Multi-Transmit Operation Scheme for a Reflector-Based SAR System

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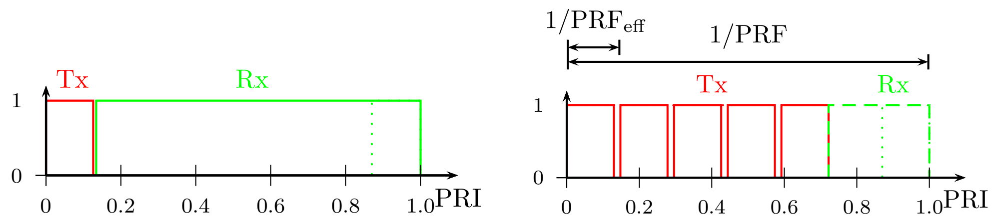
Abstract: *A transmit scheme that uses several timed and directed sub-pulses to cover one common swath is proposed. Timing and ambiguity suppression is presented. The advantages of the proposed scheme are an increased sensitivity compared to one transmit pulse per swath and a simpler activation scheme of the receivers in combination with lower data compression effort on-board a satellite.*

1. Introduction

Reflector-based antennas with several feeds can be used efficiently to implement spaceborne SAR systems with digital beamforming capabilities [1]. They are applied in several designs for spaceborne SAR systems for different frequency bands ranging from P- to Ka-band.

Concepts like sub-pulses or ping-pong modes [2] are e. g. used to introduce two phase centres that cover the same swath in order to add interferometric capabilities to a system, while preserving the pulse repetition frequency and the swath width. Using several sub-pulses to cover with each one a different part of one common swath has already been introduced in [3] as *intrapulse beamsteering in elevation* using *multidimensional waveform encoding*, that can cover transmit (Tx) signals of different power, duration or phase codes.

In this paper, the option to illuminate the far-range of a swath first and then to continue to near-range for the case of a side-looking SAR is discussed in detail in terms of timing and possible ambiguity suppression resulting from the shortened Rx window. A system with a reflector based antenna setup is chosen as an example for evaluating the achievable ambiguity suppression. It is shown that no further coding of subsequent sub-pulses is required to achieve sufficient suppression of ambiguities arising from neighbouring sub-pulses. The advantage of this transmit scheme is an increased sensitivity for constant peak power and a simplification in the activation of the Rx elements.



(a) SCORE timing scheme with duty cycle DC = 0.13

(b) Transmit scheme with $N_{\mathrm{sp}} = 5$ sub-pulses and same DC as in (a)

Figure 1: Different timing schemes (DC = 0.13,$N_{\mathrm{sp}} = 5$)

2. Concept

The basic idea of the proposed transmit scheme is to shorten the required receive (Rx) time in order to maximise the transmit (Tx) time as shown in Fig. 1. This is done by sending several timed and directed sub-pulses from far-range to smaller look angles, such that the backscattered signals arrive back to the receiver at the same time for signals from different look angles. For an antenna array, as it is also the case for a reflector antenna with several feeds, the antenna can cover a certain overall beamwidth that is set up by N subbeams. The only difference is that, with a planar array all elements would be used for transmission of one subbeam and not just a sub-group. The N subbeams will be grouped in $N_{\mathrm{sp}} < N$ segments to transmit $\mathrm{N_{sp}}$ directed beams in the corresponding directions. The timing of the Tx signals is arranged in a way, that on Rx all elements will receive simultaneously at the specified Rx window. This means that echo signals for different segments of the swath will arrive at the same time. For small angular intervals as a first approach linear dependency between look angle and slant range can be assumed. In general the angular intervals should be adapted such that almost equal intervals in time are received with the different groups. For larger overall swaths this leads to not necessarily equal amount of subbeams in the groups. Since all N_{sp} groups will receive the echo signal at the same time, these N_{sp} simultaneously received signals need to be separated by a spatial filter, which would in the case of the reflector be through the different feed elements. In the case of the planar array this would be done through beamforming. A sufficient (range) ambiguity suppression between the elements receiving at the same time from different regions is required. As a consequence each subgroup has to consist of more than one feed element.

