Staggered SAR: From Concept to Experiments with Real Data

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Abstract

Staggered SAR is an innovative synthetic aperture radar (SAR) concept, where the pulse repetition interval (PRI) is continuously varied. This, together with digital beamforming (DBF) in elevation, allows high-resolution imaging of a wide continuous swath without the need for a long antenna with multiple azimuth apertures. Criteria for the design of sequences of PRIs and data processing strategies are presented, together with some system design considerations. The impact of staggered-SAR operation on image quality is furthermore assessed, using highly oversampled F-SAR airborne data and operating TerraSAR-X in staggered-SAR mode.

1 Introduction

Synthetic aperture radar (SAR) is a remote sensing technique, capable of providing high-resolution images independent of weather conditions and sunlight illumination. This makes SAR very attractive for the systematic observation of dynamic processes on the Earth's surface. However, conventional SAR systems are limited, in that a wide swath can only be achieved at the expense of a degraded azimuth resolution, i.e. reducing the pulse repetition frequency (PRF).

This limitation can be overcome by using systems with multiple receive apertures, displaced in along-track, which simultaneously acquire multiple samples for each transmitted pulse, but a very long antenna is required to map a wide swath. If a relatively short antenna with a single aperture in along-track is available, it is still possible to map a wide area: Multiple swaths can be, in fact, simultaneously imaged using digital beamforming (DBF) in elevation, but "blind ranges" are present between adjacent swaths, as the radar cannot receive while it is transmitting (**Figure 1** (a)). Several applications, however, require a wide continuous swath, which also allows a more efficient coverage of large geographical areas.

Staggered SAR is an innovative concept, where the pulse repetition interval (PRI) is continuously varied, thus allowing the imaging of a wide continuous swath without the need for a long antenna with multiple apertures [1], [2].

2 Concept

If the PRI is continuously varied, even in a cyclical manner, i.e. repeating a sequence of *M* PRIs, there will still be ranges, from which the echo is not received, because the radar is transmitting, but in general those ranges will be different for each transmitted pulse (**Figure 1** (b)). If the overall synthetic aperture is considered, it turns out that at each slant range only some of the samples are missing. In particular, sequences of PRIs can be designed such that the missing samples are almost uniformly distributed across the swath, i.e., a relatively small percentage of pulses is missing at each range, and azimuth compression can still be performed over a wide continuous swath.

2.1 Design of Sequences of PRI

Two criteria for the design of sequences of PRIs are proposed in the following, assuming within the sequence a linear variation of the PRI between PRI_{max} and PRI_{min}:

a) The PRI span is the minimum such that the missing samples are almost uniformly distributed across the swath and the number of PRIs of the sequence *M* is such that few cycles (e.g. 5) cover the overall synthetic aperture (*slow PRI change*). This variation scheme allows to tilt the blind areas, such that at each slant range and for each cycle of variation of the PRI a large azimuth gap, i.e., a series of consecutive missing samples, is present in the raw data (**Figure 1** (b)). However, these large periodic gaps will determine – after azimuth compression – high sidelobes in the azimuth impulse response. This variation scheme is interesting if the different azimuth bursts, separated by the large gaps, are processed independently, to obtain several independent low resolution images, which can then be multi-looked and used to either enhance the radiometric resolution or to reduce interferometric phase errors;

b) The maximum PRI, the minimum PRI and the number of PRIs of the sequence *M* are selected so that two consecutive azimuth samples are never missed for the desired slant ranges of in-

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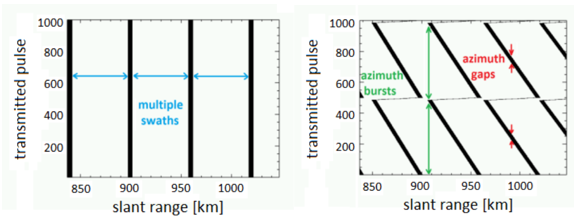
terest, therefore minimizing the size of the gaps. This criterion results in sequences with *fast PRI change*, which allows to get rid of the high sidelobes in the azimuth impulse response, provided that the azimuth signal is averagely oversampled.

