Tandem-L: SAR System Design Aspects

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I. Introduction

Tandem-L is Germany's proposal for a SAR mission in L-band [3], [4], aiming at a systematical observation of dynamic processes on Earth's surface. Among the applications are, for instance, the estimation of the above ground biomass on a global scale, the monitoring of tectonic activity, like earthquakes, or the measurement of ocean currents in coastal regions. Designed for interferometric acquisitions, Tandem-L comprises two identical satellites flying in formation. The SAR sensors shall deliver data over a mission lifetime of 10-12 years and allows for a global coverage at least once a week. These basic conditions give rise to a sophisticated system design which is able to support single/dual polarization acquisitions over a swath width of 350 km and quad polarization acquisitions over 175 km, in both cases with azimuth resolution down to 7 m.

New in the heritage of spaceborne SAR satellites is that large unfurlable mesh reflectors, fed by an array of digital transceivers, shall be employed. Although array-fed reflectors have a rich history in satellite communications or ground based radars, this type of antenna has been re-discovered for spaceborne SAR applications. Mesh reflectors can be realized with aperture sizes well beyond the 15 m diameter intended for Tandem-L at relatively light weight. Here, a rigorous SAR antenna design approach is presented, which is based on near field simulations.

Gapless SAR acquisitions are an important feature for the scientific community. Therefore, Tandem-L is operated according to the recently developed staggered SAR principle [6]. In this context new design challenges arise which lead to a unique system architecture. Specifically, the need of oversampling the SAR data in azimuth requires a well designed feed array concept [1] in order to fulfill the demanding requirements for Tandem-L's main design driver, the quad-polarization mode. The Tandem-L SAR instrument is realized as a fully digital, highly integrated system with a digital beamforming (DBF) unit at its core. This unit allows to cope with a second challenge induced by staggered SAR operation, namely the parallel generation of up to five digital beams, simultaneously scanning the swath. A further feature of this DBF network is the fact that the non-constant frequency behaviour of the SAR antenna can be accounted for using frequency dependent weights. Finally, a third issue related to PRI staggering is the large data volume generated as consequence of the required oversampling in azimuth. For this, Tandem-L will employ a specific unit which firstly performs interpolation of the non-uniformly sampled data and secondly decimation such that the data link capacity requirement of 8 TB per day can be met. This work addresses these central design aspects concerning the SAR antenna as well as the SAR instrument architecture on a conceptual level.

II. Array-Fed Reflector SAR

The principle of array-fed reflectors is to illuminate a reflecting surface with a primary radiator (feed element) instead of pointing the radiator directly towards the target. At L-band frequencies (1.215 GHz - 1.3 GHz) the feed elements are typically patch radiators. Since feed elements are small in terms of their aperture size, they will produce a sufficiently wide beam to illuminate the reflecting surface. Light weight mesh reflectors are for instance made of gold-plated molybdenum. The reflector in turn generates, due to its large aperture, a narrow high gain beam, which is called secondary beam. Juxtaposing several feed elements in the focal plane, as indicated in Fig. 2, consequently, allows covering a wide scan angle domain.

A. Feed Array Design

From an antenna design point of view the question arises how the length and width of the feed array have to be chosen in order to produce a footprint meeting the coverage and resolution specifications. A simple and straight forward way would be to do the dimensioning of the feed array based on ray optical considerations. In this case the length

