Motion error extraction from the signum-coded SAR raw data

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Abstract

We explore the extraction of the motions errors of an aircraft platform from the signum-coded Synthetic Aperture Radar raw signal (SC-SAR data). The SC-SAR has a one bit representation infact it only provides information about the zero crossing of the SAR recorded data. Displacement from the line-of-sight (LOS) direction and forward velocity of the SAR platform are extracted from this signal by using the Reflectivity Displacement Method (RDM) [1]. Comparison is made between the motion parameters extracted from the original and from the SC-data.

1. Introduction

The Synthetic Aperture Radar (SAR) is a coherent radar which can produce high resolution two-dimensional maps [2]. The SAR system is generally borne by a satellite or an aircraft. The obtained image is in the plane defined by the slant range and the sensor forward velocity vectors. In the range direction high resolution is achieved by transmitting short or modulated pulses. To obtain a high resolution also along the flight direction (azimuth), it is necessary to coherently add the received pulses; this requires that errors due to spurious motions and accelerations of the SAR platform must be compensated. Recently a new method for the extraction of the aircraft motion errors has been presented [1]. It is referred to as the Reflectivity Displacement Method (RDM) and is essentially based on a specific property of the azimuth spectrum of the SAR signal.

On the other hand, there is an increasing interest in processing SAR signum-coded (SC-SAR) signals [3-4]. The SC-SAR data can be obtained by passing the SAR raw signal through an ideal filter which only provides the information about the sign of the input. The benefits of the signum-coding reside in a smaller transmission bandwith and a simpler processing algorithm [5]. Examples of processed SC-SAR data in which the degradation of the speckle of the image is not appreciable are available [3].

The basic motivation of this paper is to show results of extraction of the aircraft motion errors from the SC-SAR raw data. Comparison of these errors with those extracted from the original data is shown. This comparison shows that the RDM method can be successfully applied to SC-SAR data, fully justifying this approach.

2. The reflectivity displacement method (RDM)

As the motion error extraction is based on the RDM algorithm [1] let us briefly summarize this tecnique. As shown in [1] the frequency shift $f(t)$ between two ground reflectivity functions from two adjacent azimuth spectra is expressed as:

$$f(t) \simeq -2\frac{V(t)^2\Delta t}{\lambda R} + 2\frac{a_{LOS}(t)\Delta t}{\lambda} \tag{1}$$

wherein R is the range of the selected range line, Δt is the time interval between the two spectra, λ is the wavelength, $V(t)$ is the forward velocity and $a_{LOS}(t)$ the acceleration in line of sight. The evaluation of the frequency shift $f(t)$ can be carried out by determining the position of the maximum of the cross-correlation between two adjacent azimuth power spectra. The separation of the forward velocity from the acceleration in line of sight can be performed by means of an high pass filter and a low pass filter. This is possible because the forward velocity has a very low bandwith in contrast with the acceleration in line of sight which has a considerabely greater bandwith and moreover only the upper frequency range is important for motion compensation.

In Fig. 1 it is presented the block diagram of the RDM. We note that the output data are respectively the displacement in line of sight and the forward velocity.

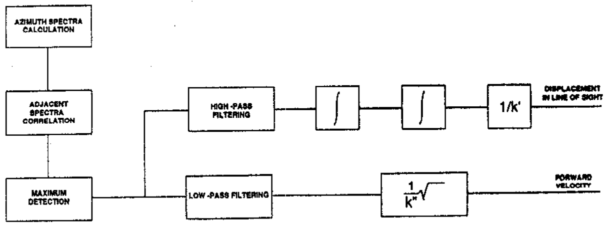

Fig 1 Block diagram of the RDM

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3. Theory of the SC-SAR signal

We shortly present the theory concerning the SC-SAR signal developed in [3]. The scene illuminated by a SAR system backscatters a signal x(t) which has the following form:

$$x(t) = z(t) + n(t) = A(t)cos(\omega t + \phi(t)) + n(t) \qquad (2)$$

wherein A(t) is the amplitude of the received signal, $\phi(t)$ is the phase of the received signal, n(t) is the thermal noise and ω the intermediate frequency after the heterodine process. The signal z(t) has a finite bandwith B centered on the frequency $\omega/2\pi$. Assume that A(t) is a slowly varying function in comparison with $\phi(t)$. We note that the two-dimensional SAR signal is unwrapped in the one-dimensional signal x(t).

