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E-SAR Upgrade to Stepped-Frequency Mode: System Description and Data Processing Approach

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Abstract

A common way to enhance the range resolution of imaging radars is to adopt stepped frequency waveforms. This paper discusses in detail stepped-frequency processing possibilities on raw and processed data level, focussing on the compensation steps required to obtain high quality results. At the same time, software changes to an established SAR processor are kept at a minimum. The paper starts with a description of associated hardware extensions performed to the front-end of the E-SAR system of DLR to accommodate the stepped frequency mode in X-band. Two alternating channels, each of 100 MHz bandwidth have been implemented, which lead to a best case range resolution of 80cm corresponding to an improvement of up to 80% compared to the standard imaging mode. The performance of the complete system (including hardware and processing concept) is investigated using real data acquired with different spectral overlap between the sub-bands.

1 Introduction

Range resolution of imaging radars is determined by the bandwidth of the transmitted pulse. Besides the signal generation and the HF parts of the radar, the AD-converters pose the highest restrictions to the usable signal bandwidth. When speaking of bandwidth to carrier ratios in the order of up to 10%, the HF front ends can easily be designed to support a much wider bandwidth than the transmitted signal. In this case the limiting factor is the trade-off between dynamic range (number of bits) and the sampling rate of the AD-converters. For inverse SAR operation in a controlled environment imaging is usually performed by stepping through the bandwidth and the sampling requirements on the ADC are usually fulfilled by any network analyser. The situation changes in case of fast and uncontrolled moving objects, when the required frequency range must be covered while at the same time, Doppler resolution must be ensured. In this case chirped waveforms are used also for ISAR systems. The situation is similar in case of SAR systems where a linear FM signal (chirp) modulation is the standard choice to transmit a large bandwidth [1]. One possible approach to circumvent high sampling requirements is through the use of deramp on receive (used especially for Spotlight mode systems). However, this limits the receive window lengths and therefore operating synthetic aperture radars in a “stepped-frequency” mode is more suitable, i.e. the carrier is alternated for subsequent chirps to cover a larger bandwidth.

Especially in case of VHF frequency SAR, no other possibilities exist to allow high resolution imaging (bandwidth to carrier ratios is in the order of 1). The high dynamic range of the received signals but also the large range migration (linked to high azimuth resolution) avoids other implementation means (like deramp on receive) [2,3]. At the same time spectral regions of severe RF interferences may be omitted by properly choosing the width and overlap of different frequency bands.

Due to increased interest in high resolution imaging, a number of X-band SAR systems were developed during the last couple of years which provide very high resolution in range via the stepped-frequency mode. Examples are the *PAMIR* system of FGAN in Germany which uses 5 parallel receive channels to cover a bandwidth of 1820 MHz [4] or the *RAMSES* system of ONERA in France with 5 successive 300 MHz chirps [5]. In a modest (but easy to accomplish) approach, also DLR's E-SAR system was upgraded recently to stepped-frequency mode in X-band, but due to the existing control system the performance is limited to two alternating channels of 100 MHz each. In this way, the range resolution of the E-SAR system is enhanced by up to 80% providing a resolution of 80cm which is comparable with the one of the *TerraSAR-X* satellite. Section 2 describes the modifications made to the X-band front end of the E-SAR system to incorporate the stepped-frequency mode.

The system modifications also determined new processing demands. Usually the “spectrum reconstruction” or “synthetic bandwidth” method is applied to concatenate individual sub-bands to one high resolution data set. A similar approach has been adopted also for E-SAR. For compatibility purposes with the existing E-SAR processor (based on the Extended Chirp Scaling algorthm (ECS) [6]) we only considered full bandwidth signal formation at raw data and processed image levels, i.e. either completely focused or completely unfocussed data. The implementation aspects of both options are described in section 3.

Section 4 is dedicated to experimental data analysis, while section 5 concludes the paper, giving suggestions for further analysis.

