

Advanced Digital Beamforming Concepts for High Performance Synthetic Aperture Radar (SAR) Imaging

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Abstract— This paper reviews advanced multi-channel SAR system concepts for the imaging of wide swaths with high resolution. Several novel system architectures employing both direct radiating arrays and reflector antennas fed by a digital array are introduced and compared to each other with regard to their imaging performance. In addition, innovative operational SAR imaging modes are proposed which enable the mapping of ultra-wide swaths with high azimuth resolution. The new techniques and technologies introduced in this paper have the potential to enhance the imaging performance of future SAR systems by one order of magnitude if compared to state of the art SAR sensors like TerraSAR-X, ALOS, Radarsat-2 or Sentinel-1.

I. INTRODUCTION

Wide unambiguous swath coverage and high azimuth resolution pose contradicting requirements on the design of spaceborne synthetic aperture radar (SAR) systems [1]. This motivated the development of advanced SAR imaging modes with different trade-offs between spatial coverage and azimuth resolution. Examples are the ScanSAR (or TOPS) mode which enables a wide swath at the cost of an impaired azimuth resolution [2][3] and the Spotlight mode which allows for an improved azimuth resolution at the cost of a noncontiguous imaging along the satellite track [4]. It is, however, up to now not possible to combine both operational modes simultaneously in one and the same data take. This dilemma motivated further research towards the development of new radar techniques for spaceborne high-resolution wide-swath SAR imaging.

A promising candidate for such a new radar imaging technique is digital beamforming on receive where the receiving antenna is split into multiple sub-apertures. In contrast to analog beamforming, the received signals from each sub-aperture element are separately amplified, down-converted, and digitized. This enables an a posteriori combination of the recorded sub-aperture signals to form multiple beams with adaptive shapes. The additional information about the direction of the scattered radar echoes can then be used to (1) suppress spatially ambiguous signal returns from the ground, (2) to increase the receiving antenna gain without a reduction of the imaged area, (3) to suppress spatially localized interferences, and (4) to gain additional information about the dynamic behavior of the scatterers and their surroundings. By this, it becomes possible to overcome fundamental limitations of conventional SAR systems [5]-[20].

II. MULTI-CHANNEL SAR SYSTEMS WITH DIRECT RADIATING ARRAYS

Several proposals resolve the azimuth resolution vs. coverage dilemma by combining a multi-channel radar receiver with a fixed small aperture transmitter illuminating a wide area on the ground. An early example is a multiple beam SAR operating in a squinted imaging geometry [6][7]. The squinted geometry allows for the simultaneous imaging of multiple swaths at an almost constant incident angle and the combination of the sub-swaths yields a wide image swath without ambiguities (Figure 1, left). Major drawback of this system is the high squint angle that complicates the processing and impairs the performance. Another promising approach is the displaced phase centre antenna technique [5]. The basic idea behind this system is to use multiple apertures in the along-track direction and to acquire for each transmitted pulse additional samples along the synthetic aperture (Figure 1, second column). As a result, the transmit PRF can be reduced which enables in turn the unambiguous mapping of a wider image swath. An extension of the DPCA technique is the Quad Array system [9] which employs additional apertures in elevation to suppress range ambiguous returns [8]. By this, one may further increase the image swath, but the drawback is a range gap in the middle of the wide swath since it is impossible to simultaneously transmit and receive radar pulses (Figure 1, third column). A further extension of the DPCA technique is the High-Resolution Wide-Swath (HRWS) SAR system [12][14]. This system combines a separate small transmit antenna with a large receiver array as illustrated in the fourth column of Figure 1. The small transmit antenna illuminates a wide swath on the ground and the large receiver array compensates the Tx gain loss by a real time digital beamforming process in elevation called scanning on receive (SCORE). Multiple azimuth channels allow furthermore for the imaging of a wide swath without rising azimuth ambiguities. The combination of the azimuth signals from multiple displaced apertures requires the application of dedicated multi-channel SAR signal processing algorithms as introduced in [13] and further elaborated in [15].

The HRWS concept relies on a fixed wide-area illumination by a separate transmit antenna. This enables an independent electrical design and optimization of the transmit and receive paths, but it requires also the accommodation of an additional antenna on the spacecraft and reduces the flexibility to operate the radar system in different SAR imaging modes like ultra-wide-swath ScanSAR, high SNR spotlight, or new hybrid modes to be discussed later. It is hence worth to consider also the application of digital beamforming techniques in radar systems that use the same antenna for both the transmission and reception of radar pulses, thereby taking advantage of already existing space-qualified T/R module technology. Since a large aperture corresponds typically to a narrow beam, this poses in turn the question of how to distribute the signal energy on the ground. The trivial solution for a large-area direct radiating array would be amplitude tapering, or as an extreme case, the use of