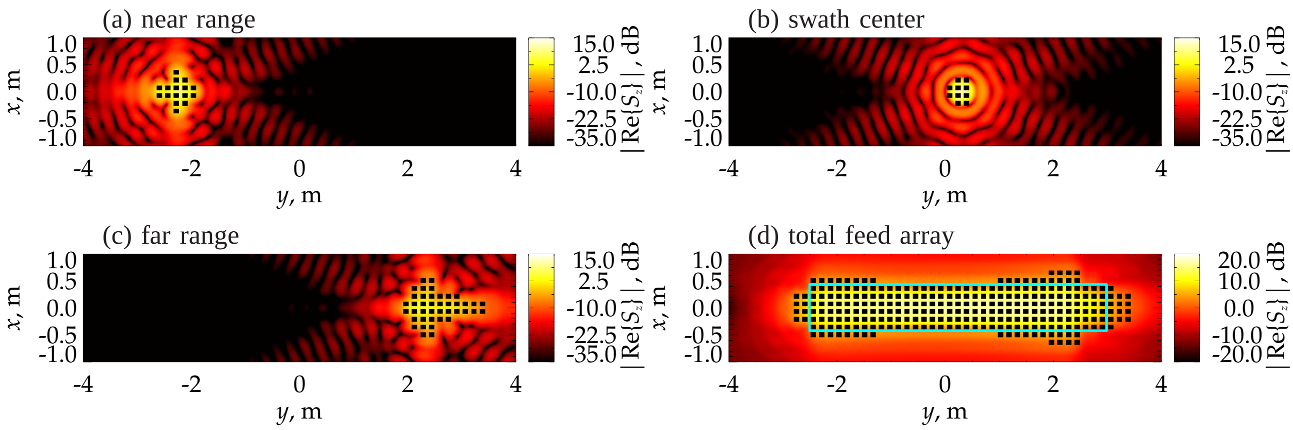


Fig. 1. Field in the feed array plane for a plane wave incident from near range (a) swath center (b) and far range (c). The entire feed array (d) results from the combination of the individual feed patches corresponding to the individual plane waves. The blue box indicates the actual feed array size for Tandem-L.

of the feed array can be found from the fact that the angular extent of the transmit beam (yellow beam in Fig. 2) covering the swath on ground has to match the angular extent of the yellow beam covering the feed array. A similar consideration involving the angular Doppler domain leads to the width of the feed array (azimuth direction). However, this method neglects the fact that the feed array lies in the near field of the reflector. Therefore, a purely geometrical approach becomes increasingly inaccurate for large scan angle ranges or small F-over-D ratios, meaning that the feed array is located closer to the reflector. A better way to design such a feed array is to adopt a reciprocal approach, where a source is placed inside the antenna footprint on ground. The plane wave originating from this source will produce, after scattering at the reflector, a field distribution in the focal plane (see Fig. 2). Examples of such field distributions are shown in Figs. 1a to c, corresponding to a source at near range, swath center and far range. Note, the x-direction refers to azimuth and the y-direction denotes elevation. These field distributions can now be covered by feed elements according to a certain power criterion. In Fig. 1 the feed elements collect 80 % of the power of a given plane wave. Repeating this procedure for all sources within the antenna footprint yields the feed array topology as presented in Fig. 1d. The blue rectangle represents the feed array size of Tandem-L, which measures $0.86\,\mathrm{m} \times 5.5\,\mathrm{m}$.

B. *Reflector SAR Operation*

Operating an array-fed reflector SAR system means activating all feed elements simultaneously when transmitting a radar pulse in order to illuminate the entire swath (yellow pattern in Fig. 2). As the radar pulse travels over ground (with the speed of light) from near to far range, a high gain beam is formed on reception following the pulse in real time. This is indicated by the beams 1 to K in Fig. 2. The rainbow color code refers to a specific beamforming