3. Timing and representation

3.1. Transmit and Receive windows

The available transmit time is divided into N_{sp} equally spaced intervals. The duty cycle (DC) is kept the same for the comparison of the presented transmit scheme with a Scan-On-Receive (SCORE) beamforming. The observed slant range (r) interval is denoted by $\Delta r = r(\theta_{\max}) - r(\theta_{\min})$. The times for the transmit events of the N_{sp} directed pulses for the corresponding angular intervals are denoted by $t_0, t_1, t_2, \dots, t_{N_{\text{sp}}-1}$, as shown in Fig. 2. The transmit times t_n correspond to

$$t_n = t_0 + n \cdot \frac{\Delta r}{N_{\text{sp}}} \cdot \frac{2}{c_0} = t_0 + \frac{n}{N_{\text{sp}}} \cdot \frac{2\Delta r}{c_0} = t_0 + \frac{n}{N_{\text{sp}}} \cdot \frac{1-2\text{DC}}{\text{PRF}} \tag{1}$$

The total Tx window consisting of the N_{sp} directed pulses is the sum of the time intervals from the starting pulse transmitted at t_0 till the last transmit event at time $t_{\text{N}_{\text{sp}}-1}$ plus the duration of the last pulse. Like this the total transmit time is calculated as

$$T_{\text{Tx}} = (\text{N}_{\text{sp}} - 1) \cdot \frac{1}{\text{N}_{\text{sp}}} \cdot \frac{1-2\text{DC}}{\text{PRF}} + \text{DC} \cdot \frac{1}{\text{PRF}}. \tag{2}$$

The echo window time T_{Rx} is the time from one Tx event to the next plus the window for fully receiving the echo from the largest distance in this interval, which corresponds to the duty cycle

$$T_{\text{Rx}} = (t_n - t_{n-1}) + \text{DC} \cdot \frac{1}{\text{PRF}} = \frac{1-2\text{DC}}{\text{N}_{\text{sp}} \cdot \text{PRF}} + \text{DC} \cdot \frac{1}{\text{PRF}}. \tag{3}$$

The total time for one Tx/Rx interval results as

$$\begin{aligned} T_{\text{tot}} &= T_{\text{Rx}} + T_{\text{Tx}} \\ &= \frac{1-2\text{DC}}{\text{N}_{\text{sp}} \cdot \text{PRF}} + \text{DC} \cdot \frac{1}{\text{PRF}} + \frac{\text{N}_{\text{sp}}-1}{\text{N}_{\text{sp}}} \cdot \frac{1-2\text{DC}}{\text{PRF}} + \text{DC} \cdot \frac{1}{\text{PRF}} = \frac{1}{\text{PRF}}. \end{aligned} \tag{4}$$

For an evaluation of the range ambiguities from one directed pulse to its neighbour an interpulse frequency that describes the separation between the consecutive Tx pulses to the different directions can be introduced. Therefore the time Δt_{Tx} between two directed pulses is taken from (1) as

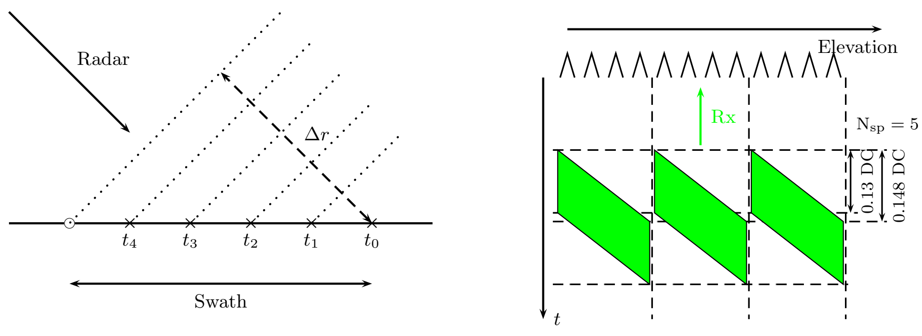
$$\Delta t_{\text{Tx}} = \frac{\Delta r}{\text{N}_{\text{sp}}} \cdot \frac{2}{c_0} = \frac{1-2\text{DC}}{\text{N}_{\text{sp}} \cdot \text{PRF}}, \tag{5}$$

and the interpulse frequency f_{ip} for the sub-pulses results as

$$f_{\text{ip}} = \frac{1}{\Delta t_{\text{Tx}}} = \frac{\text{N}_{\text{sp}} \cdot \text{PRF}}{1-2\text{DC}}. \tag{6}$$

3.2. Representation using timing diagrams

A representation to visualise the swath coverage for different pulse repetition frequencies is the timing diagram. Only the visible and non-visible areas due to transmit events are represented. Coverage aspects due to the applied antenna patterns are not included. For the generation of a timing diagram for several transmitted sub-pulses each pulse alone with its temporal position to the Rx window is considered. The overall coverage is then obtained by overlaying the covered areas of all sub-pulses. Using this approach even allows to determine swaths that are covered by more than one sub-pulse, which is interesting for applications like interferometry, mentioned in the beginning. The interval between subsequent sub-pulses can either be a fixed portion of the pulse repetition frequency or a constant time, e. g. due to certain hardware constraints.



