Calibration Issue in SMART Synthetic Aperture Radar Based on Scan-On-Receive

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ABSTRACT

A new spaceborne Synthetic Aperture Radar (SAR) system based on SCan-On-REceive (SCORE) algorithm has been recently proposed in order to overcome the trade-off between spatial resolution and swath wide of current SAR systems. The compound architecture of the receiver, which employs multiple channels and Digital Beam-Forming technique, places new challenges to spaceborne SAR internal calibration (Cal) and requires the definition of a new Cal approach. In this paper a novel method for onboard internal Cal of the multichannel receiver of a SAR system based on SCORE is proposed and numerically analyzed.

INTRODUCTION

Currently intensive research is ongoing in the field of Smart Multi-Aperture Radar Techniques (SMART) for high-resolution wide-swath Synthetic Aperture Radar (SAR) imaging [1-4]. Main characteristics of SMART SAR systems are the employment of multiple transmit/receive channels and the introduction of Digital Beam-Forming (DBF) in the conventional SAR processing. This allows for a relaxation of SAR system design constraints, higher imaging quality and mitigation of the trade-off between swath width and spatial resolution inherent to conventional SAR [5].
Among SMART SAR, the system proposed by Suess et al. [1, 2], denoted as HRWS, merges the advantages of an extensive illumination capability with the high gain and directivity of a large antenna, and combines the flexibility offered by a multi-channel architecture with a limited download data volume. The HRWS SAR system is based on an algorithm for steering the elevation receive beam pattern, called SCan-On-REceive (SCORE): a wide swath is illuminated by using a small transmit antenna; whereas in reception a large multi-channel antenna and DBF are employed in order to obtain a sharp and high gain pattern, which follows the pulse echo as it travels along the ground swath.
The mutichannel receiver is realized through an antenna array followed, behind every element, by an analog front-end (FE), an analog-to-digital converter (ADC) and a field-programmable gate array (FPGA) (see Fig.1). Each analog FE performs the down conversion of the signal received from the sub-aperture; it is connected to a local oscillator and consists of low-noise amplifier, mixer, as well as bandpass and lowpass filters. The FPGAs constitute the DBF units; they are connected by a digital bus, which outputs the signal obtained from the combination of the single channel contributions.
The compound architecture of the receiver places new challenges to spaceborne SAR internal calibration (Cal). Moreover, the DBF is a novel component of the SAR processing, which requires the definition of a new Cal strategy [6]. In particular, possible amplitude and phase errors introduced by the electronic devices could affect in a different way, over frequency and temperature, the signals on each channel. As a consequence, with respect to the conventional SAR internal Cal, not only it is necessary to measure and compensate the errors on a single channel, but it should be also verified and guaranteed the alignment of all the signals. In addition, as the digital signals corresponding to each channel are combined on board by the DBF technique, any possible errors/imbalance occurring before the DBF units should be promptly measured and compensated before the application of the DBF processing.
In this paper a novel approach for onboard internal Cal of the SAR system receiver is proposed and numerically analyzed. The impact of Cal accuracy on SCORE performance is investigated by the definition of a new figure of merit and evaluated through numerical analysis. Cal parameters such as Cal interval and signal-to-noise ratio (SNR) have been evaluated, in order to assess the impact of possible residual Cal errors on SCORE performance.