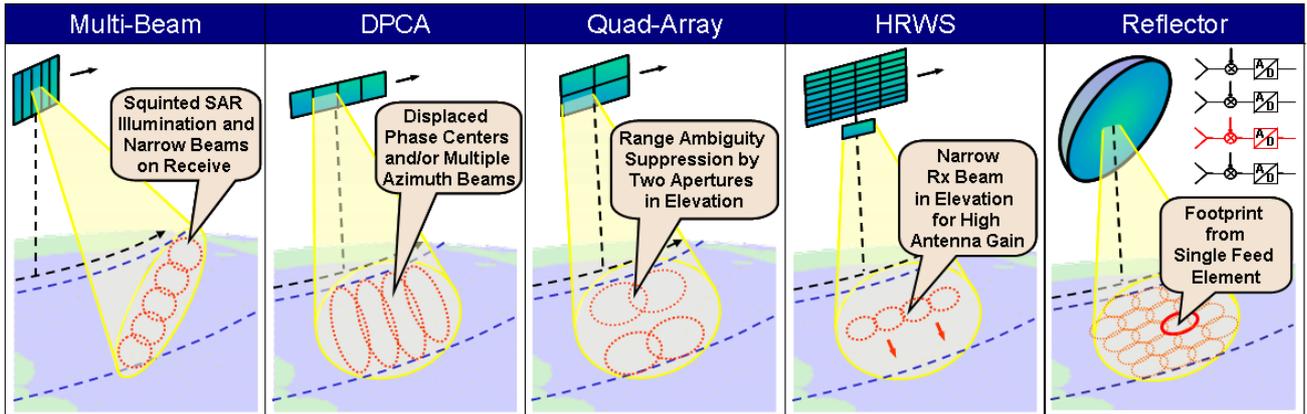


Figure 1– Solutions for high-resolution wide-swath SAR imaging. Left: multiple beam SAR [6][7]. Middle left: displaced phase center antenna technique [5]. Middle: quad-element rectangular array SAR [9]. Middle right: high-resolution wide-swath (HRWS) SAR [12][14]. Right: High resolution wide swath SAR employing a reflector antenna in combination with a digital feed array.

only a part of the antenna as suggested for the Multi-Beam or Quad-Array SAR, but this causes a significant loss of efficiency. Another option is phase tapering, but the derivation of appropriate phase coefficients is an intricate task which requires in general complicated numerical optimization techniques. Further promising solutions are spatiotemporally non-separable Tx waveforms [17] or the combination of reflector antenna technology with a multi-channel feed system as outlined in the following section.

III. REFLECTOR ANTENNAS WITH DIGITAL FEED ARRAYS

An interesting alternative to a direct radiating array is the combination of a reflector antenna with a digital feed array as illustrated schematically in Figure 2 on the left. Such a hybrid architecture has the potential to combine both the flexibility and the capabilities of digital beamforming with the high gain and directivity provided by a large reflector aperture¹ [18][19][20]. To lower the stowed satellite volume and weight, and therefore the launch costs, the reflector could be deployable as already suggested for several future L-band radar missions [21][22][23]. Unfurlable reflector antennas are now a mature technology with extensive flight heritage in space telecommunications and satellites with lightweight mesh reflectors spanning diameters of more than 20 m will be deployed in space in the near future [24].

The reflector based digital beamforming architecture offers several very attractive features for future high performance spaceborne SAR systems. For example, the simultaneous activation of all feed elements generates a broad transmit beam for wide area illumination. At the same time, spill-over losses are minimized since only a small central portion of the reflector aperture is illuminated by the feed array. The red curve in the center plot of Figure 2 shows as an example the L-band transmit pattern of a 15 m reflector antenna with a f/d of $2/3$ and a centre fed linear array that consists of 24 feed elements. The opportunity to use all feed elements simultaneously for the generation of a wide transmit beam avoids the necessity of a separate transmit antenna as suggested for the HRWS system and/or the use of sophisticated illumination strategies in case of using a combined Tx/Rx array [17]. On the other hand, radar echoes arriving as plane waves from a given direction activate typically only one or a small number of feed elements if the feed array is located close to the focal plane (cf. Figure 2).

The systematic correspondence between beam direction and activated feed array element(s) is well suited to significantly enhance the imaging performance of future side-looking radar sensors where the scattered radar echoes arrive at each instant of time only from a rather narrow angular range². The angle of arrival migrates in synchrony with range time as the radar echoes arrive in successive order from near to far range. By using this correspondence, a significant improvement in the sensitivity (NESZ) and range ambiguity suppression can be achieved via a simple dynamic routing and recording of those feed signal(s) that exceed a given threshold level. The solid and dotted blue curves in the centre plot of Figure 2 show the

¹ A reflector antenna offers moreover the potential to use one and the same aperture for multiple frequency bands simultaneously, thereby paving the way for future multi-frequency SAR systems.

