VHF-Band SAR for Detection of Concealed Ground Targets

Dr. Lars M. H. Ulander
FOI - Swedish Defence Research Agency
Department of Radar Systems
P.O. Box 1165
SE-581 11 Linköping
Sweden

E-mail: ulander@foi.se

SUMMARY

Airborne synthetic aperture radar (SAR) operating in the VHF band and used in conjunction with change detection has shown promising results for wide-area surveillance of ground targets. By using VHF-band frequencies, both targets in the open as well as concealed by foliage may be detected in a robust manner. VHF-band SAR is able to detect hidden targets because both foliage attenuation and clutter backscatter is small. The clutter is further suppressed through the use of change detection, thus significantly reducing the false alarms. VHF-band SAR is suitable for change detection since temporal decorrelation is small.

An extensive data base of VHF-band SAR and target data was collected during the summer of 2002. The primary goal of this collection was to evaluate VHF-band SAR change detection performance under various operating conditions. In general, the results show that a VHF-band SAR employing change detection can reliably detect truck-sized targets hidden in foliage. However, the detection performance deteriorates under certain operating conditions, e.g. for near-grazing angles.

1.0 INTRODUCTION

Advances in sensor and information technology over the past decade will significantly improve future intelligence, surveillance and reconnaissance (ISR) systems. In particular, performance will be greatly enhanced by utilising a wider portion of the electromagnetic spectrum. One of the main reasons for the expected performance improvement is that it becomes increasingly difficult to enable counter-measures (low signatures, jamming, etc) over a very wide bandwidth. Furthermore, future systems will be more adaptable to different conditions in the battlespace. Because of the difficulties in realising such wide-band systems, however, it will often be beneficial to distribute the capabilities among several platforms while sensor data are processed and communicated to the user.

Future network-centric capabilities include a common ground picture with updated target and terrain information. The generation of a wide-area situation picture is a difficult problem because of the large number of targets involved and the variability found in both targets and background. The ground situation also provides a lot of opportunities for hiding, camouflage and deception. With this in mind, it is clear that a single sensor technology will not provide the desired ground picture since each sensor only solves part of the problem. The only viable solution to the common ground picture is therefore a “system-of-systems”.

ISR systems at large stand-off distances operate in the radio- or microwave bands due to their capability of penetrating clouds, fog, rain etc. Active and passive sensor technologies, i.e. radar and electronic support measures (ESM), complement each other. The latter are effective against emitting targets, but suffer from poor angular resolution and the prerequisite that a target must emit electromagnetic energy. Radar

Paper presented at the RTO SCI Symposium on “Sensors and Sensor Denial by Camouflage, Concealment and Deception”, held in Brussels, Belgium, 19-20 April 2004, and published in RTO-MP-SCI-145.

systems, on the other hand, are effective also against targets without self-emission. The geometrical resolution and sensitivity of radars are significantly improved using advanced signal processing techniques. Examples of the latter are synthetic-aperture radar (SAR) and ground moving target indication (GMTI) which enables both stationary and moving targets to be detected, positioned and classified at large stand-off distances.

There is currently a significant effort to develop new technologies for the difficult case of detecting low-signature and concealed ground targets. Foliage is an effective means of concealment available to military forces. Recent conflicts have demonstrated the shortcomings of current ISR systems in this respect. Camouflage and stealth techniques are also effective in reducing target-to-background signatures.

One of the most promising technologies for wide-area surveillance of low-signature and concealed ground targets is airborne SAR operating in the UHF and VHF bands. FOI - the Swedish Defence Research Agency – has performed research and development in this area since the mid-80´s. The work has resulted in two airborne demonstrator systems, CARABAS-I [1] and CARABAS-II [2], operating in the 20-90 MHz band. LORA (low-frequency radar) [3] is a new demonstrator system which succeeds CARABAS, extends the frequency band up to 800 MHz and also includes a GMTI capability. In this paper, we will review this work with an emphasis on recent results from the CARABAS-II system. We show comparisons between VHF-band and microwave SAR data, as well as detection performance curves for different operating conditions.