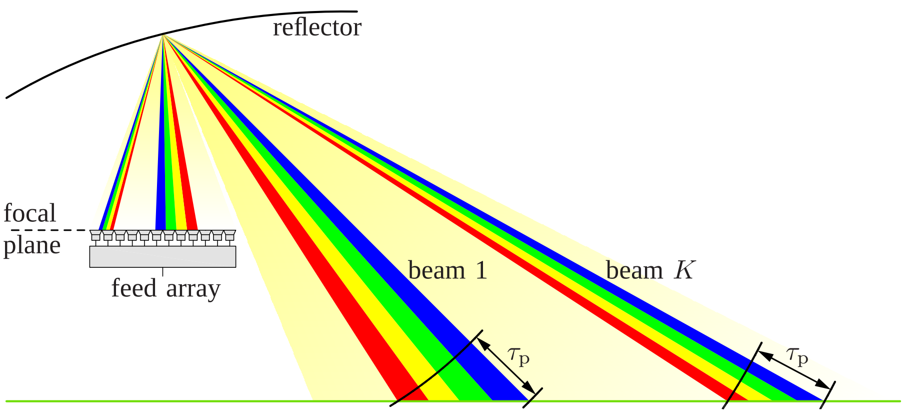


Fig. 2. Operation principle of an array-fed reflector SAR. The satellites' flight direction is into the paper plane (azimuth). The radiators of the feed array are located in the focal plane. On transmit a wide beam (yellow) illuminates the scene. In the receive case, K beams simultaneously follow the pulses of length τ_p on ground.

approach in elevation, which is explained later. Determining the number of active elements on receive, basically two approaches could be adopted. The first option would be to activate always a fixed set of feed elements for a given direction. However, due to the geometrical conditions, the pulse in near range (beam 1) requires more feed elements in order to collect the pulse energy, compared to the same pulse at far range (beam K). Consequently, a feed activation approach based on a threshold law would be more suitable for array-fed reflectors

$$G_i \geq \alpha \cdot G_{\max} \ , \alpha \in [0, 1] \ . \tag{1}$$

One could for instance require every channel 10 dB below the gain maximum to be active for a given elevation angle. These scan operations happen in real time, which means beamforming coefficients have to be periodically adapted in time intervals of a few micro seconds. This requires sophisticated hardware concepts, which shall be outlined in the next sections.

III. Tandem-L SAR System Concepts

Modern SAR sensors can adopt in principle two methods preventing blind ranges in stripmap acquisitions. First, one could employ multi-azimuth channel SAR systems [2] with long antennas. In case of reflector based SAR systems it is possible to realize an elliptical aperture, with the long half axis in azimuth, in combination with a 2-D feed array. This 2-D feed array would have several azimuth columns which are treated as individual digital channels to be downlinked to ground. The drawback of this approach is that it requires a reflector with a diameter in azimuth of roughly 40 m fed by an array with three azimuth channels in order to achieve 7 m azimuth resolution and 350 km swath width, assuming a pulse repetition frequency (PRF) of 570 Hz. Note, for a planar antenna the length would be $2 \cdot v/PRF = 26.3\,\mathrm{m}$. However, due to the suboptimal illumination of the reflector by the feed elements, the reflector diameter in azimuth needs to be larger by a factor of approximately 1.5 compared to a direct-radiating array. The hardware effort as well as the increased data rate are major cost drivers for spaceborne SAR missions. Therefore, Tandem-L implements a staggered SAR concept [6], where the pulse repetition interval (PRI) is changed from pulse to pulse. With this method the blind ranges are distributed in a deterministic (or random) way over range and a gapless SAR acquisition can be created by interpolating the SAR raw data. A precondition for this method to perform well is that the SAR data needs a certain oversampling in azimuth. Choosing the mean PRF too low will manifest in increased azimuth ambiguities in the SAR images. Consequently, this staggered SAR operation impacts the SAR instrument design in three main areas. First, driven by the nature of staggered SAR azimuth ambiguities and the demanding requirements of the Tandem-L quad-pol acquisitions, a beamforming concept in azimuth is needed with the specific goal of generating narrow azimuth beams. Secondly, the mean staggered SAR PRF will be approximately five times larger compared to a multi-channel SAR system. This requires the SAR sensor to track five pulses traveling across the swath at the same time, which must be reflected in parallel instrument hardware structures. Finally, since Tandem-L is planned as single-azimuth channel system, it is possible to implement data reduction concepts which help to reduce the amount of data to be transferred to ground.