² For a long chirped transmit pulse, the radar echoes arrive from slightly different angles for each range frequency. Optimum sensitivity requires hence a “dispersive Rx beam”. Such a beam can be synthesized by a bandpass decomposition (in range frequency) for each recorded feed element signal, followed by a different feed element combination for each sub-band. Simply speaking, this corresponds to a division of the echo from a long chirped Tx pulse into multiple echoes from short narrow-frequency pulses and an optimum beam can then be formed for each of these short sub-pulses.

resulting antenna patterns for activating feed elements #12 and #22, respectively. It is clear that the gain of the narrow Rx pattern is about 10 dB higher than that for the broad Tx pattern, thereby compensating the gain loss from the illumination of a wide image swath.

A further improvement of the performance can be achieved by combining the signals from multiple feed elements. This improvement can be seen from the illustration on the right hand side of Figure 2 which shows the Rx “sensitivity” patterns for (1) selecting for each angle the element with maximum gain (dotted blue), (2) linear summation of the signals from 5 neighbouring elements with unity weights (solid blue), and (3) optimum phase and amplitude weighted combination of 5 neighbouring element signals (conjugate field matching, black solid line, see also [26]). It becomes clear that the digital combination of multiple feed element signals can significantly improve the performance, yielding a higher and smoother sensitivity pattern. The latter is especially desired to avoid phase jumps for interferometric applications and to relax radiometric calibration requirements.

Digital beamforming in a reflector based antenna system involves typically only the combination of a low number of array elements. This significantly reduces the on-board processing requirements if compared to a direct radiating array. For example, only 5 element signals have been combined at each instant of time in the conjugate field matching simulations of Figure 2. In contrast, a real time scan-on-receive with a 15 m high planar array would require the onboard combination of more than 50 element signals. The increased performance achievable by a large reflector aperture relaxes also the satellite’s thermal, power and energy demands and/or allows for longer operation times as desired for future wide area systematic Earth monitoring missions which ask for long orbital duty cycles [25].

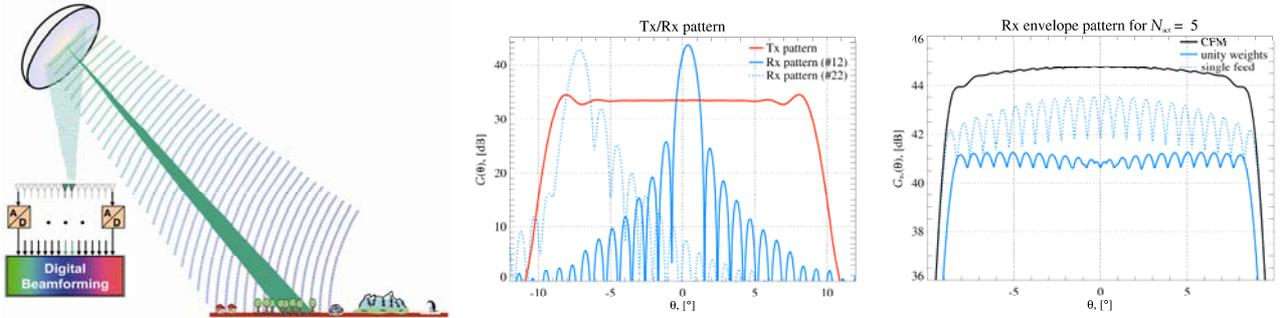


Figure 2 – Digital beamforming with large reflector antennas. The beam direction to feed element correspondence enables implementations of digital beamforming with reduced complexity, e.g. via selective routing or real-time conjugate field matching by a coherent combination of a small subset of element signals which exceed a given threshold.

IV. OPERATIONAL MODES

In the previous two sections we discussed different multi-channel architectures for future high-resolution wide-swath SAR systems. In the following, we introduce and compare different SAR imaging modes that take advantage of the new digital radar architectures. As a design example we consider a system which shall be able to map a swath width of approx. 400 km with an azimuth resolution of 5 m. Such a system exceeds by far the capabilities of current spaceborne SAR sensors. To avoid a too strong variation of the incident angles we assume in the following an orbital altitude of 750 km.

