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Analysis and Correction of the Inter-channel Mismatch in Synthetic Aperture Radiometer

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Abstract

A Ka-band two dimensional synthetic aperture interferometric radiometer (SAIR) called SAIR-2D has been developed for concealed weapon detection. The inter-channel mismatch due to amplitude, phase and group delay differences between each receiving channel pairs can result in an undesired effect called fringe washing function (FWF). As the security application usually needs a wide field of view, the FWF is unavoidable and could lead to radiometric performance degradation. This paper presents a general method to analyze the impact of inter-channel mismatch on SAIR. Based on the analysis, the performance degradation of the SAIR-2D is mainly introduced by the group delay difference. To compensate the degradation due to group delay difference, a channel synchronization method is proposed in this paper. Validation experiments have been conducted on SAIR-2D. The experimental results show that the group delay differences are significantly reduced and can meet the requirements of SAIR-2D by means of the proposed method.

Keywords*: remote sensing, synthetic aperture interferometric radiometer, inter-channel mismatch, fringe washing function*

1. Introduction

The Synthetic aperture interferometric radiometer was introduced in the late 1980s as an alternative to real aperture radiometer for earth observation. This technology can synthesize a large aperture by sparsely arranging a number of small aperture antennas to achieve high spatial resolution at low microwave frequencies with reduced mass and mechanical requirements [1]. Recently, due to high imaging rate with lower cost and lower complexity of the receiving array, the millimeter-wave imager based on SAIR technique has been deleloped in many applications [2-4]. A two-dimensional passive Ka-band imager based on SAIR technique used for concealed weapon detection has been developed in Beihang University.

Performance of SAIR system will be degraded due to the decorrelation or called FWF effect [5-8], which is caused by the different channel responses called inter-channel mismatch in the two receivers forming the baseline. The effect becomes non-negligible, when the group delay difference of channel becomes comparable with the correlation time, which is defined by the inverse of receiver's bandwidth. The group delay comprises of a slant delay and a channel equivalent delay. As is shown in Figure 1, the slant delay is caused by the signal from a slant direction θ reach two antennas in different time delays, while the channel equivalent delay is resulted from the inter-channel mismatch prior to correlation. Considering security applications usually require high imaging rate and large field of view (FOV). The FWF has to be accounted for and corrected because high imaging rate means low integration time and high bandwidth to achieve sufficient radiometric sensitivity, while large FOV leads to high slant delay. In order to reduce the FWF effect, the band division correlation (BDC) technique [7] has been proposed. It requires partition the band into smaller sub-bands, which naturally leads to an increased correlation time. However, this technique implies the number of correlators increasing, as it increases times the number of sub-channels. Thus it will result in an increasing on complexity of receiving channel and correlator unit. In practice, a SAIR usually consists of tens of receiving channels. In this case the cost of BDC is very high.

In this paper, we propose an approach that corrects the group delay difference to minimize the impact of FWF on the radiometric performance. Firstly, this paper theoretically

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studies the impacts of inter-channel mismatch including amplitude, phase and group delay differences on FWF, respectively. According to the analysis and the specification of SAIR-2D, the FWF is mostly introduced by the group delay difference due to sample clock skew between Analog-to-Digital Converters (ADCs) [9]. Then, a channel synchronization method is presented to correct the skew with introducing few hardware requirements. Based on the instrument of SAIR-2D, a set of experiments are conducted. The measurements verify the theoretical analysis and the correction method. In order to demonstrate the performance of SAIR-2D, the corrected FWFs of SAIR-2D are estimated using the 3-delay method [8]. The experiment results are presented and prove the performance can meet the requirement of SAIR-2D.

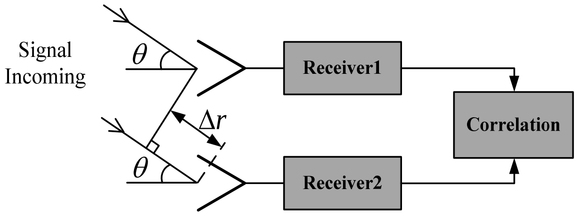


Figure 1. Slant Delay is $\Delta r / c$, which is Introduced by a Signal From a Slant Direction Reaches the Two Channel of a Baseline

2. Imaging Principle and the Impact of FWF

The main function of SAIR is to measure the spectral components of the brightness temperature distribution in the FOV by computing the cross correlations of the signals collected by a sparse array of small antennas. Complex correlations obtained by the SAIR can be called visibility function samples $V_{12}(u,v)$, which are obtained by the cross correlation of the signals collected by antennas. (u,v) are the vectors between receivers in wavelengths. The relationship between the modified brightness temperature $T_M(\xi,\eta)$ and the visibility function sample is given by:

$$V_{12}(u,v) = \iint_{\xi^2+\eta^2\leq 1} T_M(\xi,\eta)\tilde{r}_{12}(\tau)e^{-j2\pi(u\xi+v\eta)}d\xi d\eta \quad (1)$$

