CODING OF SAR RAW DATA USING REVERSIBLE TRANSFORMS*

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ABSTRACT

A Synthetic Aperture Radar (SAR) is an active, all-weather capable imaging system. The collected raw data rate is in the order of hundreds Mbit/s. With increasing requirements on the resolution the raw data rate will increase in the future. Due to restricted transmission channel capacity the necessity of an efficient coding scheme can be recognised. The aim is to reduce the high SAR raw data rate by means of both lossless and lossy source coding techniques. Because of the very poor correlation of SAR raw data it is not useful to apply lossless coding techniques directly. In this paper a new method for efficient coding of SAR raw data will be presented. This method is based upon reversible transforms of raw data. It can be easily shown that the transforms are indeed reversible and numerical well conditioned. Measurements of the statistical properties of the transformed data show that with entropy coding techniques a compression ratio of 4 can be achieved.

1.0 INTRODUCTION

A SAR system consists of a platform which can be a satellite or an airplane and an antenna fixed on one side of the platform. Short pulses are sent by the antenna to the earth. In most cases an analog or digitally generated chirp pulse is applied. The collection of SAR raw data can be understood as a two dimensional process. The one dimension is called range and is given by the distance from the antenna to the illuminated earth surface. The other dimension is the flight direction of the platform, so-called azimuth. The SAR geometry is shown in Fig. 1. The amount of collected raw data is a compromise between the desired spatial resolution which determines the complexity of the system architecture and the restricted channel capacity. A common method to reduce the raw data rate at cost of lower image quality is a coarse quantisation. In an airborne system the raw data is usually quantised with 8 bits/sample. In a spaceborne system the illuminated ground swath is much larger than in the airborne case so the problem of large data rate is more pronounced due to limited power resources on board. A quantisation with 4-6 bits/sample allows to handle the data downlink, for example the quantisation in the ERS-1 system in SAR image mode is 5 or 6 bits/sample (Attema, 1991). But, it is expected that the requirements on higher resolution and image quality will increase the data rate in the future. In this case a data downlink cannot be achieved, unless efficient encoding schemes are provided. Generally the coding techniques are subdivided into two classes. The class of lossless coding and the class of lossy coding. Lossless coding preserves all information contained in the data so that an exact reconstruction is still possible. In this case the signal

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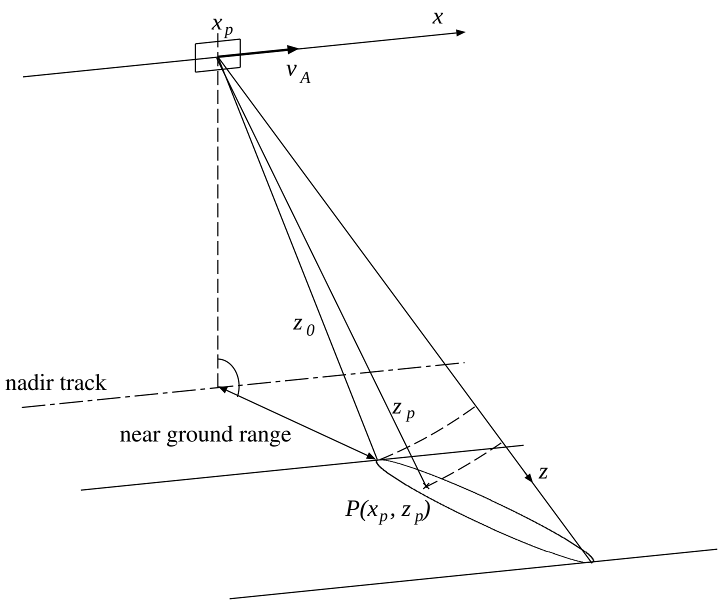

Figure 1: SAR System Geometry

statistics are exploited by redundancy reduction techniques also referred as entropy coding. The analysis of the statistical properties of SAR raw data gives a possible compression ratio in the order of 1.15-1.2. On the contrary the reconstruction of lossy compression techniques gives only an approximation of the original data. As long as the reconstruction error remains under the perceptibility threshold the coding process is called irrelevancy reduction. Best results in the order of 4 and more are reported by applying vector quantisation techniques, e. g. (Curlander, 1991), (Moureaux, 1994). A major drawback of this approach is a considerable image degradation.