A. Multi-Channel Stripmap Mode

We first consider a multi-aperture mapping in standard strip-map mode. The timing diagram in Figure 3 reveals that the imaging of a contiguous 400 km swath requires a PRF of approximately 400 Hz. For this PRF, the minimum and maximum incident angles are 24° and 48° , respectively. To avoid azimuth ambiguities, the necessary antenna length can be approximated by $l_{ant} \approx 2v/PRF$ which yields an antenna length of $l_{ant} \approx 35$ m. The azimuth resolution of a conventional single channel SAR would then be in the order of $\Delta az \approx 20$ m. By illuminating a wider Doppler spectrum and dividing the receiver antenna into multiple azimuth apertures with individual receiver channels it becomes possible to improve the azimuth resolution to $\Delta az \approx l_{ant}/(2N_{az})$ where N_{az} is the number of independent azimuth channels. The desired azimuth resolution of 5 m would hence require at least $N_{az}=4$ channels. Such a resolution improvement by multiple azimuth Rx channels is possible for both the direct radiating array and the reflector configuration. As illustrated in Figure 4, the performance gain can be understood in the former

case as the acquisition of additional samples along the synthetic aperture and in the latter case as the acquisition of additional frequency sub-bands with different Doppler centroids to increase the overall azimuth bandwidth.

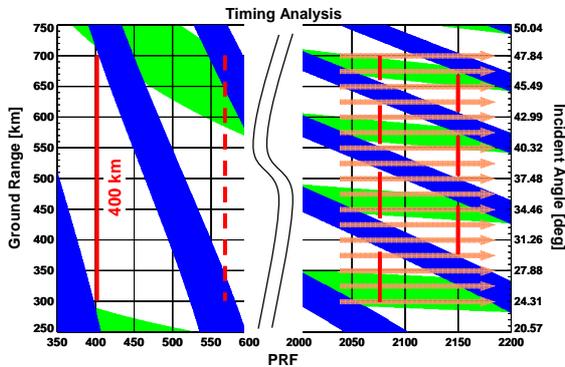


Figure 3 – Timing for $h_{sat} = 750$ km and a duty cycle of 16%.

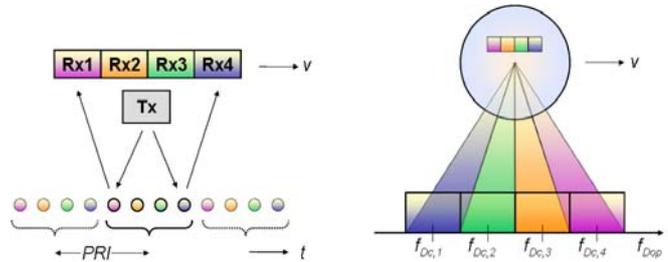


Figure 4 – Left: Multi-aperture receiver antenna for the acquisition of additional samples along the synthetic aperture. Right: Reflector antenna configuration with displaced feed elements for the simultaneous acquisition of multiple azimuth frequency sub-bands with different Doppler centroids.

B. Multi-Channel ScanSAR Mode

The major drawback of the multi-channel stripmap mode is the long antenna required for unambiguous wide swath SAR imaging. An alternative to map the 400 km swath is the ScanSAR or TOPS mode [2][3]. Assuming an antenna length of 12 m, the minimum PRF is in the order of 1.25 kHz. Timing considerations reveal that at least 4 bursts would be required to cover a 400 km swath. The azimuth resolution is then $\Delta az > (N_{burst}+1) \cdot l_{ant}/2$ where N_{burst} is the number of bursts. The achievable azimuth resolution is (under optimistic assumptions) in the order of $\Delta az \approx 35\text{-}40$ m. To achieve an azimuth resolution of $\Delta az = 5$ m one may again employ multiple azimuth channels connected to displaced antenna elements. The minimum number of azimuth channels is $N_{az} > l_{ant} \cdot (N_{burst}+1) / (2\Delta az)$. Hence, at least 7 channels will be required. Challenges may arise for the multi-aperture processing from the large squint angles, the varying target Doppler spectra, and the different burst PRFs. The middle column of Figure 5 illustrates the Doppler frequency dependent weighting by the multi-channel azimuth reconstruction filter network [16]. As a result, the azimuth ambiguity to signal ratio (AASR) shows a significant variation with both the azimuth position and the burst PRF as illustrated in Figure 5 on the right. A detailed performance analysis together with an extension to a multi-channel TOPS mode can be found in [16].