2.0 PHENOMENOLOGY

Detection performance of a radar system is directly related to the target-to-background backscattering statistics evaluated for the specific operating conditions. In general, radar backscattering is a complicated function of target geometry and its electromagnetic properties. Backscattering from the target background also contributes and competes with the target backscattering in the radar resolution cell. The coherent combination of target and background backscattering results in a statistical variability which reduces detection performance.

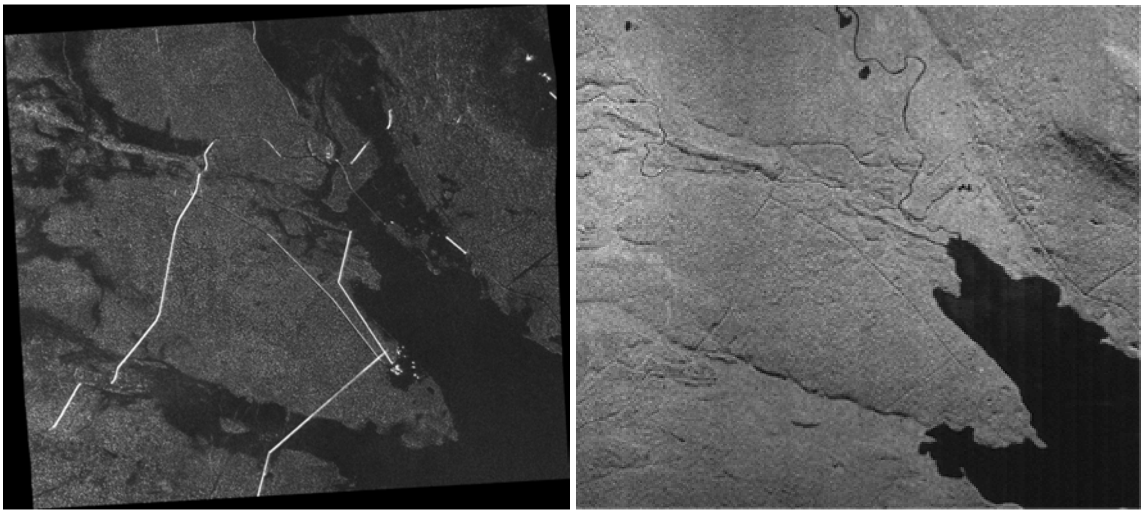
For SAR systems operating in the UHF and VHF bands, backscatter phenomenology is quite different from microwave frequencies. Target sizes are often in the resonance region, i.e. of wavelength size, and the angular variation of the backscattering is much smaller than at microwave frequencies. Another important effect is the interaction between the target and the ground surface, i.e. the coherent combination of the direct and ground-reflected backscattered waves. This effect reduces target backscattering for lower frequencies since the direct and reflected waves tend to cancel each other. The effect becomes more pronounced for grazing angles and for small target heights above the ground compared to the wavelength.

For targets concealed in foliage, both attenuation and backscattering from foliage need to be considered. A number of experiments have been performed in order investigate the optimum choice of frequency band [1,4-7] The main conclusion is that foliage becomes increasingly transparent below 1 GHz, and below 100 MHz the two-way attenuation is most often less than 3 dB. In terms of the foliage backscatter, it is only below 100 MHz that backscattering decreases when the tree stems enter the Rayleigh scattering regime. However, even below 100 MHz it still significantly affects detection performance.

The main mechanism for foliage backscatter below 100 MHz is direct and ground-reflected backscattering from tree stems [8]. Branches as well as leafs and needles have a secondary effect due to their smaller size. Typically, stems have a diameter of up to about half a meter which implies that their backscattering drops significantly when the radar wavelength is larger than about five meters. This mechanism suggests that the optimum radar wavelength for detection of a vehicle-sized target under foliage is in the lower VHF-band.