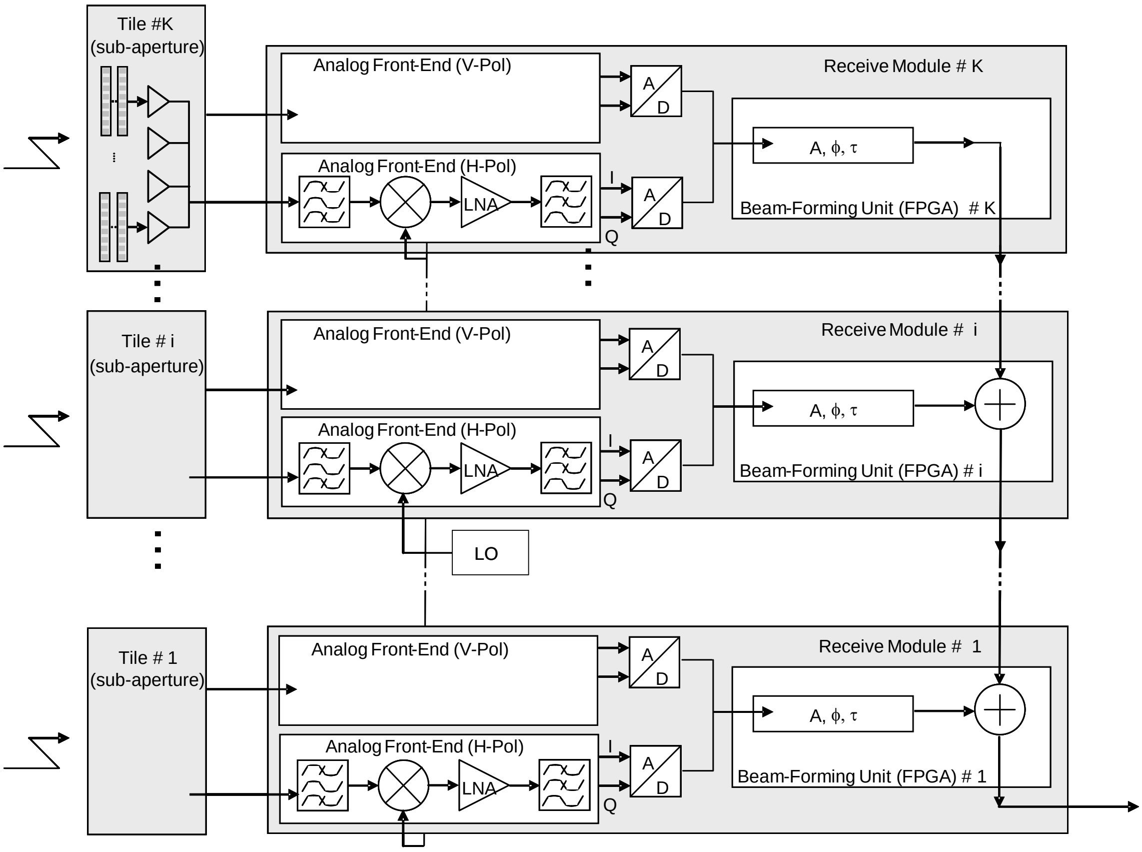

Fig. 1. HRWS multichannel receiver architecture.

COMPLEX SINUSOID INJECTION DEDICATED TIME INTERVAL (CSIDTI) APPROACH

The Cal network is integrated onboard the SAR receiver. It injects the same Cal signal at the input of each analog FE. The Cal signal is a radio frequency (RF) sinusoid, with frequency within the SAR chirp bandwidth and known mean power. The simplicity of the Cal waveform minimizes the complexity involved in the generation and processing of the signal. Moreover, it is worth noting that the alignment of the signal on each channel requires the observation of the signals at the output of the ADC in each module. Nevertheless, the direct access to the data is possible only on the output bus, after all the DBF units (see Fig. 1). The use of a sinusoid with a low (baseband) frequency allows to fully exploit the bus capability through simultaneous transmission of all signals on the bus.
The Cal is executed in a dedicated Cal interval, during which the SAR data acquisition is not performed. The Cal procedure is based on the measurement and correction of amplitude/phase mismatches, present on the signals at the output of each ADC. Two main stages of Cal can be identified: i) Phase1, performed before the SAR data acquisition; ii) Phase2, performed during the SAR acquisition. In Phase1 the amplitude/phase mismatches can be assumed to be constant versus time; whereas in Phase2 possible amplitude/phase drifts can occur. Moreover, in Phase2 the Cal interval must be as short as possible in order to minimize the loss of SAR data.
More in detail, by using a baseband representation, the injected Cal signal is given by:

$$s_k^{inj}(t) = A_0 e^{j(2\pi f t + \phi_0)} = A_0 e^{j(\omega t + \phi_0)} \qquad \text{with} \qquad k = 1, \cdots, K \,, \tag{1}$$

where, A_0 and ϕ_0 are the amplitude and phase of the Cal signal, respectively; f its the baseband frequency, which belongs to the SAR chirp baseband interval; k denotes the $k-th$ Rx module; K the total number of Rx modules.
Each FE introduces on the injected signal a complex amplitude factor, which in general depends on the specific hardware components of the module. Then the observed signal at the output of the ADC can be represented as:

$$s_k^{obs}(n) = A_k e^{j(2\pi f\, n+\phi_k)} + d_k(n) \qquad \text{with} \qquad k = 1,\cdots,K\,, \tag{2}$$

where, n is a discrete index associated to each sample of the signal; A_k and ϕ_k are the amplitude (real and positive) and phase of the complex sinusoid, respectively; $d_k(n)$ denotes additive noise.