A new coding method based upon reversible transforms of the poorly correlated SAR raw data will be presented in the next section of this paper. The reversibility of the transforms ensures a lossless reconstruction of the raw data. Due to the two dimensional spread of the information contained in the raw data the transforms are performed in two directions. In a first step a range transform is carried out and in a subsequent step an azimuth transform. This kind of processing is very similar to a conventional SAR processor. The difference is that no information is lost and a perfect reconstruction can be achieved. The aim of the transforms is to provide access to the correlation of the SAR data for bit rate reduction. The applied lossless coding techniques will be treated in section 3.0. The paper will finish with current results in 4.0 and a short discussion of the achieved results in 5.0.

2.0 TRANSFORM OF SAR RAW DATA

A block diagram of the proposed system for SAR data compression and decompression is shown in Fig. 2. For clarity reasons the range T_R and azimuth T_A transforms have been combined to a single transform T in Fig. 2.

As input to the system serve the demodulated complex SAR raw data denoted by I and Q for the **I***n-phase* and **Q***uadrature* components of the demodulation operation. The demodulation of the real SAR raw data from the carrier frequency f_c into the complex baseband data is performed by the SAR system and

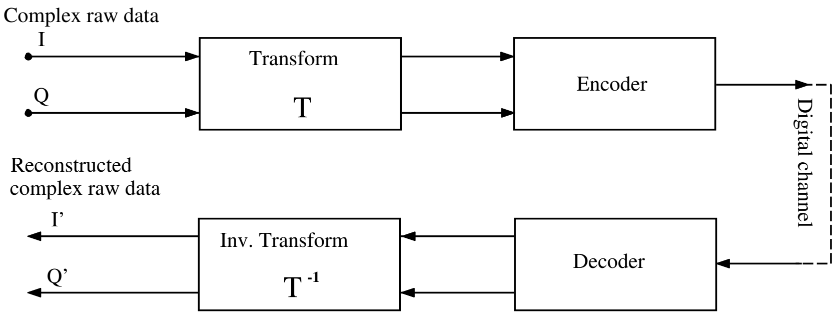

Figure 2: Digital System for SAR Raw Data Compression and Decompression

doesn't need to be integrated into Fig. 2. We denote the complex SAR raw data as follows:

$$s(x, z = 0, t) = I + jQ. \tag{1}$$

This notation signifies that the raw data is dependent on the azimuth direction x and the arrival time t of the reflections; $z = 0$ means the raw data are collected directly at the antenna where the range is assumed to be zero, see also Fig. 1.

In Fig. 3 the transform T has been split into the two separate processing steps denoted by T_R and T_A.

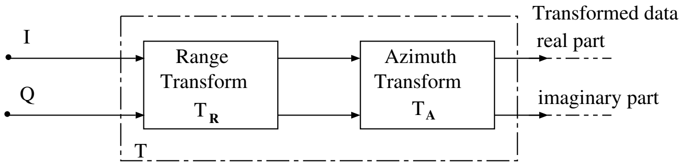

Figure 3: Two Step Transform T

From Fig. 3 it can be seen that in order to preserve exact reconstruction of the SAR raw data both separate transforms T_R and T_A are not allowed to introduce any loss to the system. In the following T_R and T_A will be described in more detail.

2.1 RANGE TRANSFORM

The aim of the range transform is to remove the chirp pulse from the collected raw data. This can be done by a *matched filter*. Because of the usual oversampling of the SAR system in range direction, T_R is a slightly modified *matched filter*. The modification consists in an adjustment of the spectrum of the reference chirp $P(\omega)$. This is necessary to guarantee the reversibility of T_R without computational losses. The modified chirp spectrum is denoted by $P_M(\omega)$:

$$P_M(\omega) = \begin{cases} P(\omega) & \text{for} \quad |\omega| \leq \pi B_p \\ const. \neq 0 & \text{otherwise} \end{cases} \tag{2}$$

where $B_p = 2\omega_p$ is the bandwidth of $P(\omega)$.

The range transform is performed in the frequency domain as a multiplication of the spectra

$$D(x, 0, \omega) = S(x, 0, \omega) \cdot P_M^*(\omega), \tag{3}$$

where $S(x, 0, \omega) \bullet\!\!-\!\!\circ\, s(x, z = 0, t)$. Capital letters denote the frequency domain and the direction of the Fourier transform can be seen by inspection of the arguments.

The inverse transform T_R^{-1} is then given by

$$S(x, 0, \omega) = \frac{D(x, 0, \omega)}{P_M^*(\omega)}. \tag{4}$$

2.2 AZIMUTH TRANSFORM

A modified wave equation migration technique introduced firstly in geophysics is applied to realize the required reversible transform in azimuth direction (Rocca, 1989). This technique is based upon the so-called *radiating reflector model*. In this model we assume that a point scatterer (P) located on the earth surface is the source (S) of an electromagnetic wave. The antenna is the receiver (R) of the signal. Using this assumption we have a one way propagation instead of the two way propagation in real case. The radiating reflector model is explained by Fig. 4.