3.0 VHF-BAND VS. MICROWAVE SAR

In this section, we give a few examples to illustrate the complementary nature of VHF-band and microwave SAR images. The image examples were acquired in the summer of 2002 [3,9]. The Vidsel'02 experiment was conducted in northern Sweden within NEAT (North European Aerospace Test range [10]) which consists of the Esrange rocket and Vidsel missile test ranges as well as a temporary air space corridor in-between. The main objective of the experiment was to perform a UAV (unmanned aerial vehicle) flight demonstration but sensor tests were also included. Example VHF-band and K_u-band SAR images from the area are shown in Figure 1. Note the rather large differences in image content due to the different wavelengths used. Lakes are dark in both images whereas open terrain and forests are brighter in the K_u-band image. Furthermore, man-made objects like power lines and houses are more clearly delineated in the VHF-band SAR image.



(a) (b)

Figure 1: SAR images from Vidsel'02. (a) CARABAS-II (20-86 MHz). Note the large contrast between forested areas (bright), open terrain (dark) and lakes (dark). The bright linear features are power/telephone lines. (b) K_u-band UAV SAR image.

Figures 2-4 show SAR images over target deployments on an open grass field in the upper-right part of the images. The targets are poorly visible in the K_u-band SAR image with 3-m resolution in Figure 2. The target-to-background ratio is significantly better in the VHF-band CARABAS image in Figure 3 due to a significantly lower background backscattering level. Figure 4 shows a K_u-band SAR image with 0.5-m resolution where the target deployment is visible on the grass field as well as buildings, two radar reflectors and a road. The high-resolution K_u-band SAR image is more useful for detection and recognition purposes but the drawback of the finer resolution is a reduced area coverage rate.

Figure 5 shows VHF- and K_u-band SAR images collected over a forested area during Vidsel'02. A road runs diagonally across the images and a lake is visible to the right. A power line stretches along the road which appears as a bright feature in the VHF-band image. A large number of targets were deployed in the forest at the time of both image acquisitions. Twenty-five targets were deployed inside the forest during the CARABAS-II data acquisition. All targets are visible in the VHF-band SAR image. Twelve targets were deployed along the road during the K_u-band acquisition, but none are visible in the resulting K_u-band SAR image.

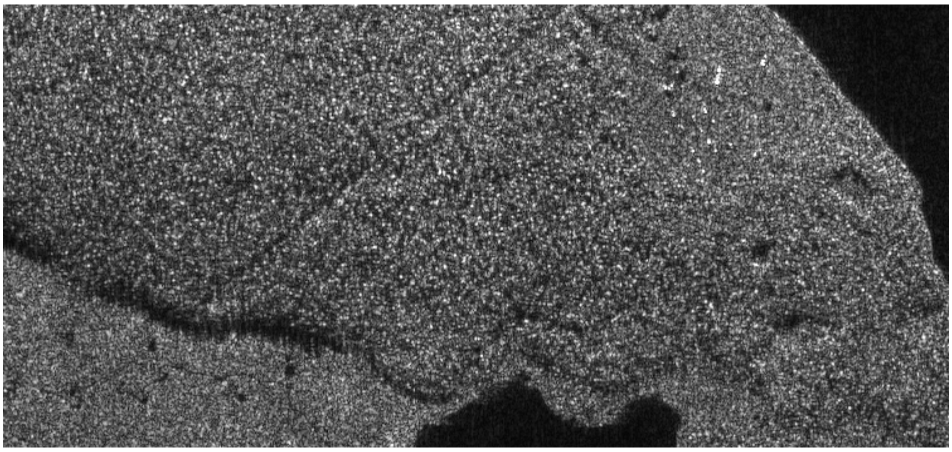


Figure 2: K_u-band SAR image (3-m resolution). 10 vehicles are deployed in the open field which also contains a few buildings located as well as two radar reflectors (2 brightest points).