Furthermore, more elaborated sequences of PRIs can be designed in which – after azimuth compression – the energy of azimuth ambiguities is spatially defocused rather than concentrated in specific areas. The PRI values for a more elaborated sequence of $M = 296$ PRIs are provided in **Figure 2.**



(a) (b)

Figure 1: Blind ranges, represented as black stripes, for a conventional SAR system with uniform PRI (a) and a staggered-SAR system with slow PRI change (b). The multiple swaths, the large azimuth gaps and the azimuth bursts are highlighted.

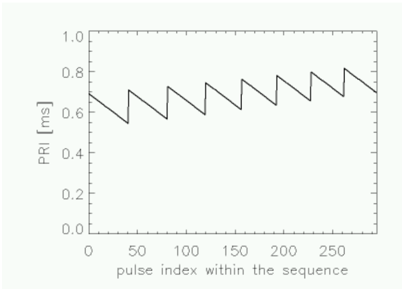


Figure 2: PRI values for a more elaborated sequence of $M = 296$ PRIs.

2.2 Processing Strategies

In principle, non-uniformly sampled raw data can be processed focusing each pixel independently, i.e., in time domain. For efficient implementation, however, raw data can be first resampled to a uniformly-spaced grid and then processed with a conventional SAR processor.

As far as the resampling method is concerned, although a simple two-point linear interpolation might still lead to acceptable results, better performances are obtained, if the spectral characteristics of the data are exploited. The power spectral density of the raw azimuth signal can be obtained from the two-way azimuth antenna pattern, and its inverse Fourier transform, the autocorrelation function, can be used to estimate the azimuth signal at arbitrary azimuth times using neighbouring azimuth samples (best linear unbiased (BLU) interpolation) [1].

Moreover, as discussed in [2], if the interpolation is performed on raw data, rather than on range-compressed data, it is possible to exploit the partially received pulses as well, so achieving the same performance with a lower average azimuth oversampling.

3 System Design Considerations

A continuously varied PRI allows to get rid of blind ranges and image a wide continuous swath with high azimuth resolution. As an additional benefit, the energy of range and azimuth ambiguities is spread over large areas: ambiguities therefore appear in the image as a noise-like disturbance rather than localized artifacts. On the other hand, a slightly higher antenna with beamforming capabilities is required to keep the same range ambiguities-to-signal ratio (RASR) for the increased mean PRI, associated to the average azimuth oversampling. The increased data volume can be instead reduced performing an on-board Doppler filtering [3].

3.1 L-Band Design Example

A design example for a fully-polarimetric high-resolution wide-swath SAR system is presented in the following, based on a 15 m reflector. The main system parameters are provided in **Table 1,** while the sequence of PRIs of **Figure 2** has been used for each transmitted polarization, in combination with BLU.

Parameter	Value
Wavelength	0.2384 m
Orbit height	770 km
Incidence angle	26.3° - 46.3°
Duty cycle	30 µs
Chirp bandwidth	85 MHz
Range sampling frequency	93.5 MHz
Tilt	31.9°
Processed Doppler bandwidth	600 Hz
Polarizations	HH, VV, HV, VH
Backscatter model	D'Aria

Table 1: System parameters for the design example.

In this design example, a 350 km continuous wide swath is imaged in quad polarization mode with a 13 m azimuth resolution. **Figure 3** displays the two-dimensional integrated side lobe ratio (2D-ISLR) and the range ambiguity-to-signal ratio (RASR). If a conventional SAR system with constant PRI and multiple elevation beams had been used, the 2D-ISLR would have been 2 dB better, the RASR would have been ap-

