The use of CLEAN processing for passive SAR image creation

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***Abstract*— The paper presents the concept of the use of CLEAN processing for strong direct signal removal in passive SAR systems. The CLEAN algorithm proposed has been successfully verified during several measurement campaigns. During the trials the passive SAR receiver was placed at ground level, and different SAR satellites (e.g. EnviSAT, TerraSAR-X) were used as illuminators of opportunity. Almost all SAR radars use the chirp sounding signal, and the presence of a direct signal in the reference channel limits the quality of the image. The removal of the strong direct signal leads to improvement of the image at a short distance from the receiver, which is the case considered in this paper.**

I. Introduction

Synthetic Aperture Radar (SAR) is a well-known technique which is widely used in remote sensing applications. Due to its day and night operation capability in all weather conditions, this technique has established a strong position as a sensor for Earth monitoring. Nowadays, SAR technology using the monostatic configuration has reached a stage of maturity, both in civilian and military application.

Recently, researchers have turned their attention to the new technology of passive SAR imaging, where the additional features of bistatic geometry can be utilized [1-9]. The radar cross-section (RCS) of the targets strongly depends on the system geometry (RCS is different in mono- and bistatic scenarios). Due to this fact, the comparison of the passive and active SAR images gathered for the same area of interest can provide more details with new information about the targets. Such information is very useful in the wider understanding of remote sensing systems.

Moreover, the passive SAR systems can be categorized as silent sensors, whose position is unknown to the potential countermeasure sensor. This feature is very desirable, especially for military users.

The passive SAR system can be operated in different configurations. One of the configurations uses a passive receiver mounted on board of a moving platform, which utilizes stationary illuminators of opportunity. Opposite mode can also be distinguished, where the illuminator is placed on a moving platform (e.g. aircraft, satellite, etc.) and the passive SAR receiver is a stationary system. In the third configuration, both the receiver and the transmitter are moving. In general, the Doppler effect between the receiver and transmitter is required to obtain the synthetic aperture in the cross-range direction (azimuth compression). In this paper, the result of the passive SAR image creation for the stationary ground based receiver and spaceborne illuminator of opportunity is presented. In such configuration the passive SAR receiver usually has two channels: one is dedicated to the reception of the reference (illuminating) signal and the second is dedicated to the reception of the echo signal [12, 13]. The geometry of the system is presented in Fig. 1b. It is also possible to obtain a passive SAR image using a single channel receiver [10, 11], which is depicted in Fig. 1a. In such case the forward scattering mechanism is exploited, which increases the effective cross-section of the observed scene, but decreases the ground range resolution [2, 11, 12].

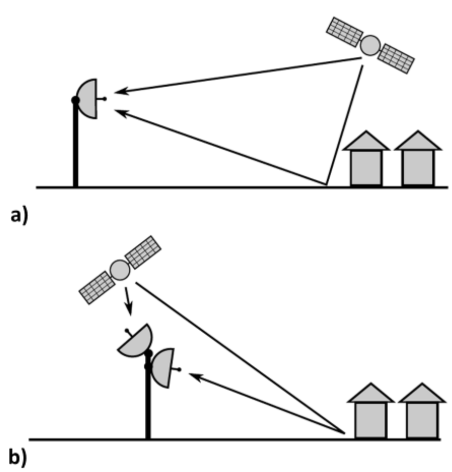

Figure 1. Passive SAR geometry: a) single channel forward case, b) dual channel backward case.

In a monostatic space-borne configuration there is time separation between the transmission of the illuminating signal and the reception of the echo signal. Moreover, the distance ratio between the beginning and the end of the scene is small, therefore the required dynamic range of the receiver is moderate. For a passive bistatic configuration there is no time separation between the illumination signal and the received echoes. The shortest distance to the scene is equal to the height of the mast on which the antenna system is mounted, whereas the longest distance is limited by the line of sight. In such bistatic passive geometry, the ratio between the shortest and longest distances can be in the order of 1000 (30 dB) and thus the strongest echo to the weakest echo power ratio can be in the order of 10^6 (60 dB). Additionally, the measurement antenna can receive a direct (illuminating) signal which is much stronger than the echo signal. To assure the required dynamic range it is necessary to use a receiver with high dynamic range. To create a good quality image it is also necessary to remove the direct signal from the received echo signals, and to perform additional cleaning of the echo signal so as to remove the strongest components.

