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ON HIGH-RESOLUTION IMAGING OF FAST-DECORRELATING TARGETS USING A DISTRIBUTED 'SWARMSAR' ARCHITECTURE

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ABSTRACT

The paper presents a novel concept of SwarmSAR for improving the azimuth resolution of fast-decorrelating targets such as ocean surfaces to generate high-resolution SAR images. The SwarmSAR concept consists of multiple simple nodes in a close formation cooperating in a MIMO-like fashion and illuminating a common footprint. Each individual node is basic but self-sufficient, guaranteeing decent target-resolving capabilities, even when operating individually. However, when operating in a MIMO-like fashion, they significantly improve the target resolution and imaging capabilities.

In this paper, we promote an S-band SwarmSAR considering a simplified geometry for resolving a fast-decorrelating point target in the azimuth direction. The results demonstrated in this work show the superiority of distributed SwarmSAR architecture over traditional monostatic SAR systems in resolving fast-decorrelating targets, and provide insight into the potential of the concept for future SAR missions.

Index Terms**—** fast-decorrelating targets, monostatic, SAR, small satellites, SwarmSAR

1. INTRODUCTION

Synthetic aperture radar (SAR) for the last few decades has been a beneficial technique for earth observation and remote sensing, being able to deliver high-resolution images of large terrain independent of weather conditions. SAR in recent years has been investigated and implemented in a wide range of size and complexity scales, ranging from less than 100 kg i.e., mini satellites [1, 2] to large satellites exceeding 1000 kg, equipped with advanced beamforming capabilities [3, 4]. SAR plays a critical role in mapping the Earth's surface to obtain detailed images. Its applications span across fields including geology, hydrology, meteorology, oceanography, and others [5].

The ability of SAR to provide high-resolution imagery is the result of the coherent integration of radar returns during the time of flight of a radar pulse along its path. One of the critical factors affecting the resolution of the images from SAR is the length of the synthetic aperture. However, the decorrelation of the target due to changes in the ground scene during the flight duration can limit the aperture length. On land, the decorrelation is often not a problem because the surface does not change during the synthetic aperture integration time. For oceans, on the other hand, the coherence time of the surface at microwave frequencies is in the order of tens of milliseconds, typically around an order of magnitude less than the nominal integration time, therefore limiting the achievable resolution [6].

To overcome these limitations, the SwarmSAR concept has shown promise. The approach involves using a swarm of antennas flying in a close formation, with short along-track separation cooperating in a multiple-input multiple-output (MIMO) fashion and illuminating a common footprint i.e., all antennas are pointing to the same area on the ground. The imaging capabilities of each individual node remain extremely basic, but still with decent target-resolving capabilities. However, when they work together, they increase the azimuth resolution and imaging capabilities [7].

Compared to a single satellite, the SwarmSAR concept takes a significantly different approach in terms of philosophy. The key feature of the SwarmSAR lies in its multistatic radar capabilities. Owing to their flexibility, cost-effectiveness, and enhanced imaging capabilities, multistatic systems (SwarmSAR) represent one of the most desired features for future SAR missions. A few multi-sensor concepts have so far been promoted either in a bistatic (single transmitter and multiple receivers) configuration [8] or MIMO

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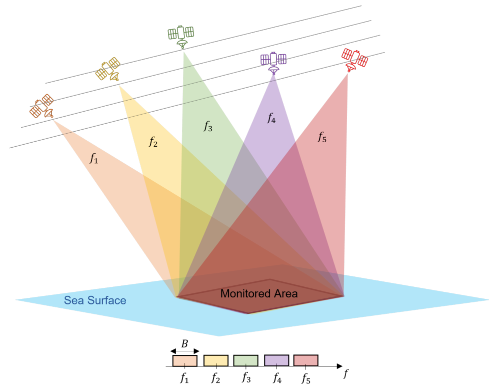

Fig. 1. Sketched Representation of SwarmSAR system.

(all units act as transceivers) configuration [9]. In this work, a novel approach for resolving fast-decorrelating targets in the azimuth direction is addressed. A SwarmSAR concept is used, with each node carrying an S-band antenna embedded with both transmit and receive functionalities. The simultaneous transmission is carried out through Frequency Division Multiplexing (FDM) strategy, as depicted in Fig. 1.

The simulation scenario adopts a simplified geometry, assuming 10 small satellites positioned with uniform separation in along-track baseline and no cross-track baseline is considered. It is acknowledged that real-world scenarios inherently involve variations and randomness in inter-satellite distances, which cannot be precisely controlled to the extent depicted in this model. Nevertheless, the purpose of this study is to demonstrate the fundamental principles of SwarmSAR for achieving high azimuth resolution of fast-decorrelating targets by combining the apertures from different satellites.

