# The Staggered SAR Concept: Imaging a Wide Continuous Swath with High Resolution

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***Abstract:*** *Staggered SAR is an innovative synthetic aperture radar (SAR) concept, based on the continuous variation of the pulse repetition interval (PRI). This concept allows high-resolution imaging of a wide continuous swath without the need for a long antenna with multiple apertures.*

## 1. Introduction

Synthetic Aperture Radar (SAR) is an established remote sensing technique, capable of acquiring high resolution images of the Earth’s surface independent of weather conditions and sunlight illumination. Further unique opportunities emerge from interferometric techniques, which are based on 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 imaging modes for different trade-offs between resolution and coverage: In stripmap mode (spatial resolution of 3 m), only 2% of the Earth’s landmass can be mapped during its 11 days repeat cycle.

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 mapping the whole Earth’s surface twice per week, in full polarization and with a spatial resolution well below 10 m. Other missions may require a higher spatial resolution, although without the need for such frequent coverage.

If a single satellite is available, frequent and seamless coverage can only be achieved if a wide swath is imaged. In conventional stripmap SAR, the swath width constrains the pulse repetition interval (PRI): to control range ambiguities, the PRI must be larger than the time it takes to collect returns from the entire illuminated swath. On the other hand, to avoid significant azimuth ambiguity levels, a large PRI, or equivalently a low pulse repetition frequency (PRF), implies the adoption of a small Doppler bandwidth and limits the achievable azimuth resolution. A wide swath can be also mapped using ScanSAR or TOPS, but the azimuth resolution is still impaired.

To overcome these limitations, new radar techniques have been developed, which allow for the acquisition of spaceborne high-resolution SAR images without the classical swath limitation imposed by range and azimuth ambiguities. These techniques are mainly based on digital beamforming (DBF) and multiple aperture signal recording. DBF on receive is used to steer in real-time a narrow beam towards the direction of arrival of the radar echo from the ground, exploiting the one-to-one relationship between the radar pulse travel time and its direction of arrival. A large receiving antenna can hence be used to improve the sensitivity without narrowing the swath width. As the unambiguous swath width is limited by the antenna length, a long antenna is deployed to map a wide swath. Moreover, to improve the azimuth resolution, the receive antenna is divided into multiple sub-apertures, mutually displaced in the along-track direction and connected to individual receive channels. By this, multiple samples can be acquired for each transmitted pulse. The coherent combination of all signals in a dedicated multichannel processor enables the generation of a high-resolution wide-swath SAR image. The need for a very long antenna represents the main limitation of the mentioned system: A 40 m antenna is, in fact, required to map a 350 km swath width on ground in stripmap imaging mode.

In order to keep the antenna length down, several new instrument architectures and modes have been proposed in [1]. Of particular interest are multi-beam modes, based on simultaneous recording of echoes of different pulses, transmitted by a wide beam illuminator and coming from different directions. In this way multiple swaths, each of width equal to the conventional stripmap SAR swath width, can be simultaneously imaged. A drawback of the multi-beam mode, however, is the presence of blind ranges between the adjacent swaths, as the radar cannot receive while it is transmitting.

## 2. The Staggered SAR Concept

The Staggered SAR concept overcomes this drawback by continuously varying the PRI in a cyclic manner. If the PRI is continuously varied, the locations of the blind ranges will be, in general, different for each transmitted pulse. If the overall synthetic aperture is considered, it turns out that at each slant range only some of the transmitted pulses are missing. In particular, if a sequence of PRIs is chosen so that the missing pulses are almost uniformly distributed across the swath, a relatively small percentage of pulses is missing at each range and azimuth compression can still be performed over a wide continuous swath [2].