A. *SAR Instrument Architecture*

Figure 3 shows a high-level block diagram of the Tandem-L SAR instrument. Here, all components like filters, mixers, limiters, etc. have been omitted in order to keep a clear representation. This block diagram represents one of the two polarisations, horizontal (h) or vertical (v). Tandem-L adopts conventional transmit/receive-module (TRM) technology, where each elevation channel is fed by an individual TRM for h- or v-polarisation. On transmission, phase control is required in order to shape the pattern for optimized swath illumination, especially in far range. In each elevation channel the radar pulse is high power amplified (HPA) and transmitted via an azimuth pre-weighting network which is explained in more detail below. On receive, the signals run through the same pre-weighting networks and the low noise amplifiers (LNA) until they are digitized in the A/D-converters. Phase control on receive, usually implemented in conventional TRMs, is not required since any phase as well as amplitude deviations can be accounted for in the DBF unit. Such a concept requires of course calibration in (near) real time in order to adjust for example for TRM drifts. After A/D-conversion the signals are digitally down converted (DDC) and fed into the DBF unit. Any digital building block is usually implemented in space qualified FPGAs or ASICs. Since these components have limited functional capacity, the DBF unit must be regarded rather as a distributed computer comprising several FPGAs (ASICs). This represents a challenge in terms of synchronization and redundancy. Generally, the purpose of the DBF unit is to map the input of the N elevation channels u_i onto K beams $u_{\mathrm{b},j}$ (five in case of Tandem-L). These beams may as well be understood as range lines. Several range lines need to be stored in a register such that azimuth filtering can be applied. The output of this unit is a single data stream, which is further reduced in volume by the block adaptive quantizer (BAQ) and stored in the solid state mass memory (SSMM) prior to downlink.

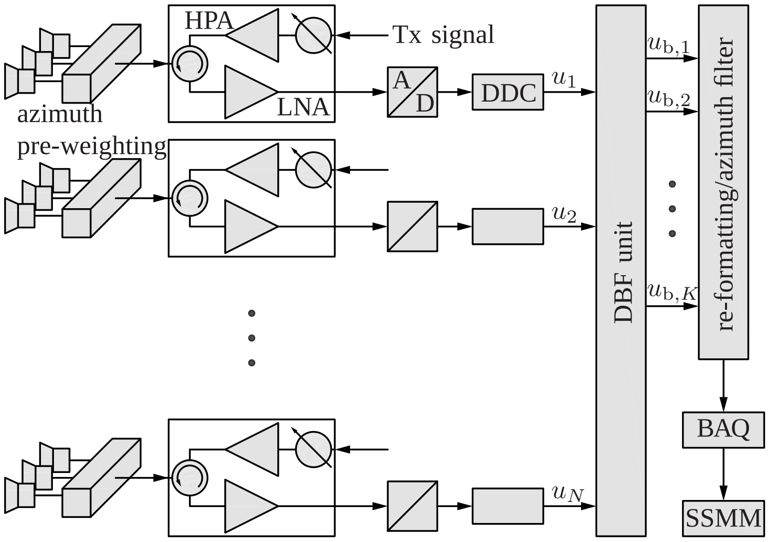


Fig. 3. Block diagram of the SAR instrument architecture. Tandem-L uses conventional T/R-modules. After the analog front end the received signal is digitized and down converted (DDC) individually for each elevation channel $(u_1, \ldots, u_N)$. The DBF unit forms K beams $(u_{b,1}, \ldots, u_{b,K})$, which are processed in a so called data reduction unit. After re-formatting and azimuth filtering a single data stream is stored in the solid state mass memory (SSMM) and finally downlinked.

B. Beamforming in Azimuth

As mentioned above, azimuth beamforming for staggered SAR operation is mandatory in order to meet the performance requirements. Inspecting the field distribution in Fig. 1d it becomes clear that several feed elements are required in azimuth to cover the Doppler domain. In the case of Tandem-L six feed elements grouped in three pairs are pre-weighted via a fixed beamforming network. This is presented in more detail in Fig. 4a. Combing two feed radiators to a doublet is done for cross-pol cancellation purposes [5]. These three doublets are combined using fixed complex coefficients e_{ik} and form as whole an elevation channel. This fixed pre-weighting network can be implemented using power dividers/combiners to adjust the magnitudes and different cable lengths for the phases of the coefficients. Due to symmetry reasons e_{i1} equals e_{i3}. To demonstrate the impact of this azimuth beamforming concept, consider the azimuth