The proposed solution for image enhancement is to use the CLEAN type algorithms based on the modeling of unwanted signal components and extracting the modeled signal from the received one. The CLEAN methods have been developed primary for radioastronomy [14-16] for imaging of weak radio sources in the presence of strong emitters nearby. Recently the CLEAN methods have been widely used in radar signal processing [17-23] for dynamic range enhancement.

II. CLEAN PROCESSING

Let us consider an SAR radar using chirp signals of length t_i and the bandwidth of f_p. After the compression filter the pulse length is $t_p \approx 1/f_p$, and the slant range resolution is $r_p \approx c/2f_p$. The side effect of compression is the presence of time sidelobes existing in the time interval $(-t_i, t_i)$ around the main peak. The maximum sidelobe level for the constant amplitude chirp signal and the use of the matched filter is equal to -13 dB. Using a tapering window it is possible to reduce the sidelobes to the level of -30, -40 dB depending on the time-bandwidth product of the transmitted signal. It is also possible to design dedicated unmatched filters with longer pulse response than t_p and lower sidelobes level, but at the cost of significant broadening of the mainlobe (usually over 2 times) and the decrease of S/N level after compression (usually more than 3 dB).

The matched filter concept is optimal in radar signal processing only in the case of a single target presence in the receive signal. In the case presented, the received signal consists of a strong direct component, some strong near-by echoes and weak echoes of far away objects. In such a complicated case, to obtain a good result more sophisticated methods than simple matched filtering should be used.

One possible solution is to form the linear equation set by creating the grid of reflection points, and solve the equation set taking into account that the reflection points' positions are known (grid points) and the complex reflection coefficients are unknown. Such an approach leads to high computational complexity and is not usually acceptable in practice. The alternative to the direct equation solving method is to use the CLEAN concept. Using the matched filter, it is possible to detect peaks which have originated from the strongest components such as the direct signal and closest ground reflections. Based on the knowledge of the illuminating signal it is possible to create a model of the strongest signal components. Knowing the modeled signals, it is possible to "clean" the received signal from the dominant components by simply subtracting from the received signal the modeled signal which originated from the strongest components. The application of CLEAN for SAR image enhancement has already been presented by the authors in [23] but in that particular work the problem was limited to dominant scatterers removal in active monostatic SAR.

The CLEAN algorithm for the passive bistatic SAR can be described in the following steps: after the range compression the position of the peaks, which have originated from the strongest component such as the direct signal, is detected. Based on the knowledge of the illuminating signal, a model of the strongest signal components (direct signal) $s_M(t)$ is created as:

$$s_M(t) = rect(t/t_p) \cdot \exp(j\hat{\phi}_P(t)), \tag{1}$$

where $\hat{\phi}_P$ is the estimated phase function of the unknown P-th order polynomial:

$$\hat{\phi}_P(t) = \sum_{k=0}^{P} \hat{a}_k t^k, \tag{2}$$

with estimated coefficients $\hat{a}_k$ that can be determined using time-frequency analysis of the signal [24, 25] or algorithms based on the matched filter principals, e.g. Extended Generalized Chirp Transform [26]. In the next step, the model of the range compressed signal $y_M(t)$ is created at the output of the matched filter. In practice the received signals are sampled. Due to this fact, in further analysis the continuous time t will be replaced by n, which denotes the sample number for the signal representation in the discrete-time domain. The final stage of the CLEAN processing is the direct signal subtraction from the surveillance channel, which can be done by:

$$y_C(k,n) = y_S(k,n) - C_R \cdot y_M(k,n) \tag{3}$$

where k is the pulse number, $y_C(k,n)$ is a "cleaned" signal in the surveillance channel, $y_S(k,n)$ is the range compressed signal in the surveillance channel, and C_R is the weight coefficient determined as:

$$C_R = \frac{\sum_{k=1}^{N} y_R^*(k,n_{\max}) \cdot y_S(k,n_{\max})}{\sum_{k=1}^{N} y_R^*(k,n_{\max}) \cdot y_R(k,n_{\max})}, \tag{4}$$

where $*$ denotes conjunction, $y_R(k,n)$ is the range compressed signal in the reference channel, N is the number of processed pulses and $n_{\max}$ is the sample number, where the signal after matched filtering reaches the maximum value.

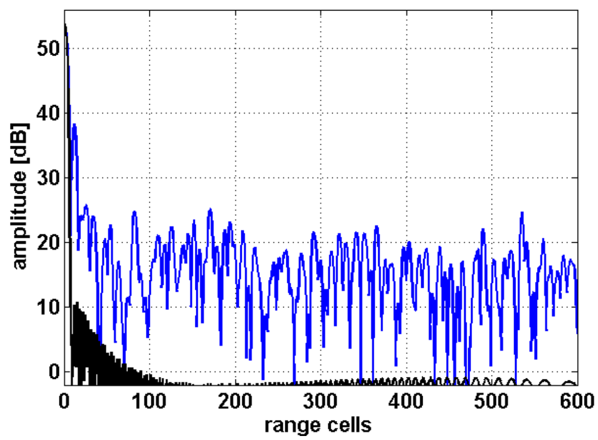

Figure 2. The range compressed signal $y_S(n)$ (blue line) versus the modeled signal $y_M(k,n)$ (black line)

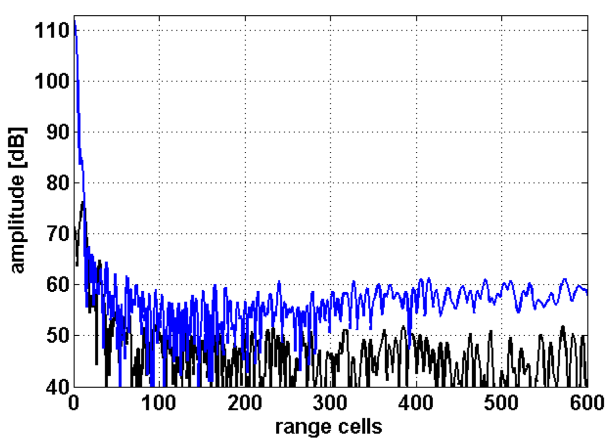

Figure 3. The range profiles of signal $y_S(n)$ after range and cross-range compression (blue line) versus the range profiles of "cleaned" signal $y_C(n)$ after range and cross-range compression (black line).

As an example the range compressed signal $y_S(k,n)$ for the one particular pulse k has been shown in Fig. 2, versus the modeled signal $y_M(k,n)$ used for CLEAN processing.

The result of the CLEAN processing after both cross-range and range compression for one particular pulse k are presented in Fig. 3. This result was obtained for the passive SAR image presented in Fig. 7 (range profiles for zero meter cross-range) and discussed in detail in the next section of this paper.

III. Results

The CLEAN algorithm proposed in the paper has been verified during several measurement campaigns, where the C-band Advanced Synthetic Aperture Radar (ASAR) mounted on the EnviSAT satellite and the X-band SAR radar mounted on the TerraSAR-X satellite were used as transmitters of opportunity. To collect the data from the C-band ASAR instrument, two independently developed passive radar receivers were used.