(a) Geometry for timing consideration

(b) Timing of the Rx signals

Figure 2: Geometry and timing of the Rx signals for the case of $\mathrm{N_{sp}} = 5$ directed pulses

3.2. 1. Optimum/adaptive gaps between sub-pulses

For each sub-pulse ($n = 0 \dots N_{\mathrm{sp}} - 1$), the time delay ($\Delta\tau$) of the Rx window has to be within a certain interval such that it can be fully received

$$\Delta\tau > \mathrm{PRI}\cdot\left(1 - \frac{1-2\mathrm{DC}}{N_{\mathrm{sp}}} - \mathrm{DC} - \frac{n}{N_{\mathrm{sp}}}\cdot(1-2\mathrm{DC})\right) = \mathrm{PRI}\cdot\left(1 - \frac{1-2\mathrm{DC}}{N_{\mathrm{sp}}}(1+n) - \mathrm{DC}\right), \tag{7}$$

$$\Delta\tau < \mathrm{PRI}\cdot\left(1 - \mathrm{DC} - \frac{n}{N_{\mathrm{sp}}}(1-2\mathrm{DC})\right) = \mathrm{PRI}\cdot\left(1 - \frac{1-2\mathrm{DC}}{N_{\mathrm{sp}}}n - \mathrm{DC}\right). \tag{8}$$

The timing is set in the way, that for all possible PRFs, the sub-pulses will not overlap and will start to arrive at the same time at the receiver. By specifying the duty cycle and the number of sub-pulses the timing is already specified and no further specification of the interval between sub-pulses is required. The resulting timing diagram is shown in Fig. 3 using the parameters from Tab. 1.

3.2. 2. Fixed time interval between sub-pulses

A fixed time interval (t_{int}) is used here. Further parameters are the duty cycle (DC) and the number of sub-pulses (N_{sp}). The conditions for the reception of a sub-pulse are

$$\begin{aligned}\Delta\tau >& \mathrm{PRI} - [\mathrm{PRI} - N_{\mathrm{sp}}\cdot\mathrm{DC}\cdot\mathrm{PRI} - (N_{\mathrm{sp}}-1)\,t_{\mathrm{int}}] - n\,[\mathrm{DC}\cdot\mathrm{PRI} + t_{\mathrm{int}}] \\ =& \mathrm{PRI}\cdot\mathrm{DC}\,(N_{\mathrm{sp}} - n) + t_{\mathrm{int}}(N_{\mathrm{sp}} - n - 1)\end{aligned} \tag{9}$$

$$\Delta\tau < \mathrm{PRI} - \mathrm{DC}\cdot\mathrm{PRI} - n\,[\mathrm{DC}\cdot\mathrm{PRI} + t_{\mathrm{int}}] = \mathrm{PRI}\,[1 - \mathrm{DC}(n+1)] - n\cdot t_{\mathrm{int}}. \tag{10}$$

4. Properties of the timing scheme

A property of the proposed transmit scheme is, that the total duty cycle of the transmitted pulse sequence is increased by the number of directed pulses N_{sp}. Therefore the sensitivity is also

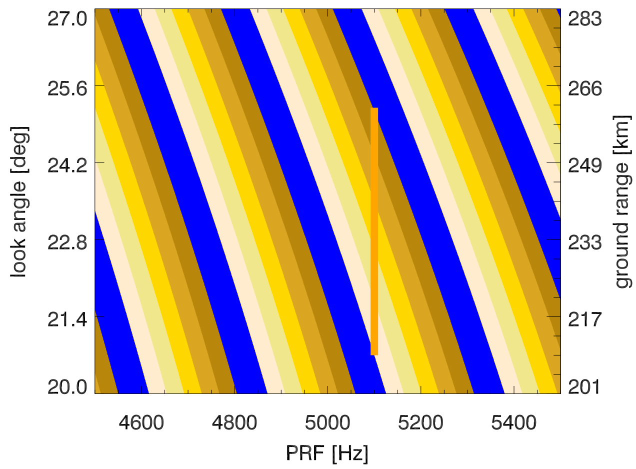


Figure 3: Timing diagram for the proposed transmit scheme, each colour represents a region covered by one sub-pulse, blue coloured strip represents the interval that is not observed, since it is not covered with a transmit event due to the receive window