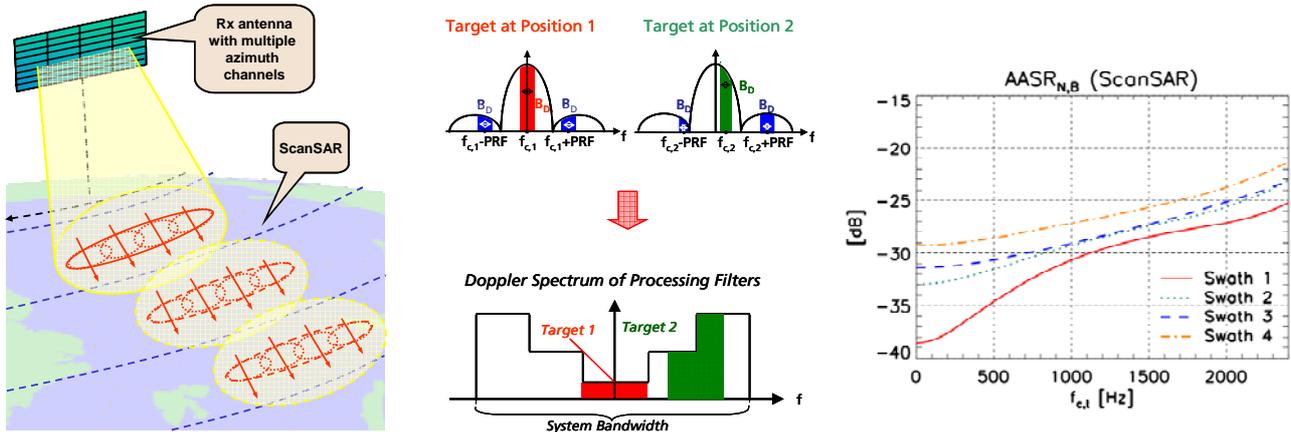


Figure 5 – Multi-channel ScanSAR and TOPS modes allow for the high-resolution mapping of a wide image swath with a moderate antenna size. The use of multiple azimuth channels in the receiving antenna enables an improved azimuth resolution if compared to a conventional ScanSAR or TOPS system. Challenges arise for the multi-aperture SAR processing due to the non-uniform azimuth sampling which results from the different burst PRFs.

C. ScanSAR with Multiple Elevation Beams

The mapping of a wide image swath with a reasonable short antenna length requires, especially in fully polarimetric mode, a large number of bursts. This impairs the performance and leads to conflicts with regard to the achievable azimuth resolution. Such problems can be mitigated by a simultaneous mapping of multiple swaths during each burst as illustrated in Figure 6.

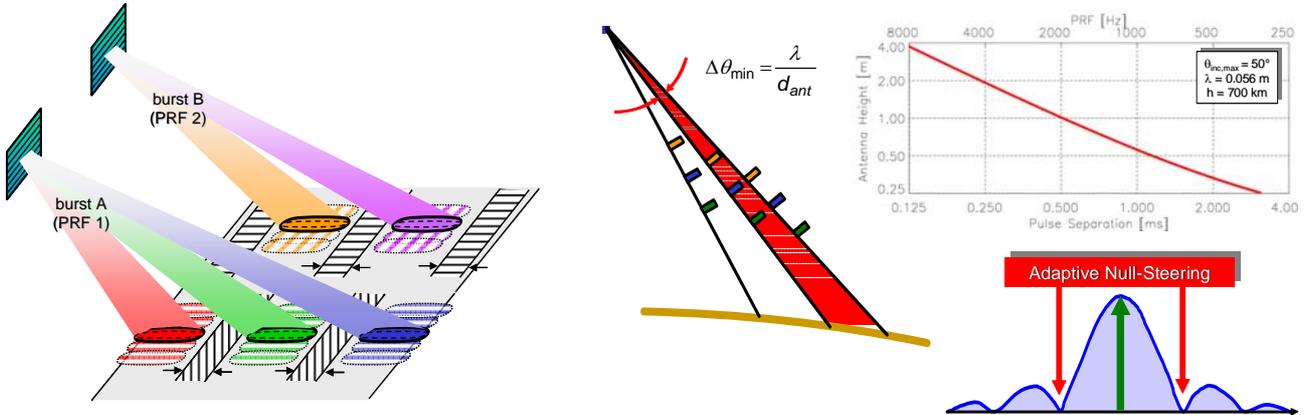


Figure 6 – SAR imaging with multiple beams in burst mode operation. Range ambiguities from the simultaneous mapping of multiple swaths can (but must not) be suppressed by null-steering.

The right hand side of Figure 3 shows that two bursts with slightly different PRFs are sufficient to map an ultra-wide swath if it is possible to suppress range ambiguities and nadir echoes by digital beamforming on receive in elevation³. The strength of the nadir signal can also be reduced by a careful design of the Tx antenna pattern and a further improvement is possible by using different waveforms for each transmitted pulse which enables a spread of the nadir energy in the received echoes.

The two PRFs in Figure 3 on the right are sufficient to “avoid” azimuth ambiguities for a 7.5 m antenna length. In combination with 3 azimuth channels one could then obtain an azimuth resolution of $\Delta az \approx 4$ m. Assuming a range ambiguity suppression via null-steering as illustrated in Figure 6 on the right, the minimum antenna heights to separate the pulses from the different swaths are 0.6 m, 1.1 m, and 4.4 m for X-, C-, and L-band, respectively, but typically a much higher antenna should be used to improve the performance.

