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Stepped-frequency radar signal processing

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ABSTRACT

Stepped-frequency radar is a prominent example of the class of continuous-wave radar systems. Since raw data are recorded in frequency-domain direct investigations referring to the frequency content can be done on the raw data. However, a transformation of these data is required in order to obtain a time-domain representation of the targets illuminated by the radar.

In this paper we present different ways of arranging the raw data which then are processed by means of the inverse fast Fourier transform. On the basis of the time-domain result we discuss strengths and weaknesses of each of these data structures. Furthermore, we investigate the influence of phase noise on the time-domain signal by means of an appropriate model implemented in our simulation tool.

We also demonstrate the effects of commonly known techniques of digital signal processing, such as windowing and zero-padding of frequency-domain data. Finally we present less commonly known methods, such as the processing gain of the (inverse) fast Fourier transform by means of which the signal to noise ratio of the time-domain signal can be increased.

1. Introduction

Stepped-frequency radar is a prominent candidate in the class of continuous-wave (cw) radars which is often realized in scientific ground penetrating radar (GPR) research by means of commercially available measurement devices, such as vector network analyzers (VNA). However, since the stepped-frequency continuous-wave (SFCW) radar works in frequency domain, its working principle is more complex compared to that of e.g. a time-domain based pulsed radar where the desired signal containing the target's reflection peaks is yielded directly by recording the echo of the transmitted pulse by means of some appropriate sampling unit.

In order to identify characteristic spectral properties of targets illuminated by the radar, an SFCW system is highly appropriate since it makes the spectrum accessible directly to the user. Hence, all particular features are immediately available. However, often a time-domain representation is desired which allows discovery of the presence of a target by means of its typical reflection patterns, e.g. when utilizing GPR for civil engineering, (Liu and Sato, 2014; Wei and Zhang, 2014), detection of pipes and cables buried in ground, (Seyfried et al., 2012; Seyfried et al., 2014b) archeological purposes (Urban et al., 2014) and unexploded ordnance disposal (Mohana et al., 2013; Yarovoy et al., 2004). A time-domain representation of frequency-domain data can be obtained by performing an inverse discrete Fourier transform (DFT) on these data. A common technique in digital signal processing (DSP) which implements a DFT is the fast Fourier transform (FFT) and its counterpart, the *inverse* FFT. (Lyons, 2011; Mahafza, 1998; Marple, 1987)

This paper is focused extensively on the arrangement of the raw data within different types of data structures on which the inverse FFT is finally applied to. We demonstrate their strengths and weaknesses especially with respect to their appropriate time-domain outcome. We also summarize and demonstrate frequently used techniques of digital signal processing such as windowing the raw data in order to reduce sidelobes of the time-domain peaks and we examine less commonly known issues such as processing gain of the FFT and the influence of phase noise on the results of SFCW radar measurements.

In Section 2 we discuss different types of data structures feeding the inverse FFT. The influence of phase noise on SFCW radar data is investigated in Section 3 by means of an appropriate model implemented in our simulation tool. In Section 4 different DSP techniques for preprocessing the radar raw data are presented. Finally in Section 5 we discuss our results and conclude our paper.

2. Data structures

Performing the forward fast Fourier transform (FFT) on a data array containing the sampled version of a time-domain signal with n purely real samples with spacing $\Delta t = 1/f_s$ (f_s is the sampling frequency) yields a data array of again length n containing the complex valued elements of the signal's spectrum for frequencies with spacing $\Delta f = f_{\max}/(n-1)$ (with the maximum frequency is half the sampling frequency, $f_{\max} = f_s/2$). Fig. 1 shows the symbolic spectrum of the time-domain signal

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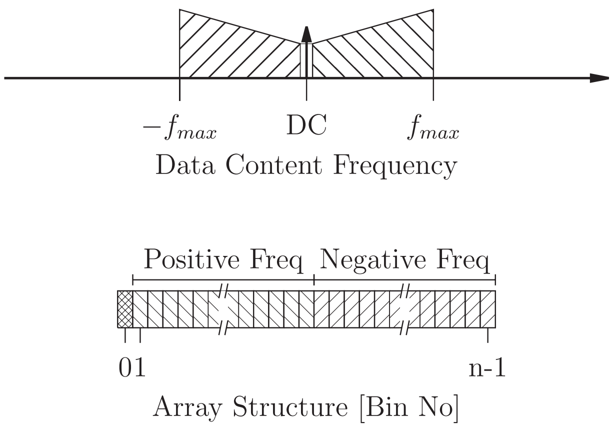

Fig. 1. The structure of the spectral data array when applying the fast Fourier transform on n purely real samples of a time-domain signal. The maximal frequency corresponds to half the sampling frequency, $f_{\max} = f_s/2$. Here, n is assumed to be odd.