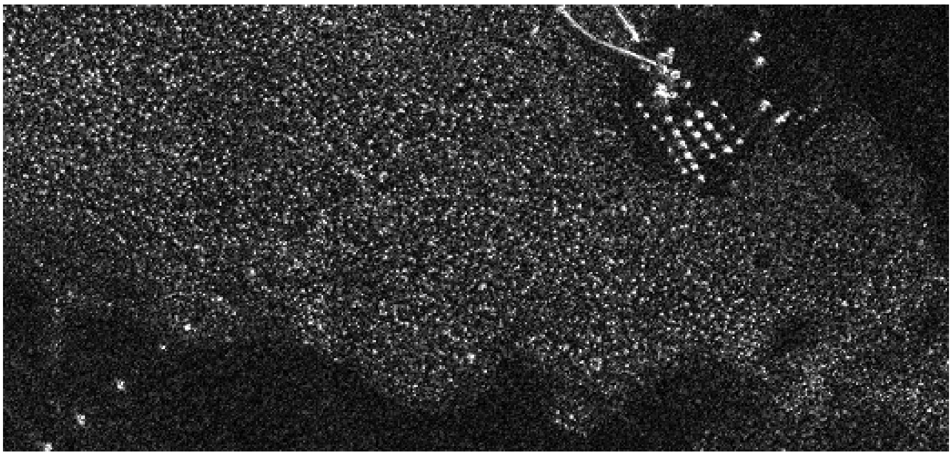


Figure 3: CARABAS-II (20-86 MHz) SAR image (2.5-m resolution). 25 vehicles of different sizes and orientations as well as a few buildings are clearly visible in the open field.

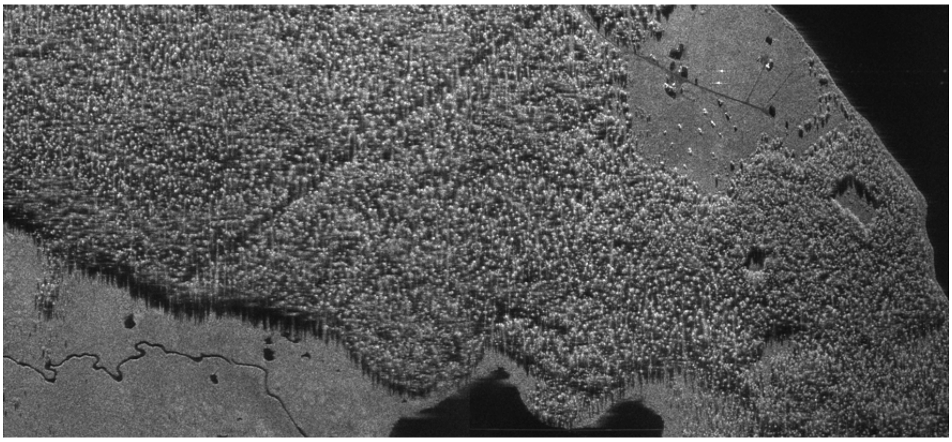
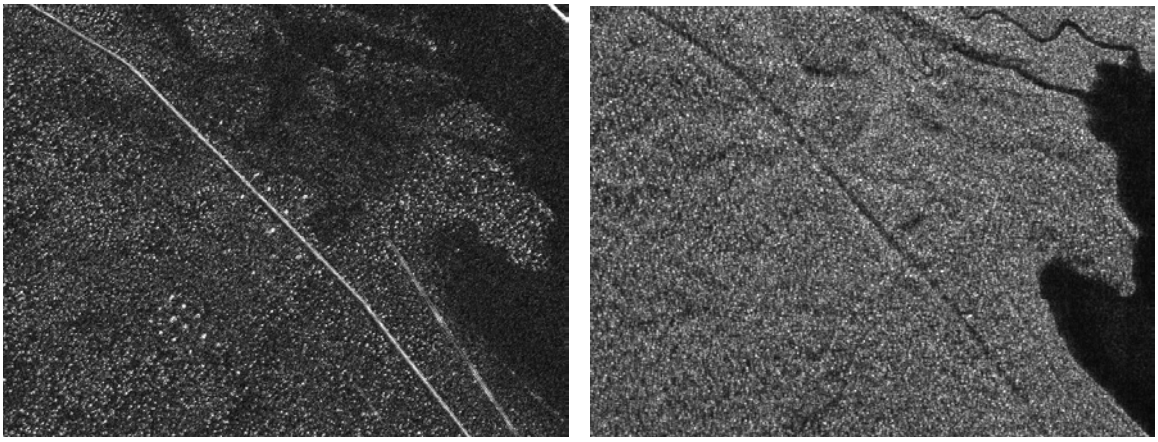


Figure 4: K_u-band SAR image (0.5-m resolution). 10 vehicles, two radar reflectors, some buildings and a road are delineated in the open field.