## 3. Design of PRI Sequences

The first issue that has to be addressed when designing a Staggered SAR system is the choice of the sequence of PRIs, which will then repeat cyclically. In particular, the minimum PRI $PRI_{\min}$ of the sequence has to be kept large enough to control range ambiguities, while the maximum PRI $PRI_{\max}$ has to be kept small enough to ensure proper sampling in azimuth. In principle, the PRIs can be arbitrarily chosen in the interval [$PRI_{\min}$, $PRI_{\max}$], however the location of the missing pulses is easily controllable, if a linear PRI trend is selected

$$PRI_m = PRI_{m-1} - \Delta = PRI_0 - m\Delta, m = 1..M-1 , \tag{1}$$

where $\Delta$ is the difference between two consecutive PRIs and $M$ is the number of PRIs of the sequence.

### *3.1 Slow PRI Change*

It the PRI is constant, blind range areas are located at fixed slant range along azimuth. If a long sequence of PRIs with a linear slowly-changing trend is employed, it can be observed that blind range areas are no longer strips parallel to the along-track axis, but they are instead tilted, where the tilt angle increases, as the PRI span increases. As a limited PRI span has the advantage to ensure proper sampling in the azimuth direction, without significantly impacting range and azimuth ambiguities, a reasonable criterion to design sequences of PRIs is to choose the minimum PRI span, such that blind ranges are almost uniformly distributed over the slant range of interest. This means that the blind areas are tilted such that at far range they span over a slant range equal to the distance of two consecutive blind ranges in a uniform PRI case. It can be shown that $PRI_{\min}$ and $PRI_{\max}$ have to be chosen such that

$$\frac{1}{PRI_{\min}} - \frac{1}{PRI_{\max}} = \frac{c_0}{2R_{0\max}}, \tag{2}$$

where $c_0$ is the speed of light in free space and $R_{0\max}$ is the maximum slant range of interest, and that $M$ has to be chosen such that the sum of the $M$ PRIs is much smaller than the illumination time at near range. As the PRI spans between $PRI_{\min}$ and $PRI_{\max}$, it can be observed that a large gap and a very short gap occur at each slant range [2]. The presence of large gaps in the raw azimuth signal, however, will determine the presence of high sidelobes in the azimuth impulse response in the vicinity of the main lobe [2].

### *3.2 Fast PRI Change*

Another possibility is to design the sequence of PRIs such that in the raw azimuth signal two consecutive samples are never missed. In this case, if the mean pulse repetition interval is decreased, i.e. if the signal is averagely oversampled, it is possible to recover the missing samples by means of interpolation, so avoiding the high sidelobes in the azimuth impulse response. With reference to (1), it can be shown that Δ and $M$ have to be chosen as

$$\Delta = \frac{2\tau}{k^*} \tag{3}$$

and

$$M = \left\lceil \frac{\left(PRI_0 + \frac{\Delta}{2}\right) - \sqrt{\left(PRI_0 + \frac{\Delta}{2}\right)^2 - 2\Delta\left(\frac{2R_{0\max}}{c_0} - PRI_0 + \tau + \left(PRI_0 + \frac{\Delta}{2}\right)k^* - \frac{\Delta}{2}k^{*2}\right)}}{\Delta} \right\rceil, \tag{4}$$

respectively, where

$$k^* = \left\lfloor \frac{\frac{2R_{0\min}}{c_0} + PRI_0 - 2\tau}{PRI_0 - \tau} \right\rfloor, \tag{5}$$

τ is the uncompressed transmitted pulse length and $R_{0\min}$ is the minimum slant range of interest. For the same $PRI_0$, this criterion leads to a much higher value of Δ, i.e. the PRI change is much faster, and to a slightly lower $PRI_{\min}$. It will be therefore necessary to increase the antenna height in order to keep the same range ambiguity-to-signal ratio (RASR). Sequences of PRIs with fast PRI change have the advantage of the limited maximum pulse separation, which allows the recovery of missing samples by interpolation. In contrast to sequences with slow PRI change, no high sidelobes are present in the azimuth impulse response in the vicinity of the main lobe.

### *3.3 More Elaborated Sequences*

However, due to the periodicity of the gaps, more distant sidelobes are anyway present in the azimuth impulse response. The energy of such sidelobes can be spread along azimuth introducing some irregularity in the sequence of PRIs, but still keeping the property for which two consecutive azimuth samples are never missing.