2 Stepped-Frequency Hardware

For experimental purposes a step frequency converter unit was developed and tested with the E-SAR system in X-band. Two systematic limitations had to be taken into account: E-SAR's 100MHz maximum system bandwidth and E-SAR's limitation in effective PRF imposed by the data formatting and recording system. Therefore the number of sub-bands is restricted to two with the normal 100MHz-chirp signal alternating between centre frequencies from pulse to pulse. The spectrum overlap is adjustable from 0% to 100%. The converter unit is integrated after the C-band IF stage, as indicated in **Figure 1**.

Two independent programmable synthesisers are used in ping-pong mode. Both synthesizers are phase locked to the same 10MHz system reference clock. SYNT1 is programmed to generate the carrier frequency f_1 and SYNT2 to generate f_2. Between PRF pulses the outputs of the synthesisers are alternated via a fast PIN-switch (about 10 nsec switch time). This way both synthesisers are always kept in stable operation and toggling between the two carriers at high PRF is possible.

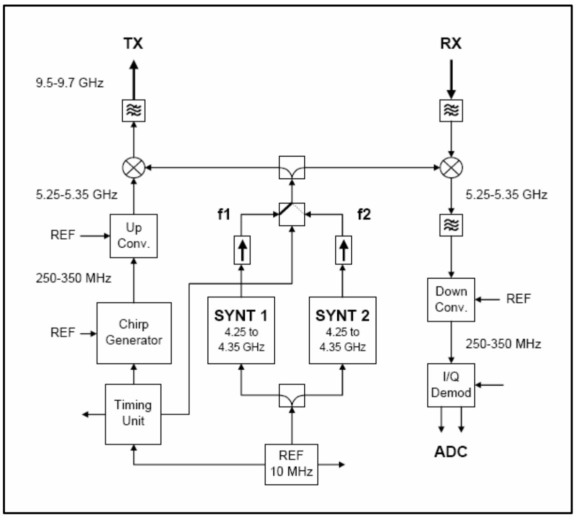

Figure 1 X-band front-end of E-SAR for stepped-frequency mode

3 Stepped-Frequency Processing

Stepped frequency processing via the „spectrum reconstruction method“ or “synthetic bandwidth” method is well described, e.g. in [2] and [3], including detailed signal formulation and design of the optimal filter. However, every SAR system has its one particularities and therefore the processing might differ in details. The aim is to perfectly concatenate the sub-band spectra in order to control paired echo level, which arise due to discontinuities on sub-spectra borders or ripples on the spectrum phase. Common to all approaches are the following steps:

- *Phase correction:* For the different narrow-band channels the propagation delay in terms of phase is different. The term for correcting this difference is given by $2\pi(f_1 - f_2)\,t_0$, where f_1 and f_2 are the carrier/demodulation frequencies of the two narrow band signals and t_0 is the two-way propagation time of the first received echo.
- *Frequency shift:* The sub-bands are shifted to the final (average) center frequency. This should be performed with the narrow band time domain signals to keep number of operations low. (Shift in frequency domain should only be performed in case of an integer number of samples).
- *Upsampling* of each narrow band signal: The up-sampling factor is usually determined by the number of sub- bands. The operation is ideally performed in spectral domain via zero-padding.
- *Coherent addition* of sub-spectra.
- *Optimal compression filter*: This multiplication in spectral domain is the most critical step, as any phase offset between channels or other residual system distortions should be incorporated into this filter. A constant spectral phase output should be obtained before the final inverse FFT [2,3].

The next two subsections discuss the generation of the optimal compression filter and further important issues to consider depending on the type of the data input for the stepped frequency processing.

3.1 Raw data spectrum reconstruction

In case the stepped frequency processing is performed at raw data level, some additional details must be considered. First, the sub-band channels must be time shifted in range by half of the chirp length to allow proper alignment during the spectrum reconstruction (for explanations, see **Figure 2**). Second, the sub-band channels must be time shifted also in azimuth by 1/PRF to each other due to the alternate pulsing.