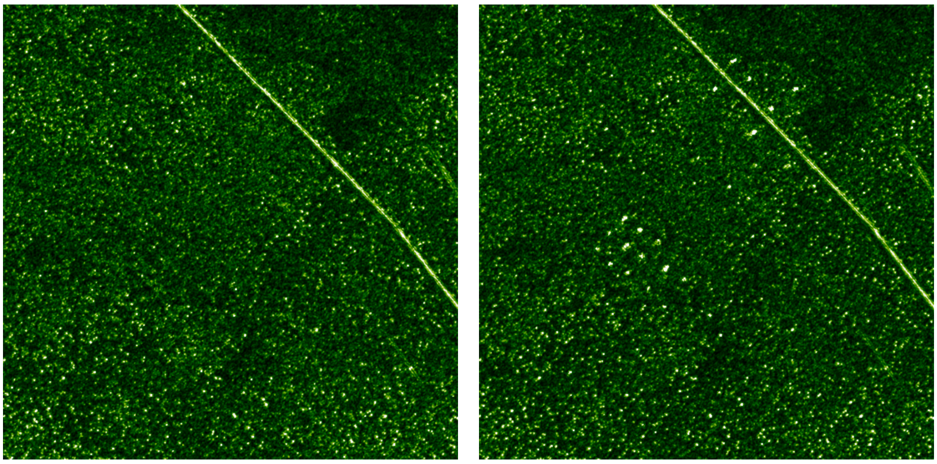


(a) (b)

Figure 5: SAR images of targets deployed in a forest during Vidsel'02. (a) CARABAS-II (20-86 MHz) SAR image with 2.5-m resolution. The bright linear feature running diagonally across the image is a power line along the road. Note the targets visible along the road and deeper inside the forest. (b) K_u-band SAR image covering the same area with 3-m resolution. Targets in the forest were deployed but are not visible in the image.

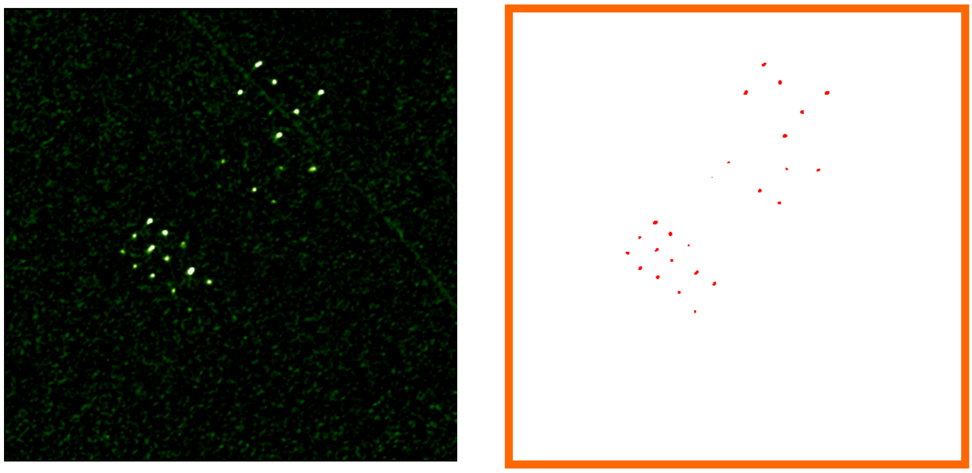
4.0 CHANGE DETECTION

Targets concealed in foliage are most often visible in CARABAS-II SAR images but the backscattering from tree stems cause false alarms. The false alarm rate may, however, be significantly reduced by applying change detection [11]. The latter relies on collecting images at several occasions and detects targets using classification methods. An example of an image pair used to detect movements of targets concealed in foliage during Vidsel´02 is shown in Figure 6. The corresponding change image is shown in Figure 7 together with the result after applying a CFAR (constant-false-alarm-rate) detector.