D. Advanced SAR Modes with Multiple Rx Beams in Elevation

An inherent peculiarity of the multiple swath ScanSAR mode is that it is not possible to adapt the burst-length to the varying ranges in order to achieve a constant azimuth resolution that is (almost) independent of slant range. In our example, the azimuth resolution varies by a factor of 1.3 across the 400 km swath with the best resolution in near range. On the other hand, one can combine more bursts in the far range beams to improve the radiometric resolution. If one wants to maximize the radiometric resolution for each range, one could even consider a continuous variation of the PRF during the target exposure time. As an example, a periodic linear increase of the PRF from 2040 Hz to 2180 Hz shifts the blind ranges smoothly across the swath (cf. arrows in Figure 3 on the right). For each range one obtains then a contiguous burst of Rx pulses as illustrated in Figure 7⁴. The SAR focusing of each burst requires an appropriate preprocessing which interpolates the (multi-channel) azimuth raw data to a uniform sampling interval.

Another opportunity arises in case of very short transmit pulses [28]. In this case, one loses for each range only a short segment of the synthetic aperture and one may then consider a coherent processing of the full azimuth spectrum, which yields a range independent azimuth resolution of approx. half the antenna length for an arbitrary swath width. The interpolation of the gaps will increase the integrated sidelobe ratio (ISLR) of the impulse response, but for short duty cycles this effect can be made sufficiently small. An azimuth resolution of 5 m would hence require an antenna length in the order of 10 m. The minimum PRF is then given by $PRF > 2v/l_{ant} \approx 1.6$ kHz and a PRF variation of about 200 Hz is sufficient to shift the blind ranges across

³ A reflector antenna based digital beamforming receiver could have the advantage to avoid possible saturation effects in the receiver channels that could otherwise arise in case of very strong nadir returns.

⁴ Note that the periodic jump from the highest to the lowest PRF may cause an additional short gap, which can, however, be interpolated without a notable performance degradation.

the whole swath width. Referring to the right hand side of Figure 6, the minimum antenna height to suppress range ambiguities would hence be the order of 1 m for a single-pol mode and 2 m for a quad pol mode in C-band. This example shows that an antenna area of about 10 m² would from signal theoretical point of view be sufficient to map an arbitrary wide swath with a single pol C-band system (up to incident angles of about 50°). Note that this result remains also valid if we choose a different azimuth resolution since the antenna length $l_{ant} \sim 1/PRF$ is always traded against the antenna height $h_{ant} \sim PRF$. The “multiple beam variable PRF” mode is also of special interest for a reflector based digital beamforming system where we can benefit from the high antenna for improved range ambiguity suppression. Moreover, a large reflector aperture allows also for a high Rx gain, thereby enabling the usage of very short Tx pulses as desired to minimize the gap losses.

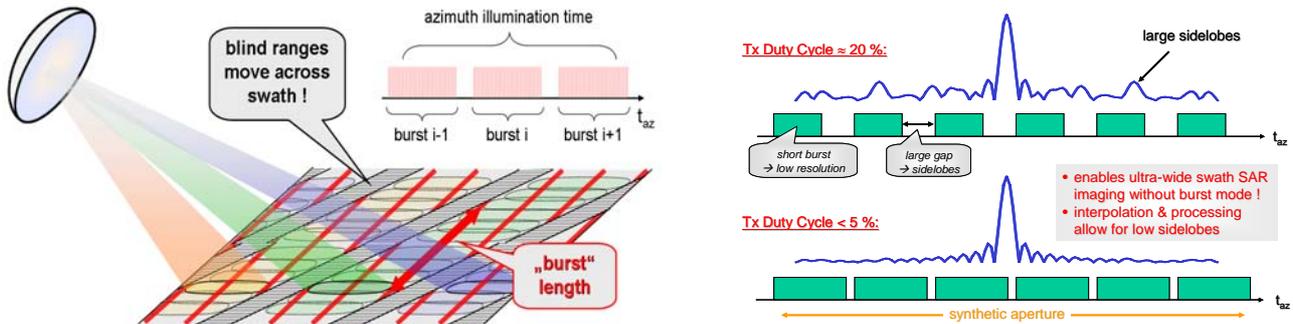


Figure 7 – Multiple swath imaging with variable PRF. Nadir echoes are sufficiently suppressed by combining the Tx antenna pattern with the narrow receiver beams obtained from the real-time digital beamforming. The use of very short Tx pulses allows even for an interpolation without a too severe increase of the integrated sidelobe ratio (ISLR).