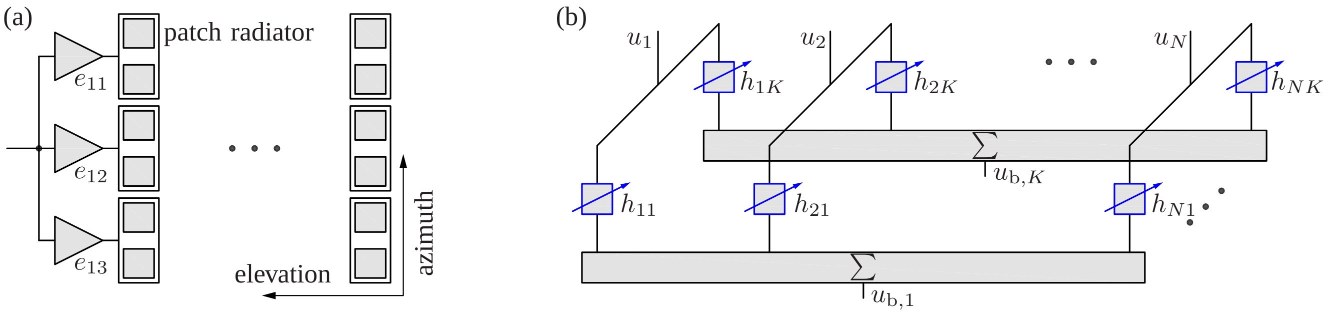
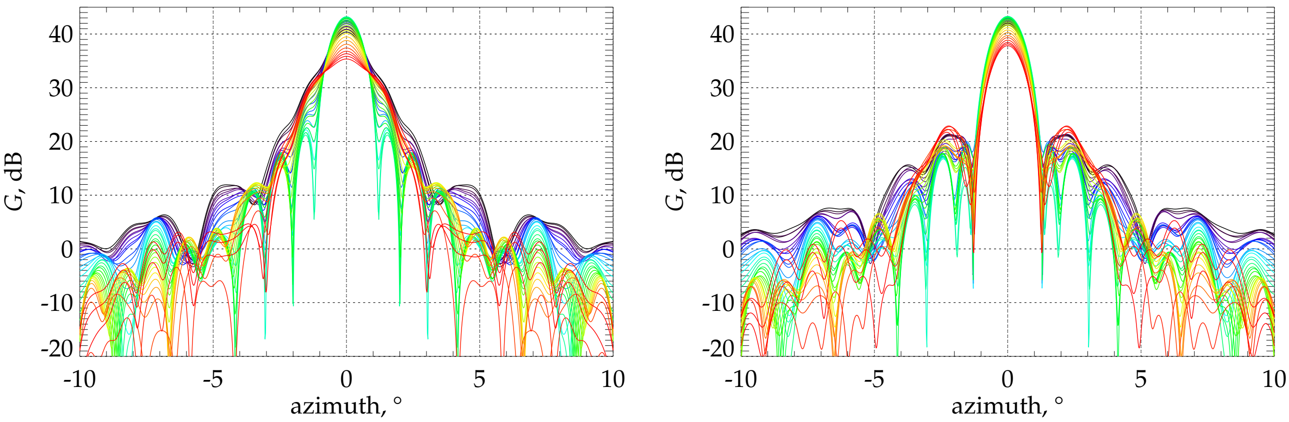


Fig. 4. a) Azimuth pre-weighting network. Two consecutive patch radiators are combined for the purpose of cross-polar mitigation. The three patch doublets are then used to shape the beam in azimuth via fixed excitation coefficients e_{ik}. b) Block diagram of the digital DBF unit. This digital processor forms out of N elevation channels K beams. The beamforming filters h_{ij} are time variant, which means they need to periodically adapt the coefficients during the scan process.