## 4. Signal Processing

As sequences of distinct PRIs are employed and the lost pulses are different for each range, the raw signal recorded by a Staggered SAR system is inherently non-uniformly sampled. Uniform sampling is not a strict requirement for SAR imaging, as an image can be obtained by focusing each pixel independently, having knowledge of the relative time delays. However, the computational cost would be significant, as the processing would be performed in time domain. As an alternative, raw data could be resampled to a uniform grid and then conventional SAR processing could be performed in frequency domain [3]-[4]. Some resampling methods are discussed in the following.

The simplest way to resample a non-uniformly sampled signal to a uniform grid is to use a two-point linear interpolator. Each complex sample of the uniform grid is obtained by a weighted average of the closest preceding and succeeding complex samples. The computational cost is small.

As the raw azimuth signal is non-uniformly sampled, but at the same time the non-uniform sampling is recurrent, an alternative approach to the resampling is based on a generalised sampling expansion and consists of recovering the uniformly sampled signal by means of multi-channel reconstruction [3]-[4], as done for multiple aperture systems. As the received azimuth signal is not strictly band-limited, a reconstruction error will be present, as the signal components outside the above mentioned frequency band fold back to the main part of the spectrum and disturb the reconstruction of the signal itself. For long sequences, however, such signal components may be significantly amplified, making the reconstruction of the signal no longer possible. Moreover, the reconstruction filters may significantly amplify the noise.

The best way to account for the statistical properties of the raw azimuth signal is to make use of the knowledge of its power spectral density (PSD) to obtain its autocorrelation function. The mutual correlations between samples can then be exploited to find the best linear unbiased (BLU) estimates of the signal itself at the desired locations.

The recovered uniformly-sampled raw azimuth signal is then focused using a conventional SAR processor. The effects of range cell migration (RCM) and their implications on the 2D signal reconstruction have also to be considered. However, it can be shown that the range offset is negligible, as the time difference between the samples in the non-uniform and uniform grids is of the order of tenths of a millisecond.

## 5. Performance Analysis

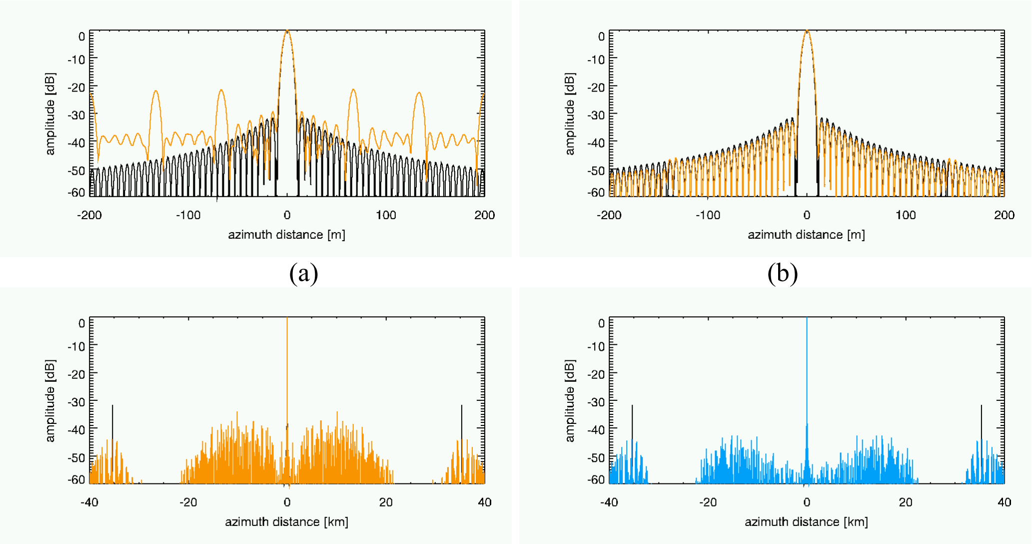
The performance of a system based on the Staggered SAR concept strongly depends on the selected sequence of PRIs and the adopted resampling method.