(a) (b)

Figure 6: Example of a CARABAS-II SAR change detection image pair: (a) Reference image from 3 June with no targets; (b) Surveillance image from 7 June with 25 concealed targets.



(a) (b)

Figure 7: CARABAS-II SAR change detection result from the image pair in Figure 6. (a) Change image based on linear Bayesian classification; (b) After CFAR detection.

5.0 EVALUATION OF DETECTION PERFORMANCE

Data collected during Vidsel´02 have been used to evaluate the change detection (CD) performance of CARABAS-II [12-14]. The primary measures of performance used in analyzing a target detection system are probability of detection (P_d) and false-alarm rate (FAR). Both of these measures are a function of the threshold used in the CFAR detector. These two measures can be combined in one graph known as a receiver operating characteristic (ROC) curve which shows P_d as a function of FAR.

5.1 Target deployments

A Swedish military garrison provided twenty-five vehicles to form target deployments during the experiment period. Three different target sizes were provided and categorized as small, medium, and large. Table 1 provides a summary of each target type. One ROC curve can be generated using all the data collected at RFN Vidsel. However, this would fail to provide insight into system performance. For a more thorough understanding of the data and the CD performance of the CARABAS-II system, several ROC curves were generated, each giving the P_d vs. FAR for a specific set of operating conditions (OCs).

Table 1: Overview of the target types used during the Vidsel data collection.

Name	L (m)	W (m)	H (m)	Role	# Used
TGB11	4.4	1.9	2.2	Personnel transport	10
TGB30	6.8	2.5	2.9	Equipment transport	8
TGB40	7.8	2.5	2.9	Equipment transport	7

The difference in dimensions between the medium and large class is not substantial. The TGB40 has the same basic design as TGB30 but is extended in length to 7.8 m and equipped with an additional rear axle. Photos of the three terrain vehicle models concealed in foliage are found in Figure 8.

(a) (b) (c)

Figure 8: Terrain vehicles (a) TGB11, (b) TGB30, (c) TGB40.

The Vidsel area was surveyed prior to the campaign for suitable target deployment locations. The primary criterion was to locate densely forested areas. A secondary criterion was that the areas must be adjacent to a road in order to facilitate relocating targets. A region on the northwest side of a fresh water lake (Naustajaure) was chosen as the site for target deployment. Inside this region, two mature forest parcels, located on predominantly level ground, were utilized for various configurations of targets concealed in foliage. Six different concealed target deployments were used during the field campaign. The twenty-five targets had different locations and orientations in each of the six different deployments.

5.1 Experimental Process

Multiple passes occurred during each of the 16 flight missions, resulting in a total of 150 image passes. The altitude of the aircraft varied to collect incidence angles of 58°, 63°, 68°, 72°, and 75°. The length of each flight path was typically 37 km. This was done to ensure sufficient variation of aspect angle to form images within a ground segment of approximately 10 km by 10 km, centered on the aim point. Some imaging passes were redundant measurements in that they contained the same flight geometry and target deployments. This was deliberately done in order to investigate temporal scene stability.

Once the data was collected, SAR imagery (approximately, 5 km x 5 km in size) was formed using a fast back-projection image formation process [15]. In parallel, multiple experiments were designed, each intended to examine performance as a function of one or more OCs listed in Table 2. Once the image formation and experimental design phases were completed, a data characterization, understanding, and mining phase took place to ensure the best use of the data during the CD experiments. The output of this process was a listing of applicable image pairs to be used in each CD experiment. Then, for each experiment, the appropriate image pairs were processed through the CD chain.

Table 2: The operating conditions over which the Vidsel 2002 data were analyzed.