For what concerns the noise we consider a gaussian noise with zero main and having the following probability density:

$$p(n) = \frac{1}{\sqrt{2\pi} n_0} exp\left(\frac{-n^2}{2n_0^2}\right). \qquad (3)$$

We assume $A^2(t) \ll n_0^2$. If x(t) is passed through a signum device, so that only the information about the sign of the signal is transmitted, the output signal s(t) will have the following form:

$$s(t) = sgn(x(t)). \qquad (4)$$

Due to the non linear process the signal s(t) will have an infinite (theoretically) bandwith. As shown in [3], the function s(t) can be written as follows:

$$s(t) = \sum_{m=0}^{+\infty} \epsilon_m \frac{j^{m+1}}{\pi} A_m(t) cos(m\omega t + m\phi(t)) \qquad (5)$$

wherein

$$A_m(t) = \fint_{-\infty}^{+\infty} J_m(A(t)q) \frac{exp(jn(t)q)}{q} dq \qquad (6)$$

$J(\cdot)$ represent the Bessel function and $\epsilon_0 = 1, \epsilon_m = 2 \quad \forall m \neq 0$. If we consider that the processing is represented by a coherent superposition of the input signal it clearly implies an averaging process over the noise n(t). Therefore, after the convolution, the signal is proportional to the expected value of s(t) with respect to the random variable n. To determine this result we evaluate first the expected value of A_m which is:

$$< A_m >= \fint_{-\infty}^{+\infty} A_m p(n) dn = \int_{-\infty}^{+\infty} J_m(A(t)q) \frac{exp(jn_0^2 q^2/2)}{q} dq. \qquad (7)$$

Eq. 7 shows that $< A_m >= 0$ for even m. For odd m,under the hypothesis $A^2(t) \ll 2n_0^2$ we have:

$$< A_m > \simeq \frac{2\sqrt{\pi}}{2^{\frac{3m}{2}} m \quad (\frac{m-1}{m})!} \left(\frac{A}{n_0}\right)^m. \qquad (8)$$

Therefore the expected value of s(t) will be represented by:

$$< s(t) >= \sum_{m=1}^{+\infty} \frac{1}{K_m} \left(\frac{A(t)}{n_0}\right)^m cos(m\omega t + m\phi(t)) \quad m \quad odd \qquad (9)$$

wherein

$$K_m = (-1)^{m+1} 2^{\frac{3(m-1)}{2}} m \quad \left(\frac{m-1}{m}\right)! \quad m \quad odd. \qquad (10)$$

We note that $K_1 = 1, K_2 = -24, K_3 = 640$. It is evident that the expected value of s(t) has infinite harmonics (only odd) the intensity of which sharply decreases with their order; in principle the single harmonics can be singled out if they don't overlap [3]. The choise of the harmonic is due to the sampling frequency and to the bandwith of the reference function. The harmonic m=1 gives us the original signal multiplied by a scaling factor.

4. Extraction of the motion errors: results

In this paragraph we explore the extraction of the motion errors of an aircraft platform from the SC-SAR data. The basic structure of the algorithm presented here is shown in Fig 2. It can be summarized as follows: the raw data $x(t)$ of a SAR system are passed through an ideal limiter so that the output data $s(t)$ (SC-data) are signum coded at the sampling frequency of the input. Then the SC-SAR signal is range processed. Finally, from the range-compressed data, the motion errors are extracted by using the RDM. As summarized in paragraph 2, the RDM analyzes the azimuth power spectra which are obtained by Fourier transforming the raw data in the azimuth direction. In particular, the RDM is based on the evaluation of the frequency shift between two ground reflectivity functions of adjacent and strongly overlapping azimuth power spectra. As a matter of fact, it is possible to get the platform forward velocity $V(t)$ and its displacement in LOS direction $D(t,r)$ from this frequency shift, t and r being time and range, respectively. The phase $\varphi(t,r)$ in the LOS-direction is obtained by multiplying the displacement in the LOS-direction by $4\pi/\lambda$. These informations give us the possibility to compensate the motion errors [1].

