STAGGERED-SAR: A NEW CONCEPT FOR HIGH-RESOLUTION WIDE-SWATH IMAGING

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ABSTRACT

Synthetic aperture radar (SAR) is the ideal sensor for the systematic observation of dynamic processes on the Earth's surface. However, current SAR systems are limited, in that a wider coverage can only be achieved at the expense of a degraded azimuth resolution. To overcome this limitation, an innovative concept is considered, Staggered-SAR, where the pulse repetition frequency is continuously varied and high-resolution wide-swath (HRWS) imaging is achieved with a single azimuth channel system. The system design, the processing required to reconstruct the non-uniformly sampled signal, as well as a performance analysis, are considered.

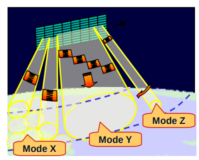
1. INTRODUCTION

Synthetic Aperture Radar (SAR) is a powerful remote sensing technique, capable of providing high-resolution images of the Earth's surface independent of weather and sunlight illumination. Further unique opportunities emerge from the coherent combination of multiple SAR images. Several applications require uninterrupted time series of radar images with short time intervals between consecutive acquisitions. However, all current high-resolution SAR systems are rather limited with regard to their acquisition capability. An example is TerraSAR-X, which provides multiple modes for different trade-offs between resolution and coverage (see upper part of Fig. 1). In stripmap mode (spatial resolution of 3 m), only 2% of the Earth's landmass can be mapped during its 11 days repeat cycle.

The lower part of Fig. 1 shows that future SAR missions may require a mapping capability one or even two orders of magnitude better than that of TerraSAR-X. A prominent example is Tandem-L, whose goal is the investigation of dynamic processes on the Earth's surface. For this, an extremely powerful SAR instrument is required, capable of continuously mapping a 350 km wide swath in full polarization and with a spatial resolution well below 10 m [1]. Other missions may require a higher spatial resolution, although without the need for a weekly coverage of the Earth.

State of the Art (TerraSAR-X)	Imaging Mode (single pol)		
	ScanSAR	Stripmap	Spotlight
Resolution	16 m	3 m	1 m
Swath Width	100 km	30 km	10 km
Orbit Duty Cycle	3 minutes per orbit		

Resolution ⟷ Swath Width ⟷ Repeat Cycle



Future Requirements	Imaging Mode (quad pol)		
	Mode X	Mode Y	Mode Z
Resolution	5 m	1 m	<< 1 m
Swath Width	400 km	100 km	30 km
Orbit Duty Cycle	30 minutes per orbit		

Fig. 1 Spaceborne SAR imaging: State-of-the-art and future requirements.

The latter requirements cannot be achieved by conventional SAR. In order to guarantee a given azimuth resolution, in fact, a PRF at least equal to the processed Doppler bandwidth, corresponding to that resolution, has to be employed. On the other hand, the selected PRF imposes a maximum swath width. Assuming a sensor velocity of 7500 m/s and an antenna length of 15 m, an azimuth resolution of 10 m requires a PRF greater than the Doppler bandwidth corresponding to that resolution, i.e. 750 Hz. This PRF theoretically allows imaging of a maximum slant range swath of 200 km [2].

This inherent limitation can be overcome by arranging several receive apertures in the along-track direction. This would, in fact, increase the resolution, without narrowing the swath. Moreover, digital beamforming (DBF) can be used to steer in real-time a narrow beam towards the direction of arrival of the radar echo, thus allowing the use of a large receive aperture (with improved sensitivity), without narrowing the swath. However, a very long antenna is needed to map a wide swath with high azimuth resolution.

Advanced concepts for ultra-wide swath imaging have been recently developed, including multi-channel ScanSAR and single-channel SAR with multiple elevation beams (a reflector can also be employed) [3]. Nevertheless, a drawback of the latter (single-channel) concept is the presence of blind ranges across the swath.

The Staggered-SAR concept overcomes this drawback by continuously varying the pulse repetition frequency (PRF), so shifting the blind ranges across the swath and achieving HRWS imaging with a single azimuth channel system. Such a concept has been already analyzed in [4]. In this paper, a new PRF variation scheme is proposed, which, in combination with proper processing techniques, leads to improved performance.

2. CONTINUOUS PRI VARIATION IN SAR

Conventional SAR systems employ a constant PRF. As the radar system cannot receive when it is transmitting, blind ranges are present across the swath. The PRF therefore defines the available swaths, which are delimited by blind ranges.

If the PRF is kept constant, there will be some blind ranges, for which none of the transmitted pulses is received, while for all other ranges all the transmitted pulses will be received. In contrast, if the PRF is continuously varied from pulse to pulse, in general, for each range, some transmitted pulses will not be received – we will say they will be "blocked". Moreover, a periodicity in the PRF variation can be considered, so that a sequence of M intervals between transmissions – or pulse repetition intervals (PRIs) – is employed. If the M PRIs are properly selected, quite a small percentage of transmitted pulses will be blocked for each range over a desired swath much larger than that achievable by a constant PRF system.