Operating Condition	Types of Measurements
Target orientation	Non-broadside and broadside orientations
Target size	Small, medium, and large targets
Heading change	Change in heading between in a change image pair: 0° or 5°
Radio frequency interference (RFI)	Low or high
Radar bandwidth	High: 30-80 MHz, Medium: 28-65 MHz, Low: 27-50 MHz
Radar incidence angle	58°, 63°, 68°, 72°, 75°
Terrain variation	Flat or hilly

Details on the CD processing chain can be found in [11] and [12]. The input to the CD process is two SAR images filtered to the desired bandwidth. Geo-coding is first performed, resulting in each pixel-pair corresponding to the same geographic location. A matching step then occurs to refine the geo-coding and ensure the two images do coincide. Third, a change image is formed through an optimum linear combination of the two images, as opposed to simple, non-coherent subtraction. Next, candidate target pixels are detected in the change image using a CFAR filter. Dilation and erosion techniques are then used to remove pixel clusters too small to be a target and form point detections. Finally a list of candidate target detections and their locations for various CFAR thresholds is generated.

The CD processing chain was not tuned for any specific OC. The system parameters were held constant for all experiments ran. The purpose of this study was not to determine the effect of the processing chain on performance, but rather to determine the effect of the OCs listed in Table 2. Significant performance increases are expected through either tuning the CD chain for each experiment or using a more sophisticated processing chain.

5.2 Example results

This section presents example results found from the CD performance study. We show results from two performance studies which analyze the effect of target size, radar bandwidth and incidence angle. The full set of results can be found in [12].

The first study examines the effect of target size and bandwidth on performance. Only two bandwidths are considered, small (27-50 MHz) and high (30-80 MHz). All target sizes and orientations are considered. However, only flights with headings which give a low RFI environment are used. Restricting data to only the low RFI case is expected to result in optimistic results when compared to overall system performance. Figure 9 shows the ROC curves associated with study one.

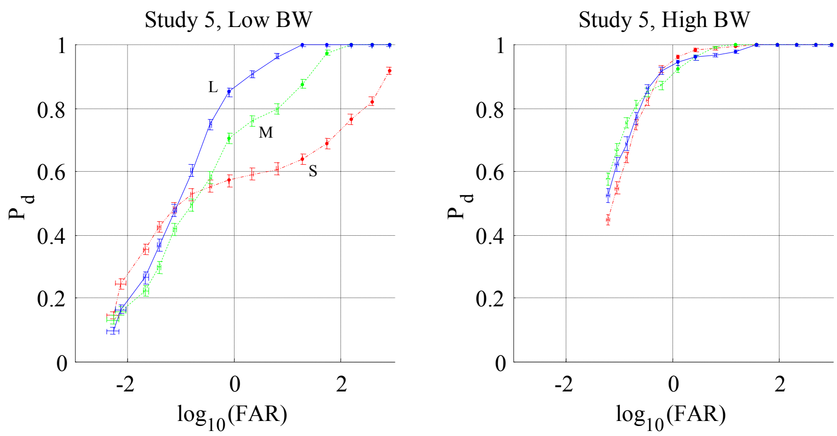


Figure 9: ROC curves for study one. Left: Low bandwidth (27-50 MHz); Right: High bandwidth (30-80 MHz). Legend: small (dash dot), medium (dash), and large (solid) targets. 23 image pairs were analyzed, including 460 small, 368 medium, and 322 large targets. FAR is in km^{-2}.

The following observations can be made from Figure 9:

- Target size has a noticeable impact at lower bandwidths but little impact at higher bandwidths.
- There is a significant but not excessive decrease in performance going from the high to the low bandwidth case for the large target class.

Figure 10 shows the results of study two, whose purpose was to isolate and examine the effect of incidence angle on CD performance. Specifically, incidence angles of 58°, 63°, 68°, 72°, and 75° are studied. There was no restriction placed on target size, orientation, or RFI environment. Thus this study is expected to provide an unbiased (neither optimistic nor pessimistic) view of the general performance across the data.

For all bandwidths, the performance decreases as the incidence angle increases. The reason for the performance degradation is the result of low-frequency scattering physics of targets standing on smooth ground. The incident field on the target is significantly reduced by interference from the ground-reflected wave. This effect becomes strong as the incidence angle increases above a critical angle defined by the target height [3].