Although, a complete SAR signal processing algorithm requires additional steps i.e., range compression, range cell migration, range cell correction, etc, however, for the sake of simplicity the description of these steps has been omitted from this work, but we encourage the interested reader to read the details of SAR processing algorithms in [10]. In this work, we mainly focus on azimuth compression and resolving the targets in the azimuth direction.

2. SIGNAL PROCESSING ALGORITHM

Let us consider a decorrelating point target, with point target amplitude A and variable decorrelation amplitude A_d, having a correlation time $\tau_c \approx 3.29\ ^{\lambda}/_{U}$, where λ is the operating carrier wavelength and U is the wind speed. In this case, we considered $U = 12\ ^{m}/_{s}$ [11]. The total amplitude of decorrelating point target A_t, is the product of A and A_d. The decorrelating point target is being illuminated by N phase centers. Let $\phi_i(t, R)$ represent the phase history of i^{th} phase center, where $i = \{1, ..., N\}$, t is the time and R is the range. The phase histories of all phase centers can be written as:

$$\phi_i(t, R) = -2k_0 R_i \tag{1}$$

where $k_0 = {}^{2\pi}/_{\lambda}$ is the wave number, R_i is the range history of i^{th} phase center. The monostatic received signal based on the phase history of i^{th} phase center can be written as:

$$s_{r,i}(\phi) = A_t.e^{j\phi_i} \tag{2}$$

Once the azimuth direction of the target is estimated, the signal from each phase center can be compressed in the azimuth direction, this can be performed by using the Fourier Transform (FT).

The compressed signal from different phase centers can then be combined and passed through the matched filter to generate an azimuth compressed single look complex (SLC) image.

Note, that SwarmSAR signal processing is not straightforward and requires additional processing steps before combining the signals and passing them through the matched filter. In order to exploit the advantages offered by the SwarmSAR concept to their maximum potential, additional windowing of received signals is required.

Considering a satellite equipped with a long synthetic aperture illuminating a fast-decorrelating target with a correlation time (τ_c). The correlation time limits the coherent aperture length for collecting SAR data from a single phase center to the order of ($\tau_c \cdot v_{sc}$), where v_{sc} is the sensor velocity. Consequently, only a small portion of the available synthetic aperture can be effectively utilized before the target's scattering properties change. As a result, the SAR image formed using SLC processing may suffer from degraded azimuth resolution when dealing with the decorrelating targets.

To overcome this limitation, a concept called SwarmSAR has been introduced, which leverages multiple sensors in a configuration resembling to MIMO systems. The SwarmSAR signal processing algorithm is illustrated in a block diagram in Fig. 2. Initially, the received signal from each sensor, is divided into K sub-signals, each representing a sub-aperture of the respective SAR sensor. The length of the sub-signals is determined based on the time required for coherent integration of the received data from the decorrelating target.

To ensure overlap between the sub-apertures from consecutive sensors, the separation between the sensors is adjusted such that the overlap ratio is 0.5. This overlap is essential to maintain the continuous frequency spectrum when combining the signals from different sensors. The Bartlett windowing is employed due to the 50% overlap between the sub-apertures from the consecutive sensors, which prevents the discontinuities or jumps in the frequency spectrum when the signals from different sensors are combined.

After passing the sub-signals through the Bartlett window, the corresponding signals from each sensor are summed to generate a sub-aperture SLC image. This process is repeated

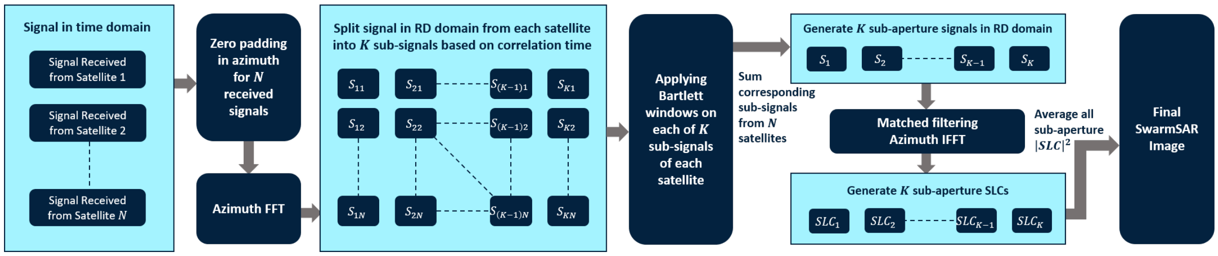

Fig. 2. Block Diagram of SwarmSAR Signal Processing Algorithm Implementation.

for all K sub-apertures, resulting in K sub-aperture SLCs. Finally, these K sub-aperture SLCs are averaged together to, produce the final SwarmSAR SLC image. Compared to traditional SAR systems, this approach significantly enhances the azimuth resolution for fast decorrelating targets. The azimuth resolution of decorrelating target with traditional SAR systems is expressed as:

$$\delta_a = {}^{0.886 R_s \lambda}\big/_{2(\tau_c v_{sc})} \tag{3}$$

while the azimuth resolution of final SwarmSAR image is given by:

$$\delta_{a_{\text{swarm}}} = {}^{0.886 R_s \lambda}\big/_{2[\tau_c v_{sc} + (N_{sats} - 1)D]} \tag{4}$$

where R_s is the reference range, N_{sats} is the number of satellites, and D is the satellite separation.