An imaging system with variable PRF has already been analyzed in [4]. In particular, a linear variation of the PRI was considered, together with long sequences, with M ranging from 580 up to 2900 pulses (the latter corresponding to the full synthetic aperture). It is shown that this technique enables the imaging of a wide swath of 350 km, although a severe performance degradation in terms of integrated side-lobe ratio (ISLR) occurs with respect to a constant PRF system: The longer the transmitted pulse duration τ, the more severe the degradation. Furthermore, the performance (azimuth resolution, ISLR) is dependent on the target position for $M = 2900$.

Long sequences, in fact, result in received azimuth signals, characterized by large gaps, as several consecutive pulses are "blocked". Those large gaps determine the presence of paired echoes in the impulse response function (IRF), after focusing. In contrast, very short sequences can be designed, following the criterion for which no more than one pulse of the sequence has to be "blocked" for ranges included in the desired swath.

An example of a periodic sequence with $M = 5$ is considered, together with a set of system parameters typical of the Tandem-L mission [5], and setting $\tau = 35$ µs. Fig. 2 shows for a given slant range ($R_0 = 960$ km), the transmitted, received and "blocked" pulses. The second transmitted pulse cannot be received (or, better, can be only partially received), as the system is transmitting the fifth pulse.

Partially received pulses are ignored (discarded) in our analysis, even though additional information might be gathered from them as well.

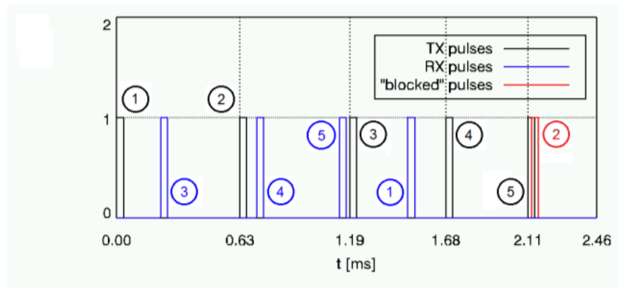


Fig. 2 Transmitted, received, and blocked samples for a given slant range (960 km) for a sequence with $M = 5$.

The diagram of Fig. 3 shows which transmitted pulse of the sequence is "blocked" for each range. It can be noticed that no more than one pulse is "blocked" for each slant range over an interval, ranging from 868 km to 1097 km.

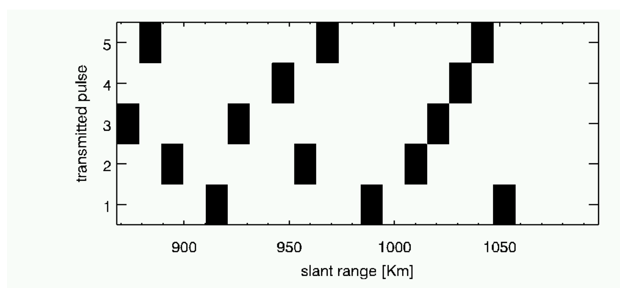


Fig. 3 "Blocked" transmitted pulses (black) for each range.

Fig. 4 shows the maximum, mean, and minimum pulse separation between the received pulses. The maximum pulse separation is even smaller than the reciprocal of the processed Doppler bandwidth, necessary to achieve the azimuth resolution of 10 m required in [5]. In contrast, the maximum pulse separation would be by far longer, if the long sequences proposed in [4] were used (up to 32 ms for $M = 580$ and up to 160 ms for $M = 2900$).

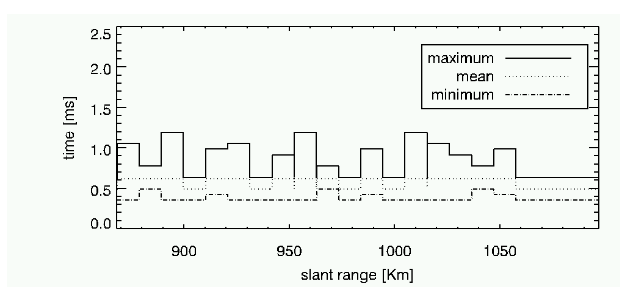


Fig. 4 Maximum, mean and minimum pulse separation.

Furthermore, it has to be noted that, depending on the minimum pulse separation, the antenna height has to be chosen large enough to suppress range ambiguities [3]: the shorter the minimum separation, the higher the antenna.

3. PROCESSING ISSUES

As a consequence of the use of a variable PRF and due to presence of "blocked" pulses, a uniformly sampled azimuth signal has to be recovered from the non-uniformly sampled gapped one, before performing azimuth focusing.