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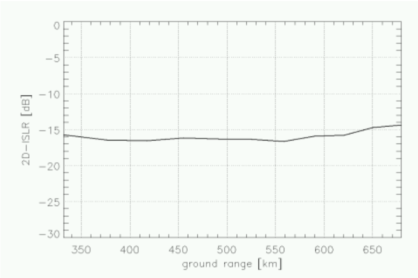
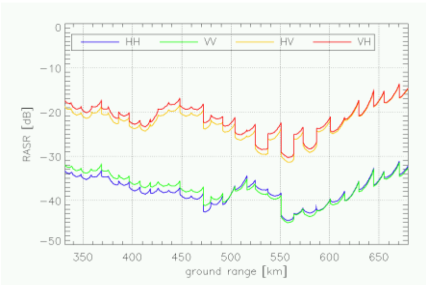
proximately the same, but four blind range areas of slant range width equal to 9 km would have been present across the swath. Moreover, it has to be stressed that for a staggered-SAR system the requirements on ambiguities can be relaxed with respect to a conventional SAR system, due to the aforementioned spreading effect.



(a)



(b)

Figure 3: 2D-ISLR (a) and RASR (b).

4 Experiments with Real Data

4.1 F-SAR

In order to better understand the implications of staggered-SAR operation on image quality, we use airborne data which were originally acquired with a PRF that was much larger than the Doppler bandwidth. From these highly-oversampled SAR data, it is then possible to extract raw data as they would have been received by a staggered-SAR system with arbitrary sequences of PRIs. These non-uniformly sampled data can thereafter be resampled to a uniform grid, using different algorithms, such as two-point linear interpolation or BLU interpolation, allowing an assessment of the reconstruction error on the staggered-SAR data. Furthermore, conventional SAR processing can be performed and the image quality can be assessed for different sequences of PRIs and resampling algorithms, especially if several corner reflectors are present in the scene. For that reason, L-band airborne data have been acquired by DLR's F-SAR sensor over the calibration test site of Kaufbeuren, Germany.

A reference data set has been also generated by decimating data in the azimuth direction and then upsampling them by means of zero-padding of the FFT. This allows to compare the results to a reference, uniformly-sampled data set with an oversampling rate representative of a typical satellite staggered-SAR system, i.e., much lower than the oversampling rate of the F-SAR data set, for which azimuth ambiguities are no longer negligible. **Figure 4** shows the focused images obtained for a reference system with constant PRI and a staggered-SAR system, where the sequence of Figure 2 is used in combination with BLU interpolation. A relative increase of the intensity in low backscatter areas can be observed for staggered-SAR, but only if data are displayed using a large log-intensity scale. In a typical satellite scenario, due to the much lower signal-to-noise ratio (SNR), this difference would be hardly noticeable.

(a)

(b)

Figure 4: Focused image acquired over Kaufbeuren, Germany, for a reference system with constant PRI (a) and a staggered-SAR system (b). A very large (100-dB) logarithmic scale has been used to highlight the differences.

Furthermore, simulated data for a scene with the same acquisition geometry, where only the corner reflectors are present, have been generated and the same aforementioned processing steps have been applied to simulated data as well. The two-dimensional responses of the corner reflector are displayed in **Figure 5**, where the spreading effect of azimuth ambiguities is well visible. The two-dimensional ISLR for the staggered-SAR system is only 1 dB worse than for the reference system.

The azimuth resolution, as measured on the twelve corner reflectors present in the area, is displayed in **Figure 6**. As apparent, the resolution loss of staggered SAR with respect to constant PRI SAR is negligible.

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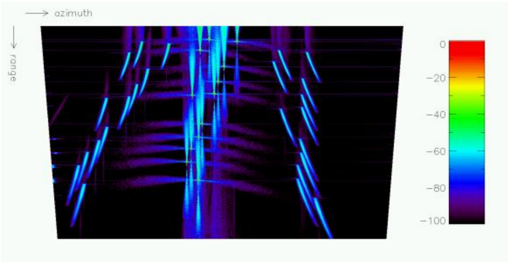
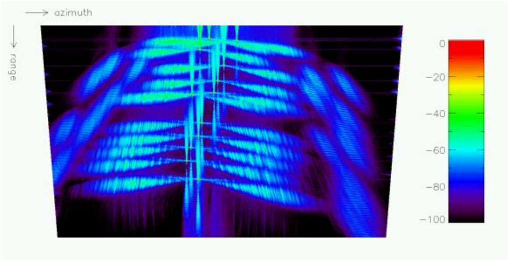


(a)



(b)

Figure 5: Focused image for simulated data (only corner reflectors) for a reference system with constant PRI (a) and a staggered-SAR system (b). A very large (100-dB) logarithmic scale has been used to highlight the differences.