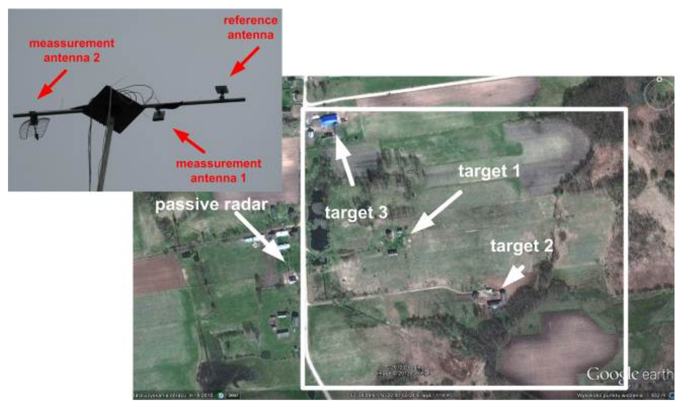

Figure 4. Measurement scenario of the experiment carried out in northern Poland

One of the two C-band receiver demonstrators for the ASAR instrument was constructed at the Warsaw University of Technology (WUT) [12]. In the system a wideband patch antenna with a gain of 9 dBi was used to collect the reference signal, whereas the imaging area was observed with two antennas - another patch antenna and a directional grid antenna with 22 dBi of gain. The measurement antennas were set so that they had different polarizations. The receive channel consisted of bandpass filters and doubled or tripled low-noise amplifiers that provided approximately 30 and 45 dB of gain. A three-channel NI PXIe-5667 RF Signal Analyzer (RFSA) was used as the receiver [12]. With the hard drive matrices it allowed real-time waveform streaming and coherent acquisition on all three channels with the bandwidth of 50 MHz. Although the signal bandwidth of the EnviSAT ASAR was only (16 MHz), some precautions were needed as the satellite was a completely non-cooperative illuminator and the authors did not have exact information on the instrument working mode (most importantly, the carrier frequency). The measurement campaign using this receiver was carried out in the Biebrza river valley in northern Poland in July 2011 [12]. Its aim was to capture both the direct illumination from the satellite as well as the echo signal backscattered from the observed area. Since the experiment was performed in a farmland area, the antennas were mounted on a deployable, 12 meter high mast. Additionally, to ensure safe operation conditions for the equipment it was set up in a camping trailer on the measurement site. The simplified view on the measurement scenario has been shown in Fig. 4. Fig. 5 represents the SAR images obtained of the area presented in Fig. 4. Fig. 5b shows the final results of applying the proposed CLEAN processing. The direct signal has been successfully removed from the passive SAR image.

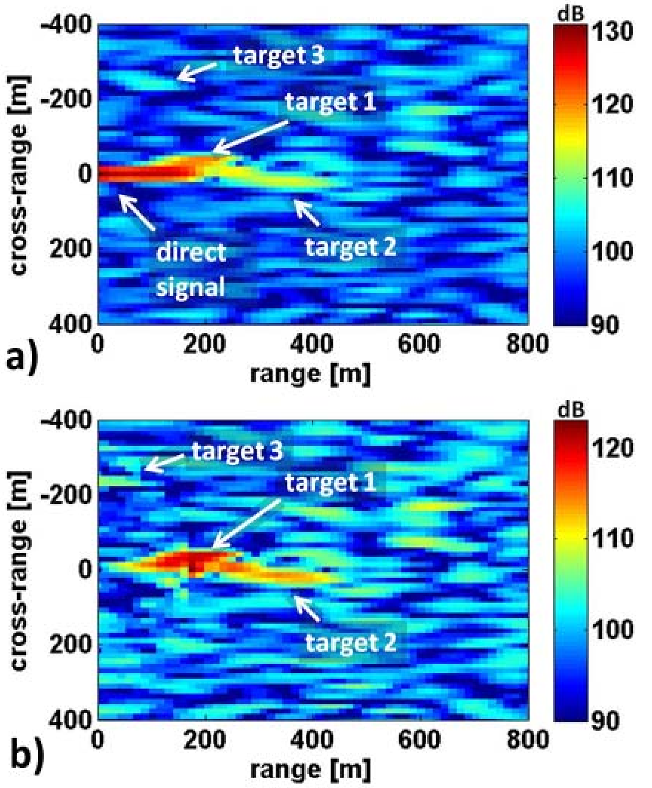

Figure 5. Passive SAR image obtained for EnviSAT illuminator using WUT receiver: a) before CLEAN processing, b) after CLEAN processing.

