Fig. 2. Detection range versus range resolutions for passive radar utilizing different sources of illumination

For the calculations presented in Fig. 2 G_T= 0 (FM) – 20 (LTE) dB, G_R= 3 (FM) – 20 (LTE) dB,S_0= 1 m^2,T_R= 300ºK, L= 8dB and D_0= 7dB.have been assumed.

The third most important parameter for SAR/ISAR imaging is the cross-range resolution. This parameter depends on several other parameters. In SAR mode the theoretical cross range resolution is limited by antenna size, when a signal from the whole beamwidth is processed coherently. In the case of a shorter integration time the resolution is a product of the antenna aperture length and the ratio of antenna beamwidth to the beamwidth used for integration. As a result a smaller antenna allows for a higher cross-range resolution. Typically, the antenna size used in DVB-T passive radars is several centimeters in size, which gives the highest obtainable cross-range resolution at a level comparable to the resolution of active radars. In ISAR processing the cross-range resolution of the target depends on the wavelength to the aspect angle change ratio. In the case of linear target motion the resolution is the same as in SAR mode, but for maneuvering targets this could be much higher – limited only by the wavelength.

III. Signal Processing for Passive SAR/ISAR Imaging

In this section the signal processing chains for passive SAR and ISAR imaging are presented. Subsection III A describes the first stages of processing, which are almost the same for both passive SAR and ISAR imaging. In subsections III B and III C the ISAR and SAR processing is described, respectively.

A. Pre-Processing for passive SAR/ISAR imaging

The first step of the whole processing is an adaptive cancelation of the direct (reference) signal from the surveillance channel of the passive radar. For this purpose the CLEAN technique is widely used [20]. Additionally, for ISAR processing purposes the ground clutter echo is removed using the same CLEAN algorithm. This step is skipped in SAR processing, where the ground echo is desirable as it has to be used to create a radar image of the observed ground area. After the direct signal and clutter cancelation the cross-ambiguity function given by the formula (1) is calculated. As a result, a two dimensional range-Doppler map is created. Next, the range-migration correction has to be applied to compensate the target movement via different ranges during the integration time [14, 15]. The resulting range-Doppler map is used further for SAR/ISAR processing as described in the next subsections.

B. ISAR processing

For ISAR processing a modified version of the well-known ISAR techniques used in active radars could be used effectively. In practice, two main ISAR processing techniques can be applied on the created range-Doppler map. One technique for the cross-range compression is using the Fast Fourier Transform (FFT) for the short period of integration – the snapshots of the range-Doppler maps for consecutive time stamps are created. This approach is valid for targets which create a Doppler history by their rotation [15-17]. The second ISAR technique is used the matched filter designed to the target Doppler history which is created due to the observed target movement [15, 28-29].

C. SAR processing

Similar as for ISAR processing, the modified version of SAR processing, well-known from active bistatic SAR radars, could be used for airborne passive SAR. Range-Doppler maps resulting from the pre-processing stage are used to create a range (fast time) - slow time raw data matrix. This matrix is equivalent to the range-slow time raw data known from active radars. After this phase a few more steps of signal processing have to be done to obtain a passive SAR image. The first is Doppler centroid estimation and correction. This step allows the removal of relative movement between the airborne radar receiver and the stationary transmitter. The second step is the range cell migration correction algorithm. For unfocussed SAR, low pass filtering in the cross-range dimension can be applied. For a fully focused SAR image the matched filtration in the cross-range has to be applied. Alternatively, the back-projection algorithm (BPA), well-known from active radars, could be applied on the range-slow time raw data matrix. For this purpose, the BPA has to be tuned to the bistatic geometry used in passive SAR imaging.