E. Irregular PRI Sampling

Another elegant solution to fill in the blind ranges has been suggested in [27]. The basic idea in [27] is to use a short repetitive sequence (burst) of transmit pulses with non-uniform inter-pulse time delays. The pulse sequence is designed such that one loses for each transmitted burst only one swath echo if a fixed range is considered. As a result, the recorded azimuth signals are sampled with a rather strong degree of irregularity since both the non-uniform PRI intervals and the missed samples contribute to the non-equidistant azimuth sampling⁵. Hence, the SAR processing requires an adequate reconstruction algorithm to avoid a too severe increase of the azimuth ambiguities [13][15].

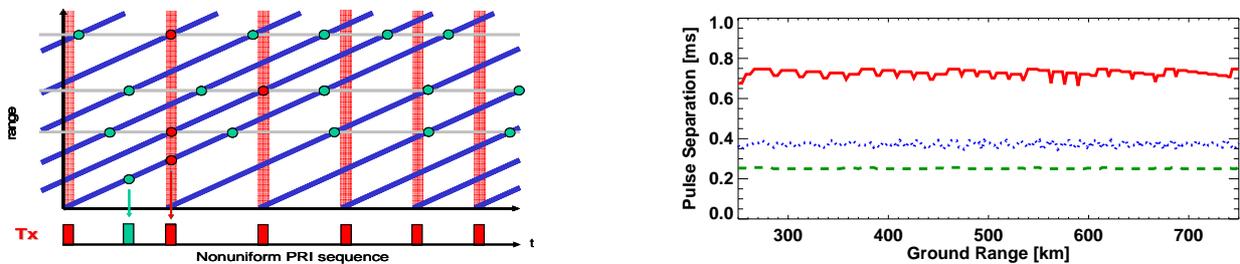


Figure 8 – (Left) Irregular sequence of Tx pulses (red) and resulting azimuth sampling for three slant range positions (green dots). (Right) Maximum (solid), mean (dotted), and minimum (dashed) separation of recorded pulses from nonuniform PRI transmission.

An alternative to the short recurrent pulse sequence is an optimized and slower variation of the pulse intervals that takes also into account the traveling pulses in a spaceborne radar geometry. This optimization yields for each considered range an almost constant number of recorded pulses. By adapting the length of the whole sequence to the satellite height one could even ensure an overlap of the Tx events with the nadir returns. The optimization can moreover employ different pulse lengths, which allow also for a range-dependent distribution of the Tx power across the wide swath. Figure 3-22 shows the azimuth sampling gaps for an exemplary Tx sequence with a non-uniform PRI variation between $PRI_{min} = 0.25$ ms and

⁵ The ratio between the maximum and minimum sampling intervals must necessarily be greater than 2 but typically a significantly higher ratio is necessary.

$PRI_{max} = 0.375$ ms. The maximum inter-pulse distance is below $2 \cdot PRI_{max} = 0.75$ ms for all considered ranges, since the optimization successfully avoided the loss of two consecutive pulses. The maximum sampling distance of 0.75 ms corresponds to a minimum PRF of 1.33 kHz and it is hence possible to avoid azimuth ambiguities with an antenna length of 11.3 m by a rather simple signal interpolation. Taking into account that the mean Rx-PRI is below 0.4 ms, one can even reduce this antenna length below 10 m, which allows for an azimuth resolution of approx. 5 m without any scalloping deteriorations as in the previous burst mode systems. A further optimization could take into account that typically not the whole but only a part of the range chirp is blocked in the receiver. Each individual range frequency is hence sampled with a higher mean azimuth frequency than the mean PRI of Figure 8. The minimum pulse separation in Figure 8 is 0.25 ms and the suppression of range ambiguities by null steering in elevation requires hence a minimum antenna height of approx. 2 m assuming a system operating in C-band. Note that this value is by about a factor of two higher than that shown for the multiple beam interpolation mode suggested in the previous section.

F. Hybrid SAR Modes

Often, the user requirements ask for high-resolution data takes within a small area like in the immediate neighbourhood of volcanoes, faults, cities or steep slopes, while at the same time more frequent wide-swath coverage with a coarser resolution is needed to follow fast nonlinear scatterer movements or to remove, e.g., large-scale disturbances from atmospheric signal delays. The brute force approach to meet these requirements is a continuous acquisition of very wide swaths with high geometric resolution as outlined in the previous sections. However, such a global-scale high-resolution wide-swath imaging is also associated with a huge data volume, thereby increasing the demands for internal data storage, downlink, ground processing and archiving. A promising solution to these challenges is the use of new hybrid SAR modes [17][25]. These modes can be tailored to provide a variable resolution within the imaged scene (cf. Figure 9, left) and are hence well suited to resolve user and application conflicts without an explosion of the data volume, thereby maximizing the information about the Earth system dynamics under the constraint of a limited downlink and storage capacity.