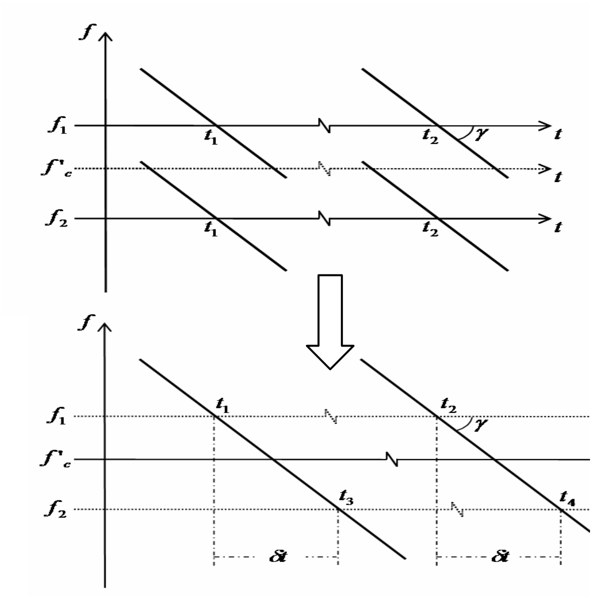

Figure 2 Requirement on range alignment (relative time shift) in case of stepped-frequency processing on raw data level

This typically makes the "spectrum reconstruction" method no longer work on 1D range lines and prevents easy update of the SAR processor. In case the stepped-frequency processed SAR raw data are intermediately stored on hard-disc, the amount of data will increase because more bits (or float format) should be foreseen to avoid additional quantisation errors. Further, one has to consider, that range migration and motion errors of the different sub-bands are related to the recording time position and thus are not the same for every sub-band. Their compensation, when processing the stepped-frequency processed SAR raw data, can only be sub-optimum. Due to these disadvantages and problems, spectrum reconstruction on raw data level is not the primary choice for operational implementation.

3.2 Processed data spectrum reconstruction

Stepped-frequency spectrum reconstruction based on processed data of the individual sub-bands has the advantage that every sub-band image can be obtained via the standard SAR processor including nearly perfect corrections (up the theoretical limit of the algorithm). Stepped-frequency processing precisely follows the steps described in the beginning of this section. The time shift in range as required for the raw data case is not necessary, as the data are already aligned. Also the azimuth time shift can be easily implemented during processing (when data are in Doppler domain). However, further important details must be considered. First, the different sub-bands should be processed taking into account exactly the same squint angle (NOT Doppler centroid). Second, during up-sampling the shift of the range spectrum according to the presence of squint (and possible motion errors) must be considered [7]. Then, coherent addition of sub-spectra should be performed in the beam-centre geometry, which ensures perpendicular range and azimuth dimensions and which brings benefits for the design of the optimal compression filter as discussed next. There are two ways to obtain the spectral phase for this filter. The first possibility is to obtain only the difference phase from the interferogram of the (common band filtered) sub-band signals. This approach is the only viable way in case no corner reflectors are present in the scene. In case of corner reflectors, it is possible to extract and compensate spectral phase variations for each channel, while at the same time estimating the phase offset. Exemplarily, the spectral phase for one corner reflector in the two sub-bands of the E-SAR system is shown in **Figure 3**. The variation can be related to system distortions and is suitably accounted for in the optimum compression filter. Results presented in the next section confirm the validity of this approach which is implemented for operational processing of E-SAR data.

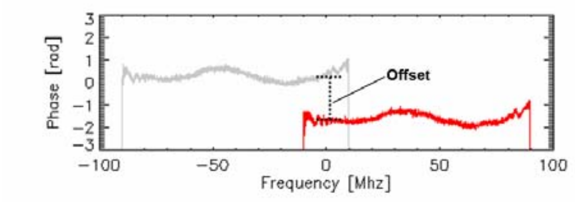

Figure 3 Spectral phase measured for E-SAR data on one corner reflector (CR 1) for the two sub-bands.

4 Real Data Investigations

Four stepped frequency data sets with different spectral overlap were acquired up to date on Oberpfaffenhofen test-site and the evaluation of two of them is presented here. Their parameters are summarised in Table 1. A complete stepped-frequency image cannot be displayed here, but zooms for the narrow-band and stepped-frequency images are shown in **Figure 4**. The stepped frequency results appear sharper on building edges and also on field boundaries.