IV. Results of Passive SAR/ISAR imaging

A. Passive ISAR example

In Fig. 3 the results of passive ISAR imaging of sea targets are shown. In the background of the picture a photo of the scene has been placed. Each ship target in the photo is connected with a corresponding target image. The Doppler shift of each target differs due to different roll motion. Due to the limit of four pages of summary for review process purposes, only one ISAR result, presented in Fig 3., has been shown. In the final paper the authors intend to show additional results from different stages of the passive ISAR processing.

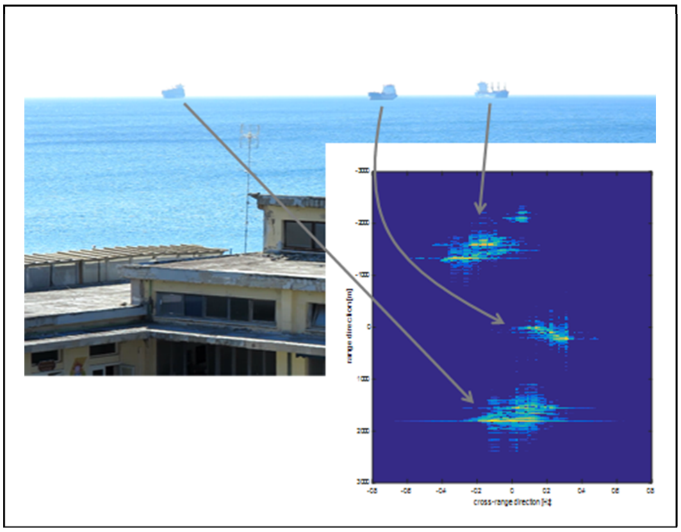

Fig. 3. ISAR image of ships with corresponding photo to the imaged targets.

B. Passive SAR example

Experimental results of an airborne DVB-T based passive SAR imaging are shown in Figs. 4-6. The range cell resolution is 36 meters (for the bistatic geometry, which equals 18 meters in the quasi monostatic case).The ground objects are visible and separated in the Doppler domain, as the Doppler shift of ground echoes are caused by the movement of the airborne radar receiver.

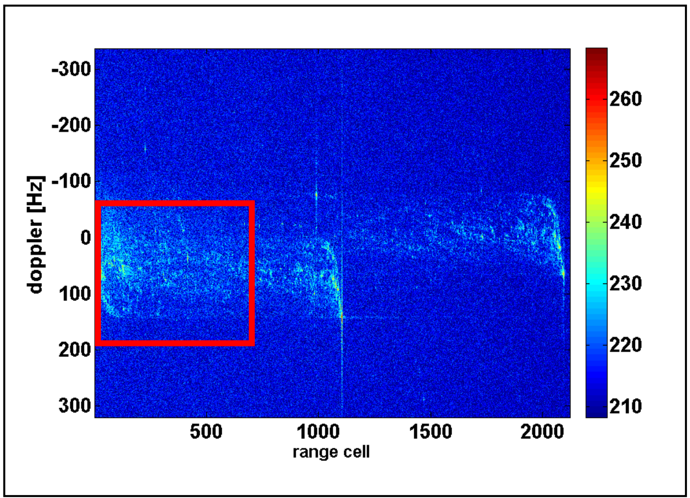

Fig. 4. Range-Doppler map for the imaged SAR area.

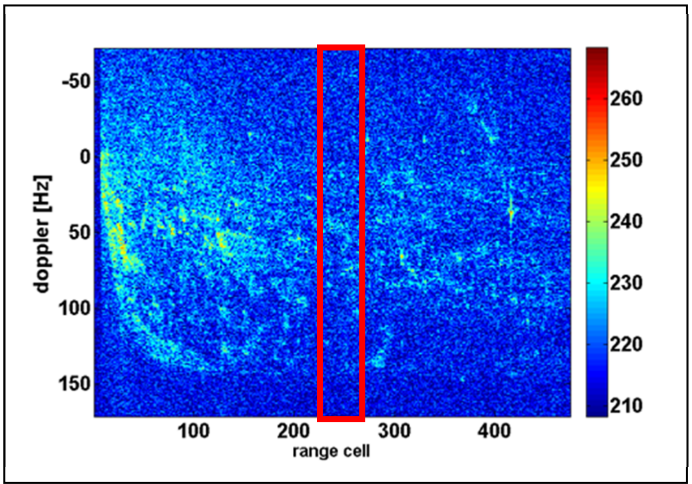

Fig. 5. Range-Doppler (zoomed) map for the imaged SAR area.