pattern plot in Fig. 5a. These azimuth patterns correspond to the central column of the feed array without pre-weighting ($e_{i2} = 1$, $e_{i1} = e_{i1} = 0$), while the different colors indicate different elevation channels (index i). One observes a strong variation in terms of beamwidth across the swath. Especially the beams in near and in far range, where feed elements are far away from the focus, suffer strong defocusing. Applying, however, pre-weighting in azimuth, which is in principle done individually for each elevation channel, allows to shape the azimuth beams such that almost no beam broadening occurs (see Fig. 5b). The coefficients e_{ik} have been computed according to a null-steering technique. These 'nulls' can be observed at azimuth angles $\pm 1.3\,^\circ$. A peculiarity in case of Tandem-L is that these beamforming coefficients have been quantized in an optimal way, such that only four different power divider/combiner ratios are required. This is basically a cost saving measure.



(a) center column

(b) with pre-weighting

Fig. 5. Azimuth cut plots of the antenna patterns taken at the maximum of the reflector beams starting at near range (red) over swath center (green) and ending at far range (blue/black). (a) Center column of the feed array. (b) Feed array after pre-weighting.

C. Beamforming in Elevation

The second architectural impact of the staggered SAR operation is related to the fact, that not only a single beam is required to track a pulse on ground but rather up to five pulses arrive simultaneously in case of Tandem-L. This is a consequence of the relatively high mean PRF required to sample the signal in azimuth adequately. In the simplest case beamforming might be implemented by multiplying each elevation channel by a complex weight in a time-variant manner, depending on the signal direction, and summing up the signals. Forming K beams means duplicating this structure K times in parallel. This is conceptually illustrated in Fig. 4b. Here, $(u_1, \ldots, u_N)$ denote the individual elevation signals and $(u_{\mathrm{b},1}, \ldots, u_{\mathrm{b},K})$ represent the output signals, or beams, of the DBF unit. These beamforming coefficients behind each elevation channel may also be implemented as beamforming filters, in Fig. 4b denoted with h_{ij}. This concept offers two advantages. First, a very long pulse could be divided into several narrow-band sub-pulses. The rainbow color code in Fig. 2 illustrates the fact that with linear frequency modulated pulses each sub-pulse is associated with a frequency (band). This means with a large antenna an individual beam could be formed for each sub-pulse, which would otherwise be lost or received with a broad low gain beam. Clearly, such a beamforming filter bank concept unfolds its full potential with large antennas and/or long duration pulses. There is, however, a second benefit, which also applies with short pulses. Employing frequency dependent weights for each sub-pulse individually allows compensating any non-constant frequency behaviour of the SAR antenna. Analysis shows, that for instance multi-path propagation between reflector and feed array modulates the frequency response of such an antenna. Insofar, such a beamforming architecture offers a high degree of flexibility. Important to mention here is that these beamforming coefficients are pre-computed on ground and stored in the memory of the FPGAs. Mathematically, this entire beamforming concept can be cast in the following form for the jth beam

$$u_{\mathrm{b},j}(n) = \sum_{i=1}^{N} \sum_{n'=0}^{N_{\mathrm{coef}}-1} u_i(n-n') h_{ij}(n,n') \ , \tag{2}$$

$$h_{ij}(n,n') = \sum_{m=0}^{M-1} w_{ij}(n,m) \overline{h}(n',m) \ . \tag{3}$$

The filter function h_{ij} is composed of the actual beamforming coefficients w_{ij}, which are time variant (discrete time variable n) and frequency dependent (variable m, M would be the number of colors in the rainbow in Fig. 2) and the fixed filter $\overline{h}$, which performs a bandpass decomposition. This means that the Tandem-L SAR sensors are capable of forming $K \cdot M$ beams at every time instance.