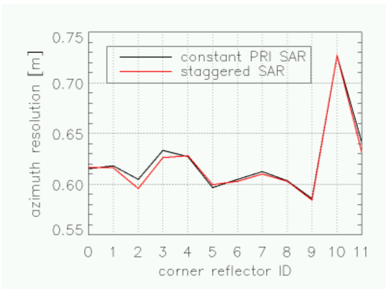


Figure 6: Azimuth resolution as measured on the twelve corner reflectors present in the area.

4.2 TerraSAR-X

A further step in the analysis is the demonstration of the staggered-SAR concept with the TerraSAR-X satellite, although without the simultaneous mapping of multiple swaths. TerraSAR-X, in fact, allows the use of 512 different PRIs, which can be continuously changed in a periodic manner during the acquisition. A sequence of 28 PRIs, where two consecutive azimuth samples are never missed, has been designed and data have been acquired over the Lake of Constance. **Figure 7** shows 100 echoes received between consecutive transmitted pulses, while **Figure 8** shows the raw staggered-SAR data, obtained rearranging the echoes on a range-azimuth grid, where the periodic pattern of missing samples is visible, and the uniformly-sampled raw data, obtained after interpolation. The latter raw data can be focused with a conventional SAR processor.

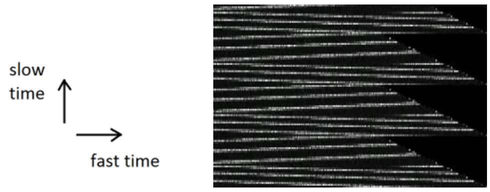


Figure 7: Set of 100 echoes received between consecutively transmitted pulses.

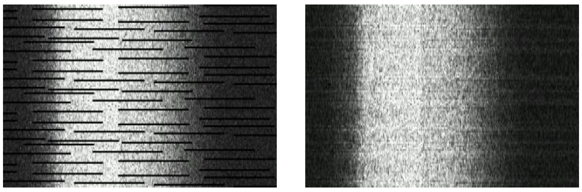


Figure 8: Raw staggered-SAR data with gaps (left), obtained after rearranging the echoes on a range-azimuth grid, and uniformly-sampled raw data (right), obtained after interpolation.

5 Conclusion

Staggered SAR, an innovative concept for high-resolution imaging of a wide continuous swath, has been analyzed and its performance has been assessed by experiments with real data. An extension of the staggered-SAR concept, where the phase centers on transmit and/or on receive are continuously varied as well, has been recently patented by DLR [4].

References

[1] Michelangelo Villano, Gerhard Krieger, and Alberto Moreira: *Staggered SAR: High-Resolution Wide-Swath Imaging by Continuous PRI Variation,* IEEE Trans. Geosci. Rem. Sens., accepted for publication

(http://ieeexplore.ieee.org/arnumber=6651848).

[2] Michelangelo Villano, Gerhard Krieger, and Alberto Moreira: *A Novel Processing Strategy for Staggered SAR,* IEEE Geosci. Rem. Sens. Lett., accepted for publication.

[3] Michelangelo Villano, Gerhard Krieger, and Vincenzo Del Zoppo: *On-Board Doppler Filtering for Data Volume Reduction in Spaceborne SAR Systems*, submitted to IRS 2014, Gdansk, Poland.

[4] Michelangelo Villano, Gerhard Krieger, and Alberto Moreira: *Synthetik-Apertur-Radarverfahren*, German Patent, DE 10 2012 219 225.5.

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