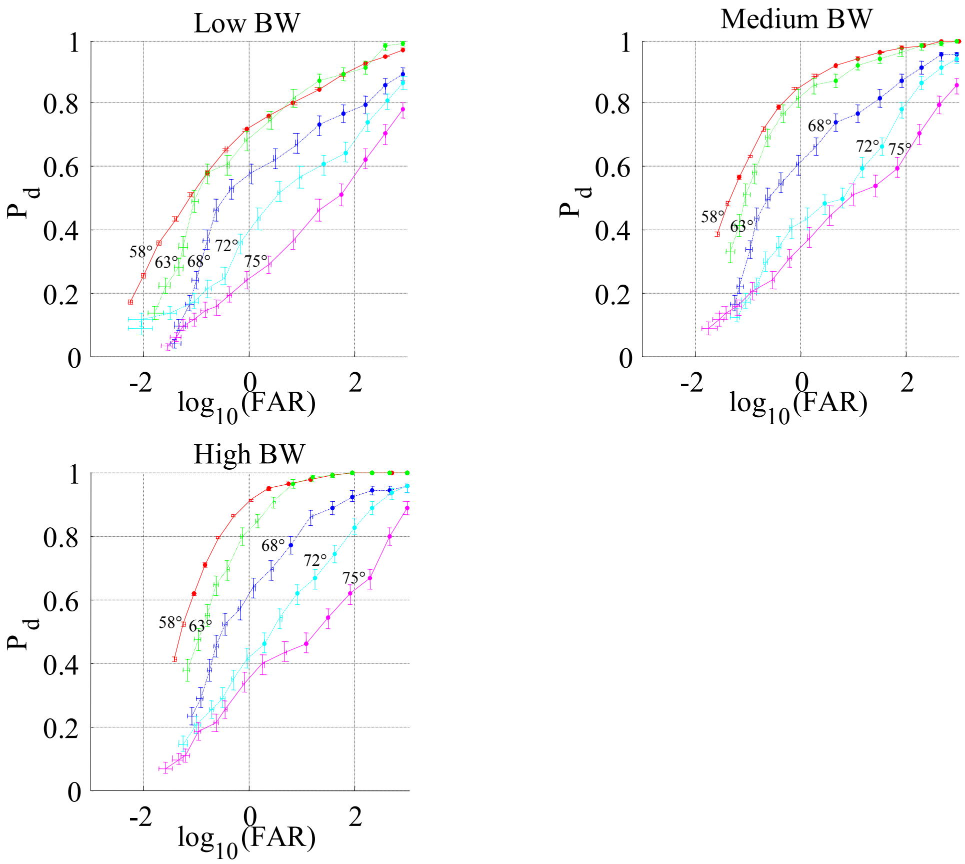


Figure 10: ROC curves for study two showing performance as a function of incidence angle for various bandwidths. The 58°, 63°, 68°, 72°and 75° incidence angle results were generated using 68, 4, 4, 4, and 4 image pairs, respectively. There were only 200 targets available for the 75°, 72°, 68° and 63° cases whereas the 58° case had 3400 target available. FAR is given in km^{-2}.

6.0 CONCLUSIONS

The paper has discussed the unique capability of VHF-band SAR for providing wide-area surveillance for the common ground picture. In particular, VHF-band SAR provides a robust means for detecting truck-sized targets concealed in foliage. The reason for the latter is that foliage attenuation and backscatter is reduced compared to higher radar frequencies which facilitates target detection performance. The target-to-background ratio is also found to be higher for targets deployed in the open, although the limited resolution inhibits target recognition capability.

Change detection is applied to VHF-band SAR images and significantly improves target detection performance. An extensive performance analysis has been performed based on data collected during the summer of 2002. In general, it is noted that a VHF-band SAR change detection system provides a useful and robust capability for detecting truck-sized targets hidden in foliage. The trends seen in the results were as predicted by the physics of VHF-band SAR and the principles of change detection. For example, performance increased as bandwidth increased. Likewise, as incidence angle increased, performance decreased.

While these empirical results provide insight into VHF-band SAR change detection performance, it is impossible for empirical results to predict how a system will perform under all conceivable operating conditions. However, this study provides performance as a function of some of the more important operating conditions used during system development and mission planning.

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