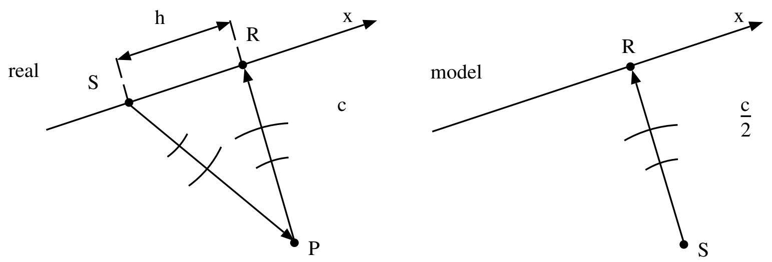

Figure 4: Radiating Reflector Model

The resulting range transformed data of Eq. 3 are the input to T_A. The data $d(x, z', -t_0)$ at time of sending the electromagnetic wave $t = -t_0$ in range $z = z'$ has to be determined.

With the above model we can write the range transformed data as the two dimensional inverse Fourier transform of their spectrum

$$d(x, z = 0, t) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} D(k_x, 0, \omega) \exp\left[j(k_x x + \omega t)\right] d\omega dk_x, \tag{5}$$

where k_x is the wave number in x. From Eq. 5 we can calculate the data at time $t = -t_0$ in range z

$$d(x, z, t = -t_0) = \frac{1}{4\pi^2} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} D(k_x, 0, \omega) \exp\left[j(k_x x - \omega t_0)\right] \exp(jk_z z) d\omega dk_x. \tag{6}$$

The exponential term $\exp(jk_z z)$ in frequency domain corresponds to a shift to the depth z in the spatial domain.

With the well known dispersion relation for waves propagating in positive direction which can be derived from the 3 dimensional wave equation

$$\omega = \frac{c}{2}\sqrt{k_x^2 + k_z^2}, \tag{7}$$

and the changes of variables $\omega = \omega' + \omega_c$, $k_z' = k_z - k_{z0}$ due to the narrowband spectrum of the SAR data ($\omega_c = 2\pi f_c$, $k_{z0} = 2\omega_c/c$, and c is the speed of light), and $z = z' + z_0$ due to the absence of reflections at ranges smaller than z_0 (*near range*) Eq. 6 can be rewritten to

$$d(x, z', -t_0) = \frac{1}{4\pi^2} e^{jk_{z0}z'} \int_{-\omega_p/c}^{\omega_p/c} \int_{-k_{xmin}}^{k_{xmax}} H_2(k_x, k_z') K \Delta \exp\left[j\left(k_x x + k_z z'\right)\right] dk_z' dk_x. \tag{8}$$

with

$$H_2(k_x, k_z') = \exp\left[-j\left(\left(\frac{ct_0}{2}\right)\sqrt{k_x^2 + (k_z' + k_{z0})^2} - k_z' z_0 - k_{z0} z_0\right)\right], \tag{9}$$

$$K = \frac{c}{2}\frac{|k_z' + k_{z0}|}{\sqrt{k_x^2 + (k_z' + k_{z0})^2}}, \tag{10}$$

$$\Delta = 2D(k_x, 0, \frac{c}{2}\sqrt{k_x^2 + (k_z' + k_{z0})^2} - \omega_c). \tag{11}$$

The limits in k_x direction can be calculated from system parameters (Rocca, 1989).

Due to $|k_x| \ll |k_z' + k_{z0}|$ eq. 10 can be approximated by a constant and will be neglected in the following. Eq. 11 represent the so-called Stolt interpolation. For our purposes this interpolation, which is a critical point if generating a SAR image, can be carried out as a simple shift of the data along the ω axis. In the $k_x - t$ domain this shift can be achieved with

$$H_1(k_x, t) = \exp\left(-j\frac{c}{4}\frac{k_x^2}{k_{z0}}t\right). \tag{12}$$

In Fig. 5 the successive processing steps to get the transformed data denoted by $d(x, z', -t_0)$ are sketched.

From eq. 9 and eq. 12 it can be recognised that the inverse transform T_A^{-1} consists in a multiplication by the same exponential terms with a plus in the exponent. Both inverse transforms T_A^{-1} and T_R^{-1} are numerical stable.