D. Onboard Data Reduction

The last major step in the onboard processing chain is the re-formatting and azimuth filtering [7] of the data. There are basically two approaches to deal with the problem of combining the individual beam signals to a single data field. One idea could be to associate each beam with a fixed sub-swath. Here, an approach shall be discussed where each

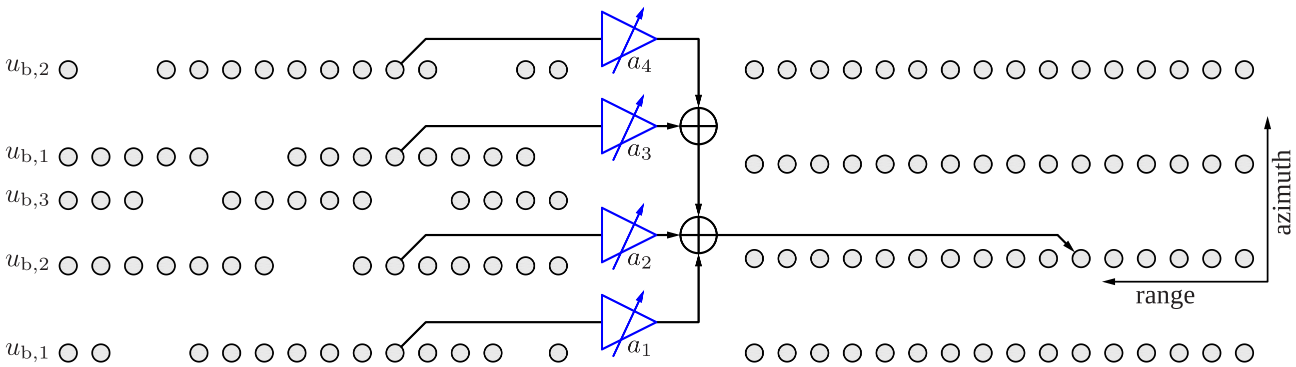


Fig. 6. Left part: The beam signals $(u_{\mathrm{b},1},\ldots,u_{\mathrm{b},K})$ (here as example $K=3$) are written into a buffer. This processing step is basically a re-formatting step. Right part: In a second step the non-uniformly sampled data with missing samples due to transmit events are interpolated on a regular grid. Decimation and interpolation can be performed with a single filter or split up in separate operations. Important here is that the azimuth filter (here as example $(a_1,\ldots,a_4)$) is range- and azimuth-variant.

beam tracks a pulse starting from near range until the pulse leaves the swath in far range. Then the beams 'jump' back to near range and track the next pulse. In this way the individual beam signals would be written in a periodic manner into a buffer. This so called re-formatting step is illustrated on the left part of Fig. 6 at the example of $K=3$ beams. The individual range lines, which exhibit missing samples due to the transmit events, have been plotted with different spacings in azimuth in order to indicate the effect of PRI staggering. The second step (right part of Fig. 6 is related to interpolation and data reduction. These operations could be performed using a single filter $(a_1,\ldots,a_4)$. For Tandem-L the filter length would be in the order of 25 coefficients. Clearly, this filter is range- and azimuth-variant since the missing samples occur at different instances in range. Depending on hardware constraints it could also make sense to separate interpolation and decimation, since the so called Best Linear Unbiased (BLU) interpolation technique would only require in the order of seven coefficients, which need to be adapted. After this, decimation could be performed using a fixed filter. Such an approach potentially leads to a reduction of the on-board data rates. The advantage of on-board data reduction is quite significant. In case of Tandem-L, the amount of data can be reduced by a factor of two for single- and dual-pol acquisitions and by a factor of 1.5 for quad-pol acquisitions.

IV. Conclusion

Being currently in a Phase B1, Tandem-L has made significant progress in terms of SAR system design. This paper presents some core design aspects, which are fundamental for an efficient operation using staggered PRI sequences. These include a sophisticated feed array design in azimuth, a parallelized beamforming network based on time-variant filters as well as a data reduction unit, which performs interpolation and decimation prior to downlink of the SAR data. Overall, the Tandem-L satellites will be capable delivering SAR products in yet unprecedented quantity and quality.

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