Aim of the Cal procedure is to align the K complex amplitudes to the same value, in order to guarantee that each FE behaves in the same way at least on the frequency of the Cal signal.

The proposed Cal procedure can be concisely described by the following steps: 1. Inject the same Cal signal at the input of each analog FE; 2. Check the reliability of each channel, based on the measurement of the mean power at the output of each ADC; 3. Align the signals of the K channels at the output of the ADC, through the estimation of the amplitude and phase of the complex signal in each channel and the alignment to a properly defined reference value; 4. Eventual repetition of the steps 1-3 for a different frequency. These steps should be performed both in Phase1 and Phase2. Moreover, in Phase2 the following final steps could be introduced in order to measure possible drifts: 5. Record the amplitude/phase estimated values during each Cal interval; 6. Based on these records, extrapolate the amplitude/phase drift trend versus time.

Basic elements of the Cal procedure are the amplitude/phase estimation of the signals at the output of each ADC. The amplitude estimate is obtained under the assumption that the additive noise mean power (or the SNR) is known as:

$$\hat{A}_k = \sqrt{E\left[\left|s_k^{obs}(n)\right|^2\right] \Big/ \left(1+1/SNR\right)}\,, \qquad k = 1,\cdots,K\,, \tag{3}$$

where $E[\,x\,] \triangleq \sum_{n=1}^{N} x(n) \big/ N$ denotes the mean value operator. The phase estimate is obtained as:

$$\hat{\phi}_k = \arg\left\{E\left[s_k^{obs}(n)\;\; \overline{s}_{ref}(n)\right]\right\} = \arg\left\{E\left[s_k^{obs}(n)\;\; e^{-j\omega n}\right]\right\} \tag{4}$$

where, $\overline{s}_{ref}(n) = e^{j\omega t}$ is a reference complex sinusoid; the notation $\overline{x}$ indicates the complex conjugate of x; $\arg\{\cdot\}$ is the argument operator, which extracts the phase value of its object on the unambiguous range $[-\pi,\pi)$.

CAL ACCURACY AND SCORE PERFORMANCE

In ideal conditions, after the Cal, the signals on each channel are perfectly aligned in amplitude and phase:

$$s_k^{cal}(n) = A_c e^{j(\omega n+\phi_c)} + v(n) \qquad \text{with} \qquad k = 1,\cdots,K\,, \tag{5}$$

where A_c and ϕ_c are the common amplitude and phase values; $v(n)$ additive noise. In real conditions, a residual Cal error affects amplitude and phase of the calibrated signal in (5):

$$s_k^{cal}(n) = A_c(1+\varepsilon_{A,k})\, e^{j\left(\omega n+\phi_c+\varepsilon_{\phi,k}\right)} + v(n) \qquad \text{with} \qquad k = 1,\cdots,K\,, \tag{6}$$

where $\varepsilon_{A,k}$ is the residual normalized Cal error on the amplitude and $\varepsilon_{\phi,k}$ the residual error on the phase, at the $k-th$ receiver. These errors depend on the amplitude/phase estimation and are expected to affect SCORE performance. As a consequence, in order to properly specify the key Cal parameters, such as SNR and Cal interval, whose value mainly affects the amplitude/phase estimation performance, it is necessary to evaluate the effect of the residual Cal errors on SCORE performance. With this aim the SCORE Normalized Gain (NG) has been defined as:

$$g_{sn} = 20\log_{10}\left\{\left|\sum_{k=1}^{K}(1+\varepsilon_{A,k})\, e^{j\,\varepsilon_{\phi,k}}\right| \Big/ K\right\}. \tag{7}$$

SCORE NG has an ideal value of 0 dB; variations from this value should be limited within and acceptable range. This imposes a requirement on the Cal accuracy and on the tolerable residual Cal errors.

NUMERICAL ANALYSIS

Two kinds of residual Cal errors are considered: 1. random, zero mean; 2. systematic. The random, zero mean, residual Cal errors correspond to unbiased amplitude/phase estimation; the systematic errors to biased estimation.

In Fig. 2 residual Cal errors with zero mean and Gaussian distribution are assumed: $\varepsilon_A \in N(0,\sigma_A^2)$ and $\varepsilon_\phi \in N(0,\sigma_\phi^2)$. Fig. 2 (left) shows the SCORE NG versus the amplitude and phase standard deviation (std), when $K = 15$; Fig. 2 (right) shows the SCORE NG versus the number of channels K, when the std $\sigma_A = 10\%$ and $\sigma_\phi = 10$ deg.