What is of greater interest is that at high ranges – around 1100 and 2000 range cells – the Doppler spread becomes very intense. This is due to the fact that the single frequency DVB-T network was used for illumination. At higher ranges echoes originate from the illumination of the second transmitter of the Single Frequency Network (SFN) net.

In Fig. 5 the zoomed area of the range-Doppler matrix is presented (marked with a red rectangle in Fig. 4). During the experiment the airborne platform was moving with a constant speed of around 40 m/s, which gave Doppler frequencies of the ground objects within the range of -200 to +200 Hz. On the range-Doppler maps, presented in Figs. 4 and 5, the stationary ground objects are visible, but since the geometry is bistatic the straightforward relation to the optical image of the ground is very difficult to observe.

After processing the range cell between 250 and 270 (the area marked with a red rectangle in Fig. 5), a passive SAR image was produced. In Figs. 6a and 6b respectively, the passive SAR and Google optical images of the same object are presented. The imaged object was a windfarm. Roadside trees are also visible. The range cell size for both axes is 3 meters in Fig. 6. The size of the passive SAR and corresponding Google optical images is around 300x300 meters.

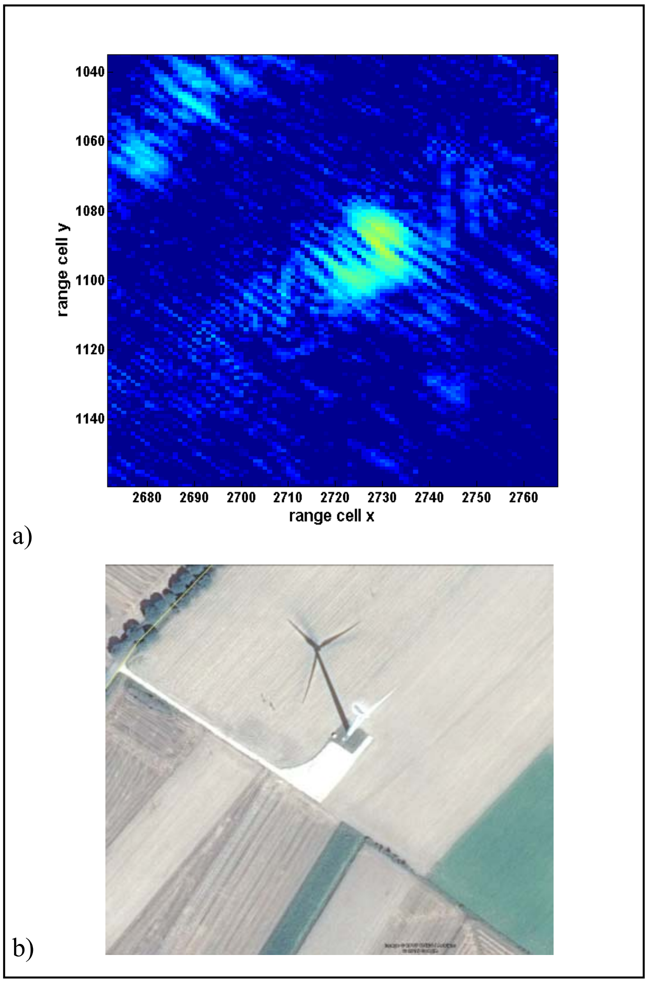

Fig. 6. Image of the windfarm: a) passive SAR image, b) optical image.