In order to show how the azimuth impulse response is impacted by the sequence of PRIs, two sample sequences, characterized by the same mean PRI (0.385 ms), are considered, one with slow PRI change and another more elaborated one, where two consecutive azimuth samples are never missed. A scenario is considered, with an orbit height $h_S$ = 760 km, a wavelength $\lambda$ = 0.2384 m (L-band) and a planar antenna of length $L$ = 10 m. The azimuth processed bandwidth is set to $PBW$ = 1050 Hz. Moreover, an azimuth Hamming window ($\alpha$ = 0.6) and a window, which compensates for the azimuth antenna pattern, are applied, leading to an azimuth resolution of 7 m. Partially received pulses are discarded in our analysis.

Figs. 1 (a) and 1 (b) show the azimuth impulse responses for the two sequences, using two-point linear interpolation for a slant range $R_0$ = 1000 km. The underlying black curves represent the reference impulse response of a SAR system with a constant PRI, equal to the mean PRI of the sample sequences. As apparent, high sidelobes are present in the azimuth impulse response in the vicinity of the main lobe, if the sequence with slow PRI change is used. This is not the case of the sequence, where two consecutive samples are never missed. For the latter sequence, more distant sidelobes are present, as shown in Fig. 1 (c), where the same impulse response function of Fig. 1 (b) is represented over a larger azimuth scale.

Concerning the interpolation technique, multi-channel reconstruction is not able for these long sequences to reconstruct the raw azimuth signal, as the signal components outside the main frequency bandwidth are significantly amplified and the resulting impulse response functions have sidelobes of the same amplitude or even higher than the main lobe. In contrast, a noticeable lower level of sidelobes is obtained, if best linear interpolation is used in place of two-point linear interpolation (cf. Fig. 1 (c) and Fig. 1 (d)). With reference to the underlying impulse response function of a reference constant PRI SAR, the level of azimuth ambiguities is much lower. This means that a Staggered SAR system is even less affected by azimuth ambiguities of point-like targets.

In addition, as far as range ambiguities are concerned, in a Staggered SAR system, the ambiguous components of a strong point like target are located at different ranges for different range lines, as the time distance to preceding and succeeding pulses continuously varies. This means that, after azimuth focusing, the ambiguous energy is spread almost uniformly at all ranges. Range ambiguities appear therefore smeared and the same applies to nadir echoes, which result from the same phenomenon. The RASR has to be evaluated for each slant range and for each of the $M$ transmitted pulses of the sequence. Due to the uniform distribution of the ambiguous energy, the RASR is then obtained for each slant range by averaging the RASR obtained for the $M$ transmitted pulses. Better results are obtained, if adaptive digital beamforming approaches are considered.

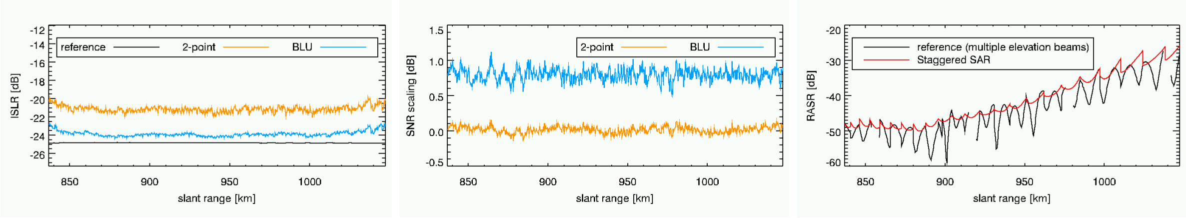


(a) (b)

(c) (d)