The next section compares the azimuth resolution of fast decorrelating targets using traditional SAR processing, and the method proposed in Fig. 2, considering the parameters presented in Table. 1.

Table 1. Simulation Parameters

Parameter	Value
Operating Frequency	3 GHz (S-band)
Bandwidth	50 MHz
Pulse Duration	30 μs
Target Correlation Time	27.40 ms
Pulse Repetition Frequency (PRF)	8000 Hz
Antenna Length in Azimuth Direction	10 m
Satellites Height	693 km
Platform Velocity	7000 m/s
Satellite Separation	95.90 m
Number of Satellites	10

It is worth noting from Table. 1 that the correlation time of 27.40 ms limits the synthetic aperture for each sensor to approximately 191.80 m ($\tau_c.v_{sc}$). With the separation of 95.90 m between sensors, a 50% overlap between the corresponding sub-apertures is achieved. To avoid introducing azimuth ambiguities due to insufficient cut-off, all the sub-signals are subject to the Bartlett window, ensuring a smooth transition in the frequency spectrum, when combining sub-apertures from different sensors.

3. SIMULATION RESULTS AND ANALYSIS

Table 1 provides information regarding satellites' height and platform velocity. These parameters lay the groundwork for our analysis, where we introduced two point targets positioned just 100 meters apart from each other. 2-D SLCs were generated using monostatic SAR without applying proper windowing techniques and SwarmSAR architecture with applying proper windowing. Fig. 3(a) and Fig. 3(b) show the signals of non-decorrelating targets and decorrelating targets after range compression, respectively. In Fig. 3(c) and Fig. 3(d), by employing the monostatic configuration, we observe two distinct scenarios: non-decorrelating targets, and decorrelating targets with a correlation time of 27.40 ms. The synthetic aperture length for the monostatic configuration is 6925.26 m, determined by the antenna length in the azimuth direction. This configuration yields an azimuth resolution of 4.43 m for non-decorrelating targets. The results presented in Fig. 3(c) and Fig. 3(d) demonstrate the impact of high decorrelation, as it gives rise to significant azimuth ambiguities.

Again, same two non-decorrelating targets and fast decorrelating targets were considered as in Fig. 3(e) and Fig. 3(f), respectively. The effectiveness of SwarmSAR is evident, where SwarmSAR configuration has greatly improved the azimuth resolution of fast-decorrelating targets compared to the monostatic case.

To further compare the azimuth resolution of these targets with different configurations, we turn to Fig. 4. For the fast decorrelating targets using monostatic configuration, we observe overlapping frequency responses that lead to significant azimuth ambiguities due to insufficient cut-off and result in significant sidelobes. The application of Bartlett windows is evident from the azimuth resolution of SwarmSAR at the final image using the entire satellite aperture. As expected, the incorporation of the Bartlett window effectively reduces the sidelobes, resulting in a more refined and improved azimuth resolution of SLC. Referring to equations (3) and (4), the theoretical azimuth resolutions for monostatic SAR for decorrelating target and SwarmSAR images are calculated as 191.78 m and 29.08 m, respectively. By measuring the 3dB width of the azimuth profile of one point target, the azimuth resolution of SwarmSAR image is 23.50 m. The azimuth resolution of the SwarmSAR configuration is worse than that of monos-