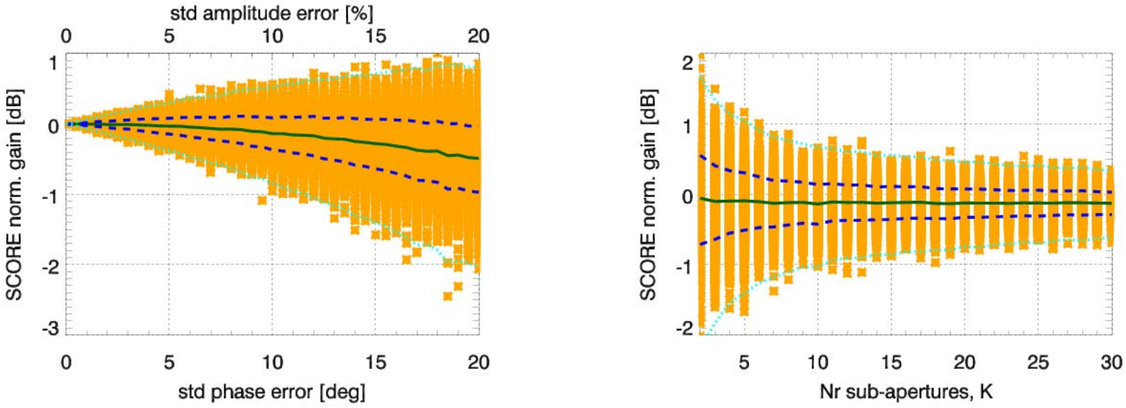

Fig. 2. SCORE NG vs.: (left) amplitude/phase std of random Cal errors, K=15; (right) number of sub-apertures, $\sigma_A = 10\%$, $\sigma_\phi = 10$ deg .

More in details, the results are derived under the assumption that the errors have the same statistical distribution on all the channels; a residual error is simultaneously present on amplitude and phase (a linear relationship associates amplitude and phase residual errors, such that from zero value they reach 20% and 20 deg, respectively). The plots are obtained by 10^3 Monte Carlo (MC) trials. The continuous dark green line shows SCORE NG mean value, the blue dashed lines the mean value ± std, the cyan dotted lines the mean value ± 3·std, the orange points the general realizations. From the reported results, for $K \geq 15$, SCORE NG variation is below 1 dB if the std of the residual error on the amplitude and phase are below 10% and 10 deg, respectively. A decrease in the number of channels degrades SCORE performance, especially until $K < 15$.

As regards the effect of systematic errors, the SCORE NG value strongly depends on the actual residual errors on each channel. Nevertheless, it is worth remarking that a constant residual error (estimation bias) on the phase, i.e. with the same value on each channel, does not affect SCORE performance; whereas a constant residual error on the amplitude of the ±12% produces a SCORE NG variation around ±1 dB, independent on the number of Rx channels.

Fig. 3 shows the amplitude and phase estimation performance. In particular, the signal (2) is considered, where A_k and ϕ_k are modeled as unknown real constants, and $d_k(n)$ as additive, white circular Gaussian noise, with known mean power P_d : $d_k(n) \in CN(0, P_d)$. The baseband frequency, f , and sampling frequency value is 11,93 MHz and 28,64 MHz, respectively. The amplitude and phase of the signal in (2) have been estimated by using (3) and (4). The estimation performance, expressed in terms of bias and std, is evaluated by MC simulations as a function of the Cal interval and the SNR at the output of the array, $ASNR = K \cdot SNR = K \cdot A_k^2 / P_d$, with K=15. The obtained results show