The second ground-based receiver, from which the data was obtained, was developed and implemented at the Royal Military Academy (RMA) in Brussels. This receiver, which is extensively described in [10], consists of a 4-element antenna array followed by four heterodyne channels tailored for C-band [10]. The receiving system is fully automated and is capable of simultaneously recording up to four channels.

Figure 6. Optical view of the observed area as seen from the receiving system installed in Brussels

For the data considered in this paper, the receiver, located on the roof of an RMA building, was pointing east toward the urban landscape of Brussels (Fig. 6), with a field of view of 60° in azimuth.

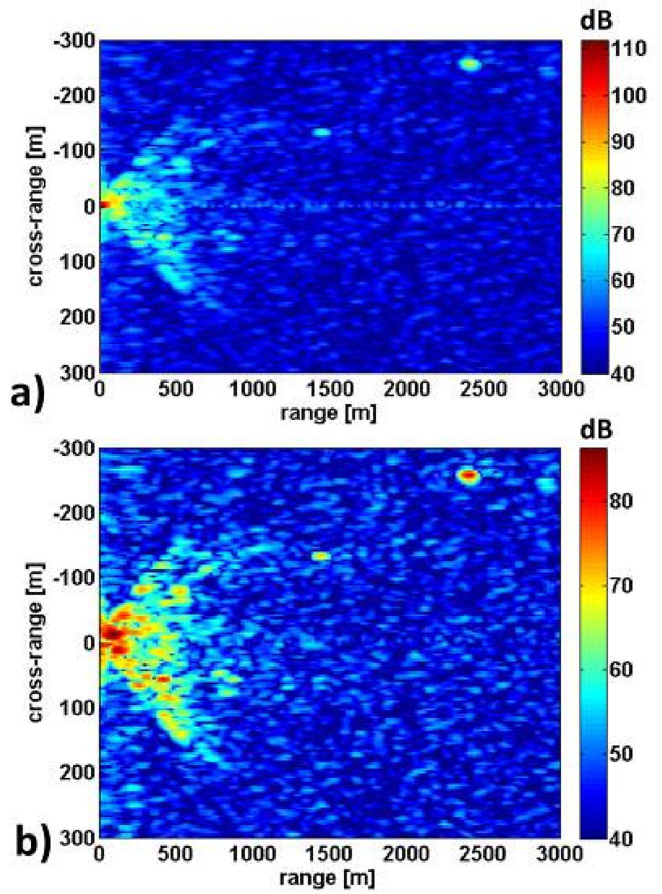

Figure 7. Passive SAR image obtained for EnviSAT illuminator using RMA receiver: a) before CLEAN processing, b) after CLEAN processing.

The acquisition corresponds to a descending pass of EnviSAT on April 7th 2012 at 09:58 UTC. Fig. 7 represents the SAR images obtained of the Brussels City Center presented in Fig. 6. During this trial only 2 channels were recorded for practical reasons and these two antennas were pointing towards the direction of the scene. In this case a single channel forward geometry depicted in Fig. 1 was exploited, while the data recorded by both channels was almost the same.