The middle plot in Figure 9 shows as an example the feed element activation pattern⁶ for one possible implementation of a hybrid SAR mode. In this example, a subset of the feed elements transmits a linear frequency modulated chirp signal of full bandwidth while the remaining feed elements transmit only a portion of the chirp with the same chirp rate. The shortened pulse durations for most of the feed elements reduce the average transmit power if compared to a full high-resolution wide-swath SAR system.

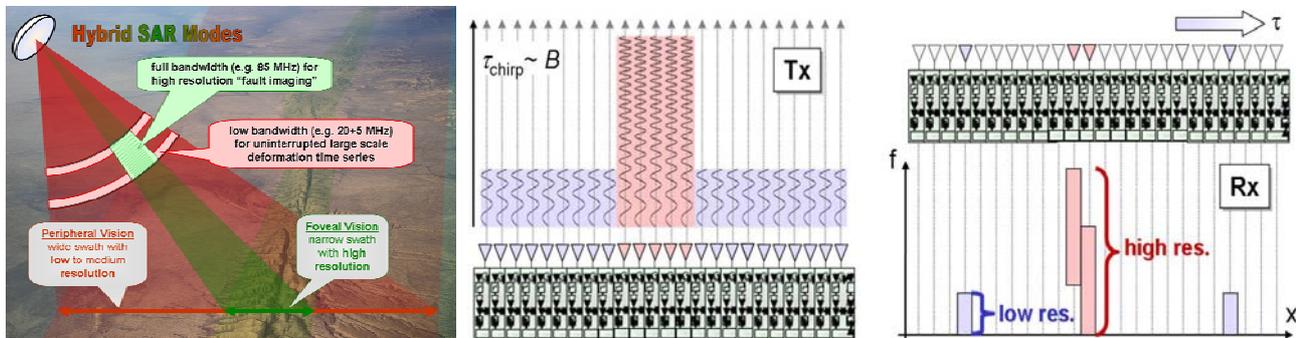


Figure 9 – (Left) Hybrid SAR modes enable radar imaging with variable resolution. (Middle) Feed activation pattern for the transmission of a space-variant chirp bandwidth and pulse duration. (Right) Snapshot of the received signals in a space-frequency representation. The filled bars denote those areas where the short term power spectral density exceeds a given threshold.

The recording of the scattered signals is shown in Figure 9 on the right. Only a small subset of the feed elements receives swath echoes at a given instant of time. From these feed elements, again only a small subset receives a full bandwidth signal while the residual activated feed elements receive a short narrow-band signal that can be sampled at a much lower frequency, thereby significantly reducing the overall data volume. The hybrid mapping of wide swaths requires in general also a systematic variation of the PRF to avoid blind ranges. One opportunity is the combination of a local high-resolution stripmap acquisition with a wide-swath ScanSAR mode. Such a StripScan hybrid provides a non-homogeneous resolution in azimuth and allows for a further

⁶ Hybrid modes can also be implemented with a direct radiating array [17].

reduction of the data volume. For this, the feed elements illuminating the wide swath are operated in bursts. This reduces both the average Tx power and the number of simultaneously activated feeds during signal reception. The hybrid of stripmap and ScanSAR makes the PRF selection more stringent, since one has to avoid gaps in both the stripmap and the ScanSAR sub-swaths. Suitable PRFs can be found since the high resolution area covers only a portion of a full stripmap swath. The timing benefits moreover from the short Tx pulses and the active nadir echo suppression via the narrow Rx beams. As an alternative, one may again consider a continuous variation of the PRF as outlined in Section IV.D (cf. Figure 7).

V. CONCLUSIONS

We have introduced several new SAR system concepts for the acquisition of high resolution radar images with ultra wide swath coverage. These innovative concepts rely on the combination of advanced multi-channel radar front-end architectures with novel operational modes. It becomes clear that from a signal theoretical point of view it is possible to design high-resolution ultra-wide-swath SAR sensors with rather compact antennas.

Regarding implementation complexity, it was shown that deployable reflector antennas are an interesting alternative to direct radiating arrays and a low number of receiver channels are already sufficient to enhance the imaging capabilities far beyond those of current spaceborne SAR systems. The implementation of digital radar systems will moreover benefit from rapid developments in integrated microwaves and semi-conductor technologies [28]. For example, direct A/D conversion, which is already possible in L-band, simplifies the design of multi-channel receivers. In the long-term, one may even think about a multi-frequency SAR which employs the same digital receiver channels for different frequency bands. New semi-conductor technologies will furthermore pave the way to more advanced SAR systems with adaptive and hybrid imaging modes [17]. These sophisticated modes are well suited to resolve contradicting user requirements regarding resolution, coverage, and data acquisition continuity while taking into account limitations from both the available RF power and the downlink capacity.

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