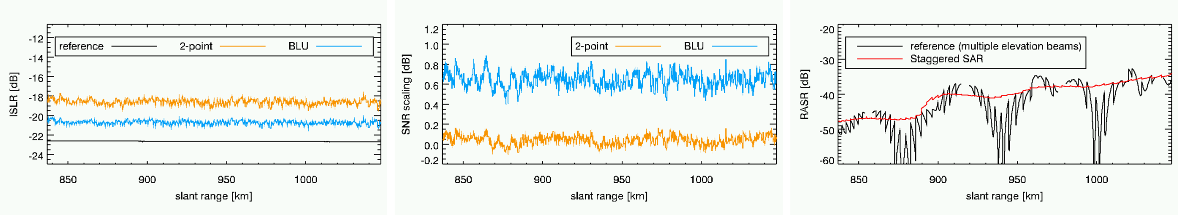
Figure 1. Azimuth impulse responses for different sequences of PRIs and interpolation techniques. (a) Slow PRI change, two-point interpolation. (b) More elaborated sequences, two-point interpolation (400 m azimuth scale). (c) More elaborated sequences, two-point interpolation (80 km azimuth scale). (d) More elaborated sequences, BLU interpolation (80 km azimuth scale).

Two design examples for an L-band SAR system are presented in the following, based on a 15 m reflector and a 10 m planar antenna, respectively. The parameters concerning the observation geometry are taken from [5]. As far as the planar antenna is concerned, it is assumed that a uniform transmit pattern over the swath of interest is obtained using specific tapers or a separate shorter antenna. Figs. 2 and 3 display the performance in terms of integrated side lobe ratio (ISLR), signal-to-noise ratio (SNR) scaling factor and RASR, for the reflector and the planar antenna respectively. One of the more elaborated sequences has been considered, while both two-point linear interpolation and best linear interpolation have been considered. In both examples a 350 km wide swath is imaged with a 7 m azimuth resolution. As apparent from Fig. 2 (c) and Fig. 3 (c), four blind range areas of slant range width of 4.5 km are present across the swath for a conventional SAR system with multiple elevation beams. The ISLR is better for the reflector, due to the lower sidelobes of the azimuth antenna pattern, while the noise scaling is comparable for the two cases. In both cases, using BLU interpolation, the loss in terms of ISLR with respect to a reference constant PRI system is always smaller than 2 dB. In addition, azimuth ambiguities appear as smeared. As far as range ambiguities are concerned, they become significant at high incidence angles for the reflector; therefore it is suggested for such a system that a tilt angle smaller than the one of the observation geometry of [5] is adopted. It has to be stressed that for a Staggered SAR system the requirements in terms of ambiguities can be relaxed with respect to a conventional SAR system, due to the above mentioned spreading effect. Moreover, a very simple antenna pattern in elevation has been used for design examples: A more careful antenna design, which is beyond the scope of this analysis, would lead to a significant performance improvement.



(a) (b) (c)

Figure 2. Performance prediction for the reflector-based design example. (a) ISLR [dB] vs. slant range. (b) SNR scaling [dB] vs. slant range. (c) RASR [dB] vs. slant range.



(a) (b) (c)

Figure 3. Performance prediction for the design example based on the planar antenna. (a) ISLR [dB] vs. slant range. (b) SNR scaling [dB] vs. slant range. (c) RASR [dB] vs. slant range.

## 6. Conclusions

Staggered SAR allows HRWS imaging without the need for a long antenna with multiple apertures. The system gets rid of blind ranges by continuously varying the PRI along the track.

The selected sequence of PRIs and the method used to resample the raw data significantly impact the performance. According to the analyses carried out in this paper, sequences have to be used where two consecutive azimuth samples are never missed, better if in combination with best linear interpolation. The slightly increased SNR scaling factor associated to the latter technique with respect to two-point interpolation, in fact, is justified by the improved ISLR. Further design criteria for the sequences of PRIs, as well as resampling methods, can be developed, but the first results already suggest that the Staggered SAR concept will play an important role in the design of future spaceborne SAR systems with high-resolution wide-swath capability.

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 [6].

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