One possibility is to use interpolation techniques, as proposed in [4]. In this paper, as an alternative approach, multi-channel reconstruction [6] is exploited together with the short sequences proposed in the previous section. Further techniques will be considered in the future.

The effects of range cell migration (RCM) and their implications on the 2D signal reconstruction are also a concern. The relative range offset, however, is likely to be negligible. If not, it has to be corrected for within the processing.

4. PERFORMANCE ANALYSIS

The system performance can be assessed with reference to the impulse response function (IRF) of the reconstructed signal. A parameter of interest is the integrated side-lobe ratio (ISLR). Besides, the signal-to-noise ratio scaling factor [6], associated to the reconstruction techniques, has also to be considered.

Fig. 5 shows the original and reconstructed IRF for interpolation and multi-channel reconstruction, for the sample sequence with M = 5, for a pulse duration τ = 35 μs, and for a processed Doppler bandwidth of 900 Hz. The example refers to a slant range of 960 km and represents the worst case (maximum pulse separation, cf. Fig. 4). It can be noticed that some paired echoes appear at regular distances in addition to the conventional azimuth ambiguities. This should not be a problem, as long as the amplitudes of the echoes are not significant.

From a quantitative point of view, the ISLR losses, referenced to the original uniformly sampled signal, are 2.9 dB and 1.4 dB, for interpolation and multi-channel reconstruction, respectively. It has to be emphasized that this is the worst case: for other ranges, the ISLR is very close or even better than the one obtained with a uniformly sampled signal.

The first analyses show that multi-channel reconstruction leads to paired echoes with smaller amplitudes in comparison to interpolation. The SNR scaling effect, however, is more pronounced in the multi-channel reconstruction case.

Using the long sequences proposed in [4] and interpolation, the ISLR losses are of the order of 6 dB, for τ=20 μs [4], and are likely to be much larger for τ=35 μs.

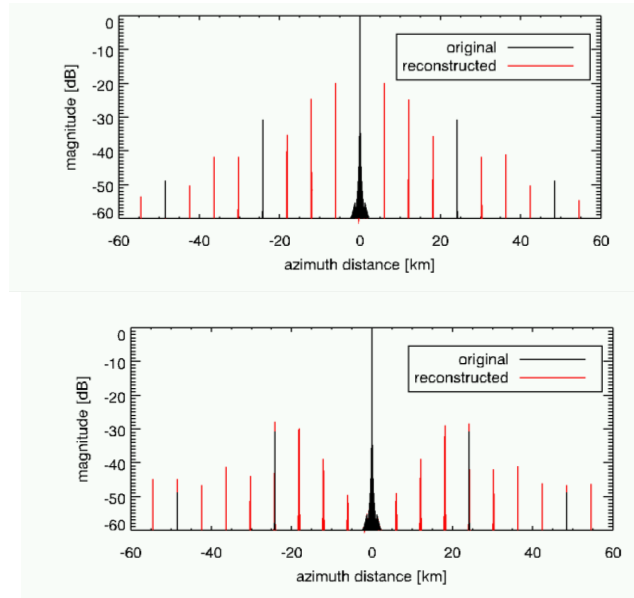


Fig. 5 IRFs of the original and reconstructed signals, using interpolation (top) and multi-channel reconstruction (bottom).

5. CONCLUSION

Staggered SAR allows HRWS imaging with a single azimuth channel system. The system gets rid of blind ranges due to "blockage" by continuously varying the PRF along the track. This concept is expected to play an important role in the design of future spaceborne SAR systems with high-resolution wide-swath capability.

6. REFERENCES

[1] G. Krieger et al., "Single-Pass Synthetic Aperture Radar (SAR) Missions", *Proc. IEEE – Special Issue on Satellite Remote Sensing Missions for Monitoring Water, Carbon and Global Climate Change*, vol. 98**,** no. 5, pp. 816-843, 2010.

[2] Curlander, J.C. and R.N. McDonough, *Synthetic Aperture Radar – Systems and Signal Processing*, Wiley, New York, 1991.

[3] G. Krieger et al., "Advanced Concepts for Ultra-Wide-Swath SAR Imaging", *Proc. EUSAR*, Friedrichshafen, Germany, pp. 31-34, 2008.

[4] N. Gebert and G. Krieger, "Ultra-Wide Swath SAR Imaging with Continuous PRF Variation", *Proc. EUSAR*, Aachen, Germany, pp. 966-969, 2010.

[5] G. Krieger et al.,"The Tandem-L Mission Proposal: Monitoring Earth's Dynamics with High Resolution SAR Interferometry," *Proc. IEEE Radar Conference*, Pasadena, CA, USA, 2009.

[6] N. Gebert, G. Krieger, and A. Moreira, "Digital Beamforming on Receive: Techniques and Optimization Strategies for High-Resolution Wide-Swath SAR Imaging", *IEEE Trans. Aerospace and Electronic Systems*, vol. 45**,** no. 2, pp. 564-592, 2009.