	Data Set 1	**Data Set 2**
Sub-band bandwidth	100 MHz	100MHz
Coplex Sample Rate	100 MHz	100 MHz
Pulse length	5 usec	5 usec
Range delay	24.3 usec	18.0 usec
Pulse Rep. Freq.	1165 Hz	1100 Hz
Avg. Flight Speed	73.2 m/s	71.7 m/s
Squint Angle	3.0 deg	3.0 deg
No. of Sub-bands	2	2
Frequency Step	80 MHz	50 MHz
Recon. Centre Freq.	9.6 GHz	9.6 GHz

Table 1: Parameters of investigated E-SAR scenes

Figure 4 Zoom of images corresponding to narrow-band (left) and stepped-frequency processing with 20% overlap (right).

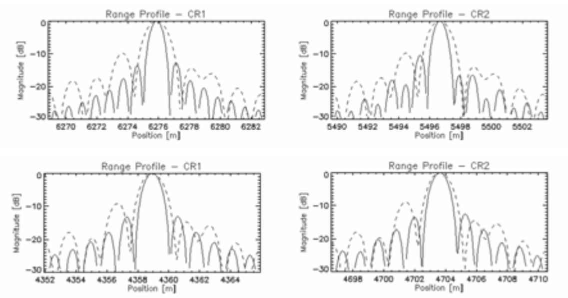

Figure 5 Impulse response function in range for two CR for data set 1 (up, 20% overlap) and data set 2 (down, 50% overlap).

			CR1	**CR2**	**CR3**	**CR4**
Data Set 1 (20% ovlap)	Rg [m]	A	1.36	1.36	1.36	1.36
		SF	**0.80**	**0.75**	**0.80**	**0.80**
	Az [m]	A	0.72	1.13	0.88	1.41
		SF	0.75	1.20	1.13	1.32
Data Set 2 (50% ovlap)	rg. [m]	A	1.36	1.36	1.36	1.31
		SF	**1.03**	**1.03**	**1.03**	**0.98**
	az. [m]	A	0.65	0.62	0.62	0.62
		SF	0.65	0.62	0.62	0.62

Table 2: Resolutions in range and azimuth measured on corner reflectors for one narrow-band channel (A) and for the stepped-frequency combination (SF). Theoretical resolutions in range are 1.35m (A) and 0.79m (SF, data set 1) and 1.03m (SF, data set 2)

A quantitative analysis is performed on the corner reflectors and is discussed next. Figure 5 shows the range impulse response function of two corner reflectors for the two data sets. Table 2 summarizes the measured resolutions in range and azimuth for 4 corner reflectors. It can be observed, that the focussing is nearly perfect, corresponding to the theoretical values. However, as the stepped-frequency filter was designed based on CR 1, the IRF shape of CR2 shows slightly non-symmetrical side-lobes. This confirms the statement that stepped-frequency radars are extremely sensitive to (residual) system distortions and much care should be taken to eliminate them.

5 Conclusions

The stepped frequency hardware of the E-SAR system was successfully tested and the E-SAR processing software was extended by suitable processing steps to combine the narrow band signals. The performance of the stepped-frequency mode was investigated on two data sets with different spectral overlap. The improvement in range resolution according to the theoretical expectations is 40 and 80%, respectively, as confirmed by measurements on corner reflectors. It was found that larger spectral overlap ensures more reliable phase offset estimation. Unfortunately, as the data rate of the E-SAR data acquisition unit (tape recorder) is limited, only two frequency steps could be implemented. Thus, a test of the adopted processing approach to the combination of several spectral bands was not possible and the achieved resolution improvement is relatively modest. From the two stepped-frequency processing approaches, the one working on the narrow-band processed data proved to be more exact and was implemented for operational use. In this way, E-SAR is able to generate images with resolution beyond the 1m limit also in range dimension. The work performed so far presents the basis for new stepped-frequency modes including more bands to be build and operated in the future.

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