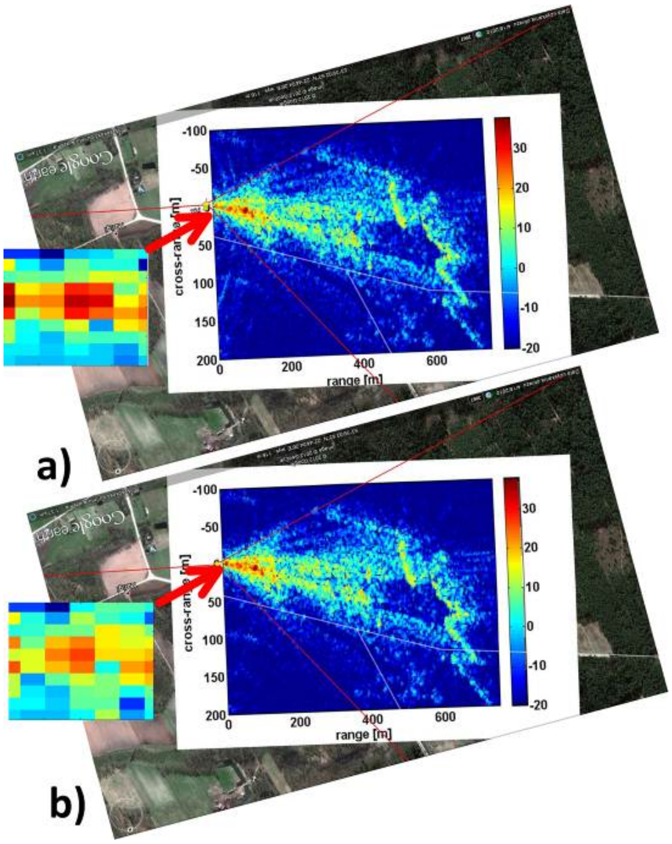

Figure 8. Passive SAR image obtained for TerraSAR-X illuminator using WUT receiver: a) before CLEAN processing, b) after CLEAN processing.

In such a case, the reference signal can be re-synthetized since on the one hand its general shape is known (linear FM chirp) and on the other hand its estimation is not impacted by the presence of echo signal due to the larger amplitude of the direct-path signal. Fig. 7b shows the final results of applying the proposed CLEAN processing. The direct signal was successfully removed from the passive SAR image and the ground targets are more visible in this result.

The CLEAN algorithm has also been verified for the X-band passive receiver developed by WUT, where as the illuminator of opportunity the TerraSAR-X radar was used. The measurement was performed in the Biebrza river valley, in July 2012. During the recording, X-band horn antennas were used for two receive channels. The reference antenna looked towards the satellite crossing path while the surveillance was pointed in the opposite direction at dispersed farm buildings. Since the NI PXIe-5667 RFSA instrument used as the receiver operates only up to 6.6 GHz, an additional stage of downconversion was applied that shifted the signals to the intermediate frequency (IF) of 1 GHz. The signals from the antennas were directed onto filters and amplifiers, and then the mixers. The problem of high attenuation of the coaxial cable at the X-band frequencies was solved by placement of the mixers on the top of the mast. To maintain an appropriately high level of the local oscillator (LO) signal that was conducted up the mast, an additional amplifier was used. Also a power divider was utilized to split the LO signal between two mixers. After the conversion the IF signals came through another stage of amplification (by approx. 15 dB) and bandpass filters.

At the IF carrier of 1GHz, the RFSA could easily acquire the measurement waveforms as in the previous case for the ASAR radar. In Fig. 8a and Fig. 8b the overlaying of the final SAR images and the Google map before and after CLEAN processing has been shown, respectively.

IV. Conclusions

The results presented in the paper of the passive SAR imaging using a CLEAN algorithm for different illuminators of opportunity (EnviSAT and TerraSAR-X), different bistatic geometry (forward and backward) and different receivers developed by WUT and RMA show effective ground clutter removal properties for passive SAR purposes. From the results presented in the paper it can be seen that the CLEAN removal is very important, especially for the single channel forward geometry where the direct signal in the measurement channel is usually much stronger than in the backward case.

The results obtained by the authors confirm that the CLEAN method proposed in the paper can be effectively used for passive SAR systems utilizing spaceborne illuminators of opportunity.

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