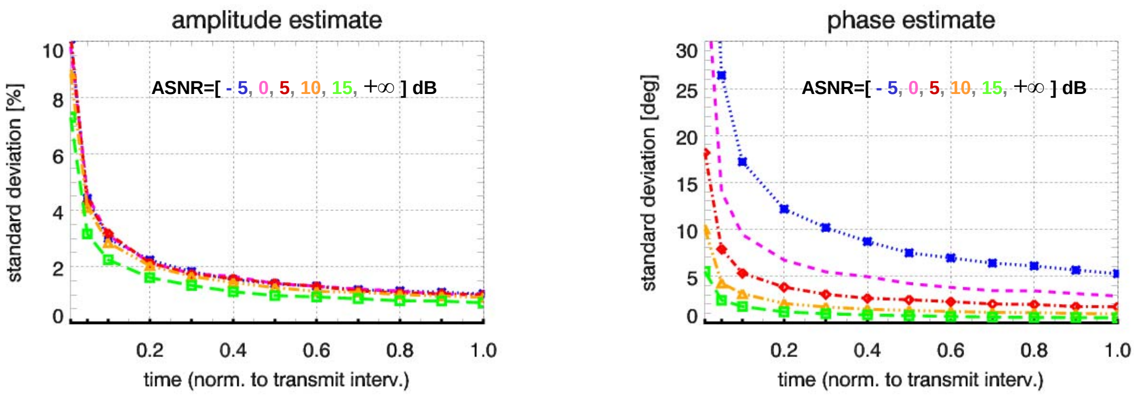

Fig. 3. Amplitude and phase estimation performance versus Cal interval normalized to $95,7\,\mu s$, i.e. the transmission time of a SAR with $PRF = 1775\,Hz$ and duty cycle = 17% . Each curve corresponds to a different ASNR value.

that both the amplitude and phase estimates are unbiased; whereas the std decreases for longer Cal intervals and higher ASNR. In particular, as the std of the estimates corresponds to that of the residual Cal errors, the values of the Cal interval and of the ASNR can be set by comparing Fig.2 (left) and Fig. 3: a Cal interval in the order $50\mu s$ (which corresponds to 0.4 of the transmit interval, for a PRF=1775 Hz and a duty cycle $=17\%$) and $ASNR \geq -5\,dB$ ($SNR \geq$ -16.7 dB) allow to contain SCORE NG variations below 1 dB.

It is worth noting that the amplitude/phase estimation performance here reported is achieved both in Phase1 and Phase2. In fact, possible drifts occurring in Phase2 are not expected to produce amplitude/phase variations over the short Cal interval. Nevertheless, in the presence of drifts, the values of the amplitude/phase on each channel could progressively differ. As a consequence, in Phase2, it is necessary to define a Cal repetition frequency, dependent on the drift velocity, such as the difference between amplitude/phase values on each channel will be contained in acceptable range of values.

CONCLUSIONS

An original method for onboard internal Cal of SAR multichannel receivers has been defined and analyzed. The effect of the Cal accuracy on SCORE performance has been evaluated through the definition of a novel parameter, the SCORE NG. Cal interval and the SNR have been evaluated, in order to limit the impact of possible residual Cal errors on SCORE performance. The obtained results show the possibility to measure and compensate errors and mismatches between channels with a Cal interval in the order half of typical SAR transmit time and a $SNR \geq$ -16.7 dB.

REFERENCES

[1] M. Suess, B. Grafmueller, R. Zahn, “A Novel High Resolution, Wide Swath SAR System”, *Proc. IEEE Geosci. and Remote Sens. Symp., IGARSS´01*, vol. 3, pp. 1013-1015, Sydney, NSW, Australia, July 2001.
[2] M. Suess and W. Wiesbeck, “Side-Looking Synthetic Aperture Radar System”, *European Patent Application*, EP 1 241 487 A1, Sept. 18, 2002.
[3] M. Younis, F. Bordoni, N. Gebert, G. Krieger, “Smart Multi-Aperture Radar Techniques for Spaceborne Remote Sensing”, *Proc. IEEE Geosci. and Remote Sens. Symp., IGARSS´08*, vol. 3, pp. 278 - 281 Boston, MA, USA, July 2008.
[4] N. Gebert, G. Krieger, A. Moreira, “Digital Beamforming on Receive: Techniques and Optimization Strategies for High-Resolution Wide-Swath SAR Imaging”, *IEEE Trans. on Aerosp. and Electron. Syst.*, vol. 45, issue 2, pp. 564 – 592, April 2009.
[5] J. C. Curlander, R. N. McDonough, *Synthetic Aperture Radar: Systems and Signal Processing*, NY, Wiley, 1991.
[6] T.W. Nuteson, J.E. Stocker, J.S. Clark, D.S. Haque, G.S. Mitchell, “Performance Characterization of FPGA Techniques for Calibration and Beamforming in Smart Antenna Applications”, *IEEE Trans. on Microwave Theory and Techniques*, vol. 50, issue 12, pp. 3043 – 3051, Dec. 2002.