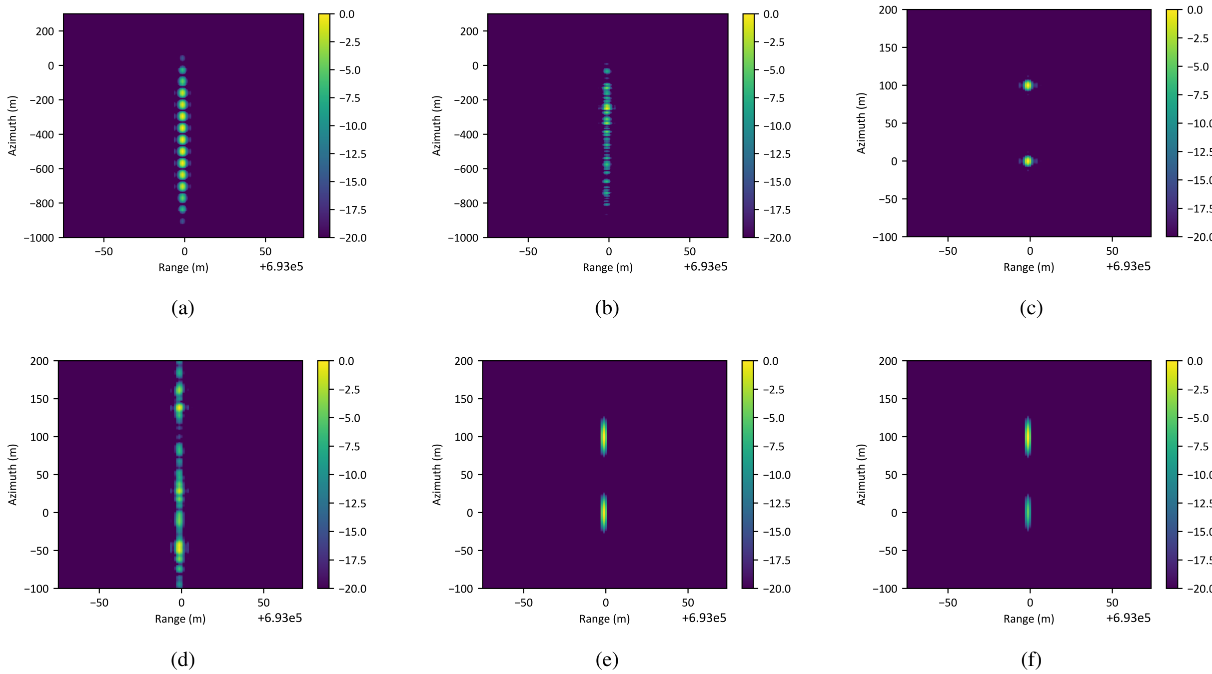

Fig. 3. (a) Signals of non-decorrelating targets after range compression, (b) Signals of decorrelating targets after range compression, (c) Image of non-decorrelating targets using monostatic configuration without windowing, (d) Image of decorrelating targets using monostatic configuration without windowing, (e) Image of non-decorrelating targets using SwarmSAR full aperture, (f) Image of decorrelating targets using SwarmSAR full aperture.

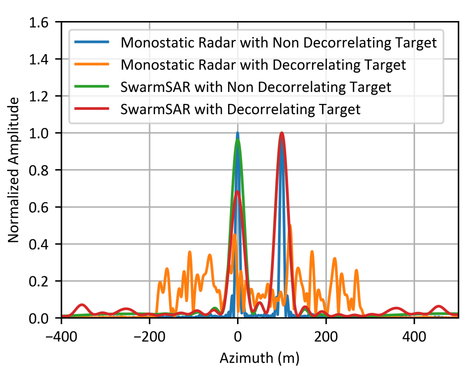

Fig. 4. The azimuth profiles of (c)-(f) in Fig. 3.

tatic SAR for non-decorrelating targets due to the shorter sub-aperture length in SwarmSAR compared to the synthetic aperture length of monostatic SAR. However, this discrepancy is not absolute; different parameters can be employed to extend the sub-aperture length beyond the synthetic aperture length of monostatic SAR, potentially improving the azimuth resolution for non-decorrelating targets under certain conditions. Nevertheless, our paper mainly focuses on highlighting the advantages of SwarmSAR for decorrelating targets.

In summary, the SwarmSAR concept addresses the limitations imposed by the correlation time of decorrelating targets in SAR imaging. By employing a MIMO-like configuration with multiple sensors, the proposed algorithm achieves improved resolution and enhanced imaging capabilities for the fast decorrelating targets, surpassing the performance of traditional monostatic SAR systems.

4. CONCLUSION

In conclusion, the potential of SwarmSAR in obtaining high-resolution images in case of fast-decorrelating targets is presented. Temporal decorrelation has a significant effect on the azimuth resolution of the SLC obtained using monostatic configuration in the presence of fast-decorrelating targets, emphasizing the need for careful consideration of multi-sensor imaging in such scenarios.

The results demonstrate a significant improvement in the azimuth resolution of images obtained using SwarmSAR configuration compared to monostatic SAR configuration in the presence of fast temporal decorrelations. The work presented here, although considering a very simplified and controlled geometry, highlights the potential of distributed SwarmSAR architecture for generating high-resolution SAR images for future SAR missions for a variety of remote sensing applications, especially for fast-decorrelating surfaces, such as ocean surfaces. However, a significant amount of effort is still required for the realization of SwarmSAR concept.

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