V. Future Works

The results of the passive bistatic SAR/ISAR imaging presented in this paper are still characterized by relatively low range resolution in comparison to the one in the modern active radars, where the resolutions of a tens of centimeters are relatively easy achievable these days. In the authors' opinion the next step in developing passive radar imaging technology would be the extension of the possible to obtain range resolution. With this respect the straightforward way is to use the wideband signal transmission for the targets illumination. Unfortunately, the passive radars depend on the available transmitters, and the wideband transmitters with acceptable power are not available in all scenarios. However, in many places the single transmitter used several DVB-T channels at different carrier frequencies, so by using sparse reconstruction technology, higher resolution should be available in the future. Besides the sparse techniques using multi illumination bands, other possible ways to increase the range resolution should be considered. One of such ways is to use multistatic configuration and then, based on the multistatic geometry of the PCL system, increase the information gathered about the targets due to the different illumination angles of the target.

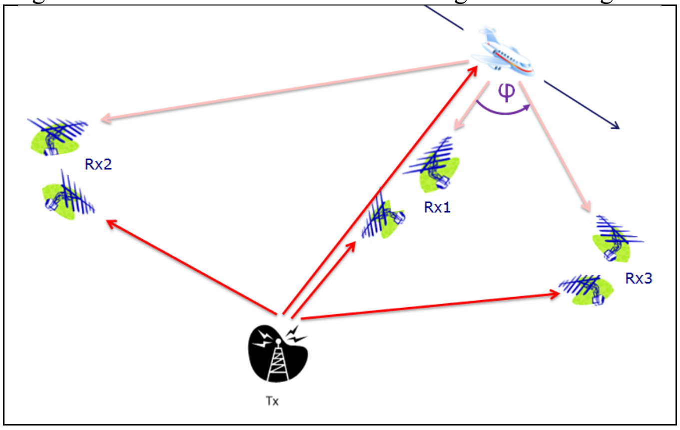

Fig. 7. Simplified multistatic geometry utlizing one Tx and multi Rx.

The preliminary research shows that use of the multistatic geometry allows to increase the resolution of the radar imaging effectively [22, 23]. As the examples the results of the simple simulation of passive ISAR image for the single reflecting point for different bistatic angles φ presented in Fig. 7 have been shown in Figs. 8a), 8b) and 8c). The range resolution for each result separately is poor and it corresponds to the theoretical one for DVB-T which is ca. 18m. However, the non-coherent superposition of these three results give much better resolution (see Fig. 8d). The authors went one step further and tried to obtain the multistatic ISAR image by using also information about phase received at each PCL receiver in the presented multistatic geometry. The final results of coherent ISAR image formation show that possible to obtain resolution in both range and cross-range is much higher than in case of non-coherent way of multistatic image formation. This topic still needs further investigation, and the authors intend to carry on their work in the near future.

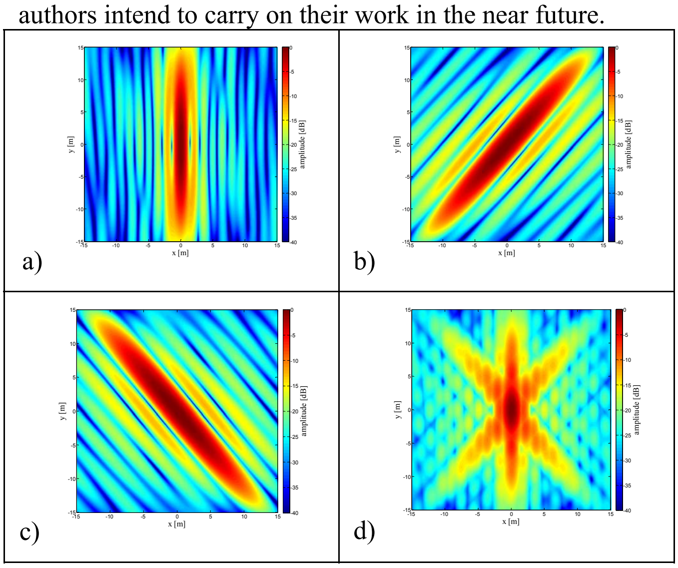

Fig. 8. Results of the simple simulation of passive ISAR image for the single reflecting point for bistatic angle: a) φ = 0˚, b) φ = 45˚ c) φ = -45˚ d) non coherent ISAR image formation based on results presented in Fig. 8 a),b) and c).