3.0 CODING OF TRANSFORMED DATA

3.1 STATISTICAL PROPERTIES OF TRANSFORMED DATA

The correlation of SAR raw data is very poor. Due to the contained so-called *speckle noise*, which is a typical phenomenon in systems working at very high frequencies, the phase of the signal is uniform distributed and can be described as a random walk in the complex plane. As a consequence the I and

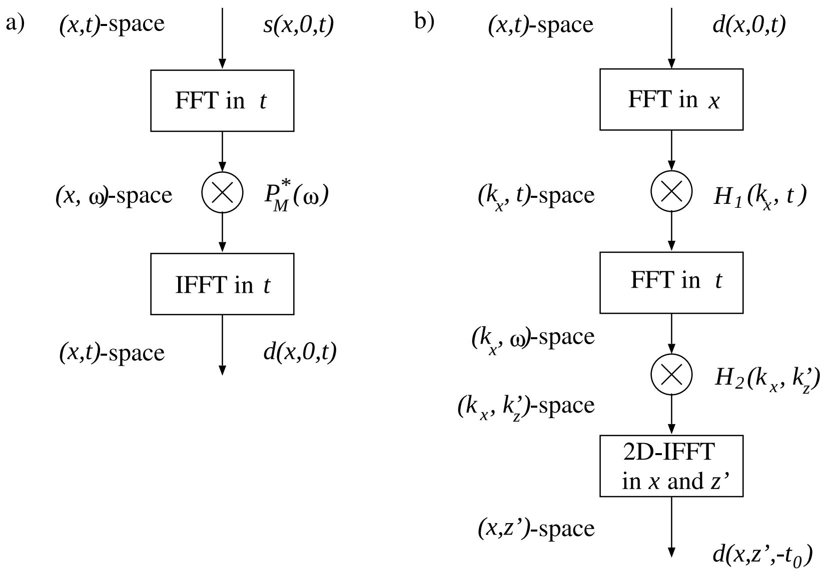

Figure 5: Processing Steps of Transform T: (a) Range Transform T_R, (b) Azimuth Transform T_A

Q components can be assumed to be Gaussian, (Goodman, 1976). The quantisation of the raw data is 8 bit/sample for the I and Q component respectively.

After performing the above described transforms we get complex transformed data which have some properties of the well examined image data. The idea is to apply the same coding techniques as in case of image data. The analysis of the statistical properties of transformed data can be performed either on real and imaginary part of the transformed data or on magnitude and phase. The calculated zero-order entropy (memoryless source) indicates that coding of real and imaginary part gives a better compression than coding of absolute value and phase due to the uniformly distributed phase. With entropy coding techniques like Huffman Coding (HC) applied to real and imaginary part of transformed data a compression ratio of 2 can be achieved. Because of the quite identical statistics of real and imaginary part only one Huffman code is needed.

Further improvement of the compression ratio is possible by applying transform coding followed by Huffman Coding. In this case the correlation of neighbouring pixels is exploited for data rate reduction (source with memory). The power spectral density (psd) in range and azimuth direction of the by transforms T_R and T_A treated data has been calculated. As a consequence it can be stated that it is not useful to apply transform coding in range because of the very flat psd. The other direction exhibits a steep psd. This signifies that correlation is available and can be exploited for coding.

The Karhunen-Loeve Transform (KLT) with transform lengths $N = 8, 16, 32, 64, 128$ has been applied to examine the possible coding gain over PCM

$$G_{DCT} = 10\log_{10} \frac{\frac{1}{N}\sum_{j=0}^{N-1} \sigma_j^2}{[\prod_{j=0}^{N-1} \sigma_j^2]^{1/N}} \quad \text{(in dB)} \tag{13}$$

with σ_j - variance of the transform coefficients, (Jayant, 1984). Eq. 13 gives the maximum achievable transform gain due to the optimum behaviour of the KLT. The results for the real part are listed in Tab. 1.

With $N = 32$ an additional gain of about 1 bit/sample can be realized (under the assumption 1 bit/sample $\hat{=} 6dB$). The choice of $N = 32$ provides on the one hand the desired gain and on the other allows to keep the processing expenses low. With $N > 32$ the coding gain increases slowly (saturation). The results of

N	8	16	32	64	128
G_{TC} in dB in azimuth	4.2	5.4	6.4	6.7	6.8
G_{TC} in dB in range	0	0.1	0.3	0.4	0.4

Table 1: Transform Gain of the DCT over PCM

the suboptimum Discrete Cosine Transform (DCT) are close to these in Tab. 1. Because of the simpler implementation the DCT has been chosen.

3.2 ENCODER SCHEME

From sections 2.1, 2.2 and section 3.1 we can derive the following encoder scheme.