Table 1: Parameters of the considered system

Parameter	Value	Parameter	Value
Frequency	35.5 GHz	No. of channels	20
PRF	5100 Hz	No. of directed pulses	5
$\mathrm{PRF}_{\mathrm{eff}}$	34 459.5 Hz	Considered Rx channels	3
Duty cycle (DC)	0.13	Reflector: Height, Width	4.5 m, 4 m
Resolution: (Az., Elev.)	5 m, 5 m	Look angle	20.7° … 25.2°

increased for constant peak Tx power, which can be expressed by the resulting NESZ

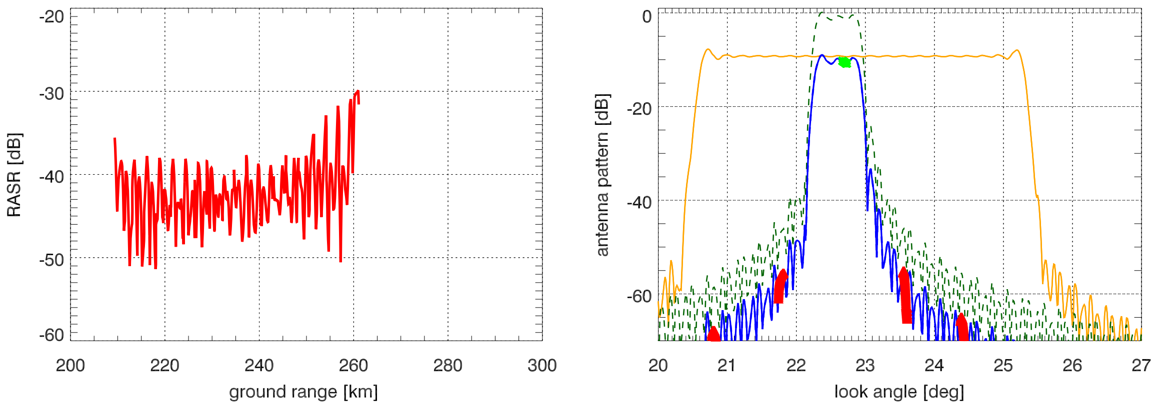
$$10 \cdot \log_{10}\left(\frac{\mathrm{NESZ}_{\mathrm{Txbf}}}{\mathrm{NESZ}_{\mathrm{Score}}}\right) = 10 \cdot \log_{10}\left(\frac{\mathrm{DC} \cdot \mathrm{N}_{\mathrm{sp}}}{DC}\right) = 10 \log_{10}(\mathrm{N}_{\mathrm{sp}}). \tag{11}$$

Using 4 directed pulses would e. g. increase the sensitivity by 6 dB.

On Rx all channels will be active during almost the complete Rx window, since they receive simultaneously from different directions. A timing scheme for Rx activation or compression of the Rx signals on-board would not be required.

5. Realisation example

As an example, a system operating in Ka-Band with 20 channels in elevation is considered [2]. The system is assumed to illuminate a swath that corresponds to one unambiguity interval at a PRF of 5100 Hz. The parameters are listed in Tab. 1. The swath is divided into 5 subswaths, which leads to 5 groups of 4 feed elements each. Fig. 4 shows the resulting RASR considering that the directed pulses are transmitted with an interpulse frequency f_{ip}, see (6). The evaluated range ambiguities are also shown for one specific beam position with the used antenna patterns.



(a) Range ambiguity to signal ratio (RASR)

(b) Range ambiguities (red) and considered Rx signal (green)

Figure 4: SAR performance for the proposed transmit scheme

6. Conclusion

The proposed transmit scheme exploits the side-looking SAR geometry in order to separate signals from different sub-pulses, that arrive at the Rx at the same time. The simultaneously arriving signals are separated due to different look angles at the Rx antenna. This scheme allows to increase the Tx window and to reduce the Rx window compared to the case with only one pulse per swath. The advantages are an increased sensitivity, when the peak Tx power is kept constant and less effort in terms of receiver activation and data compression on-board the satellite. At the example of a reflector-based setup it has been shown, that the resulting (range-) ambiguities are supressed sufficiently. It has to be noted that in principle the proposed Tx scheme is not limited to systems with reflector antennas, as any standard SAR system can be operated like this. The only requirement is that the simultaneously arriving signals can be separated properly along elevation. Therefore reflector-based SAR systems with several feeds are a good candidate, as these systems typically show a very high range ambiguity suppression.

References

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