The third possible way of increasing the range resolution is the narrow-band Doppler ISAR/SAR image formation [24-26]. This technique seems to be promising, however, at this moment the weak point of this technique relates to target ambiguities caused by the effect of masking weaker targets by the strong ones in the scenes [24-27]. In their further work the authors intend to focus their research also on applications of narrowband Doppler imaging to more complex scenes.

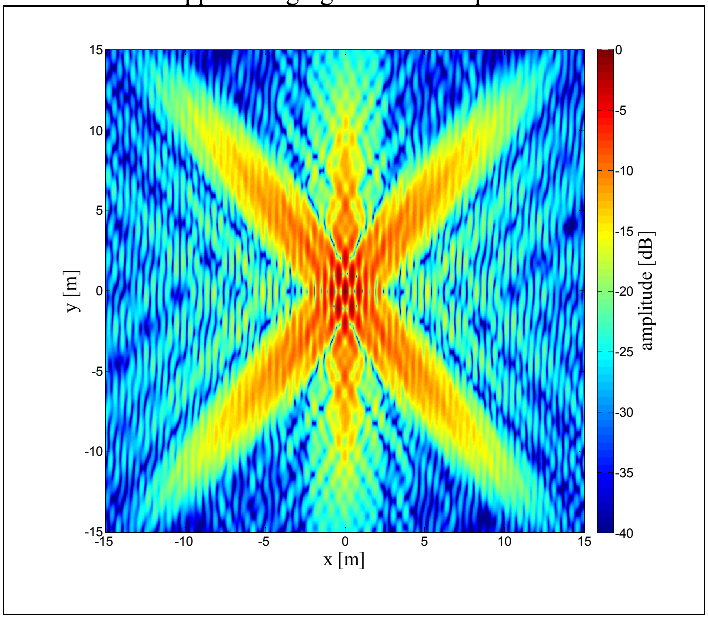

Fig. 9. Coherent ISAR image formation of the single reflecting point target based on results presented in Fig. 8 a),b) and c).

Yet another challenge which has to be faced in the future in airborne passive SAR imaging utilizing ground based transmitters as the illuminators of opportunity is that the illumination angle is low so long shadows could be expected from the single transmitter. Exploiting multiple illuminators could diminish an influence of this difficulty and increase final image resolution. Although further investigation is needed in this area, the authors believe that passive technology is not in competition with the active one, but it will provide additional capabilities and supplementary information about targets in the future.

VI. Conclusions

Passive radar technology is now entering a stage of maturity in surveillance application. The theory of passive radar is now well developed, many demonstrators exist and commercial companies are currently finalizing products both for military and civil markets. Observing the history of active radars one can see that they were first applied for ground based air surveillance. Later, radars were mounted on board ships and airplanes, providing platform protection. The next step was the exploitation of Doppler effects not only for ground clutter removal, but also for Doppler beam sharpening (DBS technique) and synthetic image formation both in SAR and ISAR modes. A similar situation can now be observed in passive radar technology. In 2008 passive radar was installed on an airborne platform and the first in-motion detection was obtained [21]. In 2014 passive radars mounted on an airborne platform were used for SAR image creation, and over the last decade several ground-based ISAR experiments have been carried out. In light of this, a prediction can be made that over the next decade ground based passive radars will be equipped with ISAR modes, and also passive radars will be placed on airborne platforms providing wide area surveillance and imaging.

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