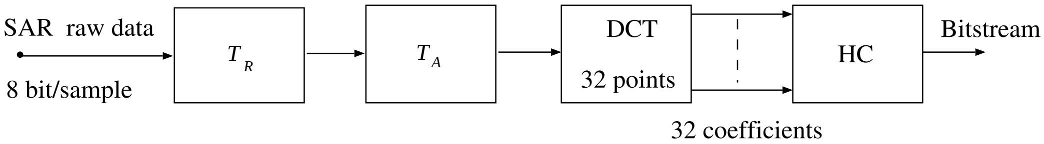

Figure 6: Encoder Scheme

4.0 RESULTS

The proposed coding method (cf. Fig. 6) has been applied to different SAR raw data sets. The length of the one dimensional DCT in azimuth was chosen to be $N = 32$. The SNR of the raw data after reconstruction was in the range $20 - 30dB$ and the achieved compression ratio 2.5-3.5. The reason for the varying quality of the reconstruction lies in the quite different image contents. The achieved SNR has to be compared with the maximum SNR of an 8 bit quantiser fed with Gaussian distributed input, which is approximately $40dB$.

In Fig. 7 two focused SAR images are shown. Image 7a) has been generated direct from original SAR raw data. On the contrary the raw data of image 7b) has been first coded with the proposed method. After decoding the reconstructed SAR raw data has been processed by the SAR processor to get image 7b). The SNR of Fig. 7a) and 7b) has been calculated to $35dB$. An important result is that the coding process didn't introduce losses in image detail. The error image is smooth and doesn't exhibit outliers. In addition, no artifacts are inserted into the focused image.

5.0 CONCLUSIONS

A new coding method for SAR raw data has been presented in this paper. This method is based upon reversible transforms T_R and T_A of SAR raw data. T_R, T_A, and their inverses perform lossless, and a perfect reconstruction of SAR raw data is possible. The following coding techniques can be chosen to

a) b)

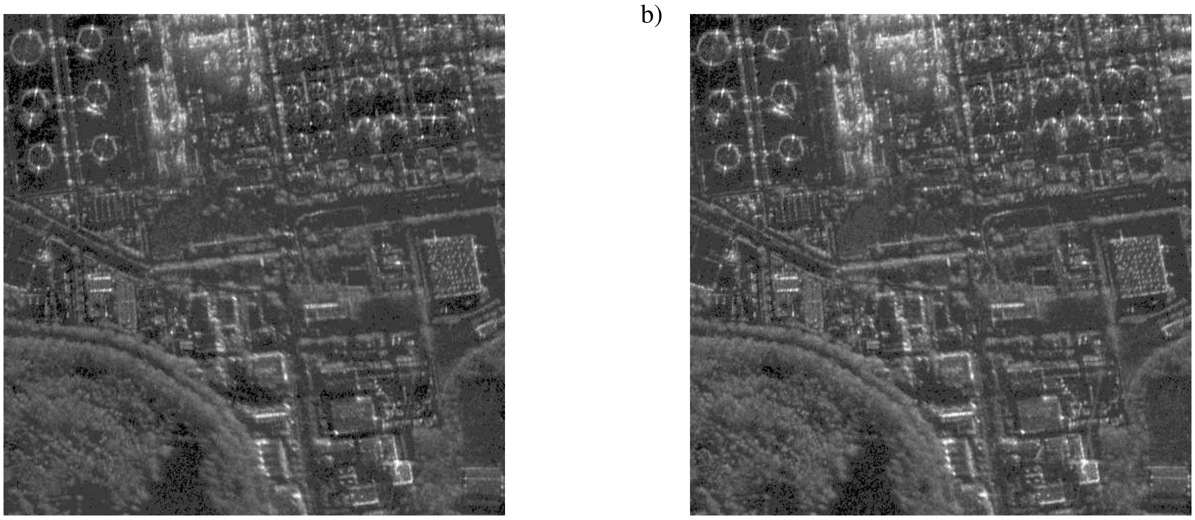

Figure 7: Simulation Results: (a) Original SAR Raw Data, (b) Reconstructed SAR Raw Data

perform either lossless or lossy. In case of redundancy coding a compression ratio of about 2.5-3.5 can be achieved. A further improvement is expected by applying irrelevancy reduction by means of e. g. vector quantisation.

An important advantage of this proposed method is that coding techniques are applied to data which exhibit a close relationship to the by a SAR processor focused data. This allows the user a better control over the losses introduced by the encoder.

6.0 ACKNOWLEDGEMENTS

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