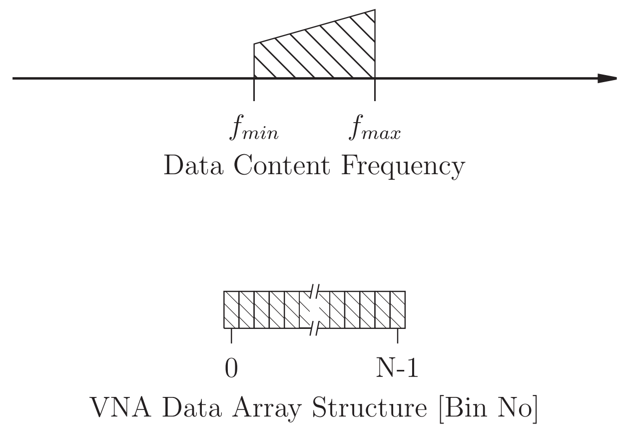

Fig. 2. The structure of the spectrum data array of length N obtained by means of a VNA. Samples are obtained for discrete frequencies in the interval Δf in the closed frequency range $f_{\min} \dots f_{\max}$.

along with the structure of the data array obtained by means of the FFT.[1] There it is assumed that n is odd. Then, the first array element contains the DC component followed by $(n-1)/2$ positive frequency components corresponding to frequencies $\Delta f, 2\Delta f, \dots, (n-1)/2\Delta f$. The subsequent bins[2] contain the $(n-1)/2$ negative frequency components which are (for, again, purely real time-domain samples) the conjugates of the positive ones in mirrored order, i.e. from $f = -(n-1)/2\Delta f, \dots, -\Delta f$. Thus, the samples for negative frequency components do not carry any additional information with respect to the positive ones. When n is even the first array element contains the DC component followed by $n/2-1$ positive frequency components corresponding to frequencies Δf, $2\Delta f$, …, $(n/2-1)\Delta f$. Bin $n/2$ contains the Nyquist frequency component, $f_{\max}$. The subsequent bins contain the $n/2-1$ negative frequency components which are again the conjugates of the positive ones in mirrored order, i.e. from $f = -(n/2-1)\Delta f, \dots, -\Delta f$.

Therefore, in order to obtain a time-domain signal from a recorded spectrum it is sufficient to have knowledge of solely the positive frequency components, as they are provided by a vector network analyzer (VNA) utilized as stepped-frequency radar. For each of in total N discrete frequencies, f_i $(i = 0 \dots N-1)$ in the closed frequency interval $f_{\min} \dots f_{\max}$, $f_i = f_{\min} + i \cdot \Delta f$, the VNA outputs a complex-valued data sample, $A \cdot e^{j\varphi}$, with amplitude A and phase φ, which incorporates a coherent sum of all contributions from T targets illuminated by the radar,

$$A \cdot e^{j\varphi} = \sum_{t=1}^{T} a_t \cdot e^{j\varphi_t}. \tag{1}$$

Here, each target reflection can be expressed in terms of an attenuation factor (in respect to the transmitted wave of constant amplitude a_{Tx}),

$$a_t = a_{t,Rx}/a_{Tx} \tag{2}$$

and a phase,

$$\varphi_t = 2\pi f t_t, \tag{3}$$

dependent on the time, t_t, through which the electromagnetic wave travels from the transmitter Tx to the t-th target and back to the receiver Rx. Fig. 2 shows the raw complex valued frequency-domain data array of length N[3] and its appropriate symbolic spectrum recorded by means of the VNA. There exist several possibilities of how to arrange this raw

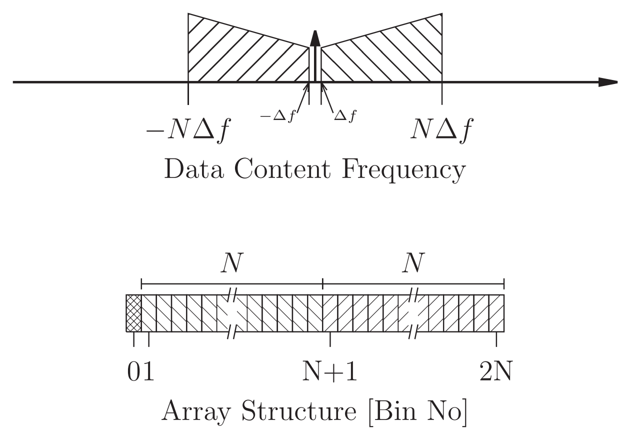

Fig. 3. For the unshifted LPT the first raw frequency-domain sample obtained means of the VNA is aligned with the DFT frequency bin representing frequency Δf. Thus, raw frequency-domain samples do not coincide with the appropriate DFT frequency bins. The negative frequency components are obtained by means of mirroring a conjugated version of the positive ones around DC. Throughout the paper, the positive and negative spectra are depicted by the same individual diagonal patterns.

data within an array on which finally the inverse Fourier Transform is applied in order to obtain a time-domain representation of the recorded data. Below we explain each type of arrangement along with its strengths and weaknesses.

2.1. Unshifted and shifted lowpass transformation

Applying the inverse FFT on an array containing the raw data from Fig. 2 arranged as shown in Fig. 3 is the first type and we refer to it as the *unshifted* lowpass transformation (LPT). The array structure exhibits (for increasing bin number) the zero DC component followed by the raw data samples followed by the conjugated raw data in reversed order.[4] The resulting extended array as well as the time-domain data array is of length $2N+1$. Hence, a major characteristic for the unshifted LPT is, that the raw data samples are not aligned within the extended data structure such, that their frequency content is in synchronization with the appropriate frequency of the bins of the inverse FFT.

The frequency mismatch can be obliterated by applying the inverse FFT on an extended data array as shown in Fig. 4 which contains

[1] In the figures the spectra of the signals are shown in a continuous representation even though they actually contains only discrete components.

[2] We use here the terms *FFT or Array bin* and *FFT or Array element* and *FFT or Array sample* interchangeable.

[3] Without loss of generality we assume throughout the paper that N is even-numbered.

[4] In all figures the positive spectrum (i.e. raw data recorded by means of the VNA) and the negative spectrum (i.e. conjugated raw data in reversed order) are plotted with the same individual diagonal pattern style throughout the paper.