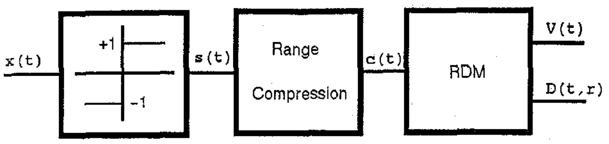

Fig 2 Block diagram of the parameter extraction procedure:
$x(t)$ are the original raw data;
$s(t)$ are the SC-SAR raw data;
$c(t)$ are the range-compressed data;
$V(t)$ is the platform forward velocity;
$D(t,r)$ is the platform displacement in LOS-direction.

In our experiments we used the raw data of the experimental SAR system (E-SAR) of the DLR during the test flight carried out on the 18th of August,1989. Typical bandwidth values are 2 Hz for the displacement in LOS and 0.05 Hz for the forward velocity. For this flight 46 corner reflectors were placed over the scene under test, so that control of the image quality was easier. The image selected quality parameters were the following: range resolution= 2.2 m; azimuth resolution= 4 m; minimum integrated sidelobe ratio (ISLR)= −15 dB; 4 looks with 50% overlap and Hamming weighting. The RDM-configuration and bandwith requirements were chosen [6] on the basis of the desired image quality.

The E-SAR raw data are characterized by the following parameters: the sampling frequency is f_s =100 Hz and $\omega/2\pi = 0$ therefore all the harmonics are spread over the fundamental one. However, this doesn't provide a significant error in the motion error extraction due to the presence of the K_m factors of eq. (10). Fig 3 shows the forward velocities extracted using original and SC-data. Let us consider the error between both curves: the standard deviation of the error is 0.3 m/s; the mean value of the error is −0.2 m/s. The similiarity of the two curves is evident.

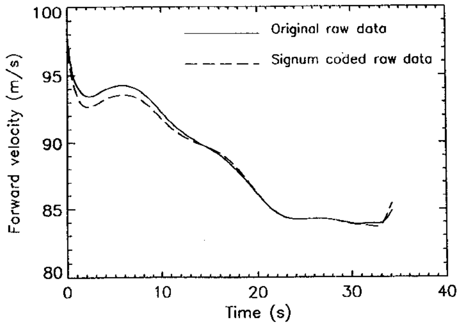

Fig 3 Extracted forward velocities from the original and from the SC-SAR raw data.

Fig 4 shows the displacement in LOS-direction extracted using original and SC-data. In this case the standard deviation of the error within the bandwith 0.1 to 1.0 Hz (corresponding to the low frequency errors) is equal to 0.033 m. The standard deviation of the error within the bandwith 1.0 Hz to 2.0 Hz (corresponding to the high frequency errors) is 0.001 m. The processed image with the motion compensation carried out by using the motion errors extracted from the SC-SAR data is shown in Fig. 5. An analysis of the impulse response of the corner reflectors on the image shows that no appreciable degradation is present.

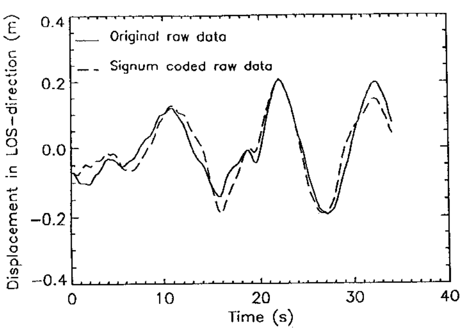

Fig 4 Diagram of extracted displacements in LOS-direction for r=3843 m.

Fig 5 SAR image of Oberpfaffenhofen (Germany)

6. Summary

The results of the extraction of the aircraft motion errors from the SC-SAR raw data are shown. A close comparison of the motion errors evaluated from the original data with the errors evaluated from the SC-data is shown.

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