Where (ξ,η) are the direction cosines, $\tilde{r}_{12}(\tau)$ is the FWF. The modified brightness can be expressed as:

$$T_M(\xi,\eta) = \frac{T_B(\xi,\eta)}{\sqrt{1-\xi^2-\eta^2}} F_{n1}(\xi,\eta)F_{n2}^*(\xi,\eta) \quad (2)$$

Where $T_B(\xi,\eta)$ is the brightness temperature, $F_{n1}(\xi,\eta)$ and $F_{n2}(\xi,\eta)$ are the normalized radiation pattern of the two antennas. The FWF can be calculated by:

$$\tilde{r}_{12}(\tau) = \frac{1}{\sqrt{B_1 B_2}} \int_0^\infty H_{n1}(f)H_{n2}^*(f)e^{j2\pi f\tau}df \quad (3)$$

Where $H_{nk}(f)$ and B_k are the normalized frequency response and equivalent bandwidth of receivers k , respectively. $\tau = -(u\xi + v\eta)/f_0$, and f_0 is the center frequency of the receivers. If the FWF is taken into account, the visibility function sample can be computed as:

$$V_{12} = \frac{\mu_{12}\sqrt{T_{sys1}+T_{sys2}}}{\tilde{r}_{12}(0)} \quad (4)$$

Where, μ_{kj} is the normalized correlation coefficient, and T_{sysk} is the system temperature of receiver k. The amplitude of FWF at the origin $\tilde{r}_{12}(0)$ is called correlator efficiency. As $\tilde{r}_{12}(0)$ away from the unity, the visibility function samples will incur a loss of correlations that causes degraded resolution in the reconstructed brightness temperature. Therefore it is a key parameter for describing the SAIR performance. The corelator efficiency will be decreased due to the combined effects of amplitude, phase and group delay difference between channels. To investigate their impacts, these differences are assumed to be statistical independent. Below, the correlator efficiency is computed for each of these differences, respectively.

Firstly, the effect of the amplitude difference is considered. If the frequency response can be written as:

$$H_{1,2}(f) = A_{1,2}\{1+\Delta A_{1,2}(f)\}e^{j\phi(f)} \tag{5}$$

Where $\Delta A_{1,2}$ is the amplitude difference between channel 1 and channel 2. Substituting the Equation (5) into Equation (3), the FWF is:

$$|\tilde{r}_{12}| = \frac{\int_{f_1}^{f_2}\{1+\Delta A_1(f)+\Delta A_2(f)+\Delta A_1(f)+\Delta A_2(f)\}df}{\sqrt{\int_{f_1}^{f_2}[1+\Delta A_1(f)]^2 df \int_{f_1}^{f_2}[1+\Delta A_2(f)]^2 df}} \tag{6}$$

If the amplitude difference between the two channels is equal amplitude $|\Delta A|$, the above expression is simplified to:

$$\tilde{r}_{12}\,| = \frac{1-|\Delta A|^2}{1+|\Delta A|^2} \tag{7}$$

The amplitude difference peak-to-peak in decibels is $20\log(\frac{1+|\Delta A|}{1-|\Delta A|})$. Figure 2 shows the effect of amplitude difference on FWF is quite small, for example a 1 dB amplitude difference results in at most 0.7 % efficiency loss.

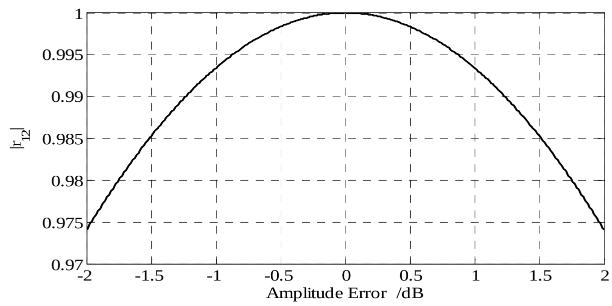


Figure 2. Dependence of FWF on Amplitude Difference between Channels

Then, the phase difference between channels is taken into account. In this case the frequency response is expressed as:

$$H_{1,2}(f) = Ae^{j(\phi+\Delta\phi_{1,2})} \tag{8}$$

Where $\Delta\phi_{1,2}$ is the phase difference between channel 1 and channel 2. If the phase difference $\Delta\phi$ is modeled as a uniform random variable over the internal $\Delta\psi$, and the probability density function of phase difference is given by:

$$p(\Delta\phi)=\begin{cases}\dfrac{1}{2\Delta\psi} \quad , & |\Delta\phi|\le\Delta\psi \\ 0 \quad , & |\Delta\phi|>\Delta\psi\end{cases} \tag{9}$$

After substituting the Equation (8) into Equation (3), the FWF is simplified to:

$$\tilde{r}_{12}=\sin(\Delta\phi)/\Delta\phi \tag{10}$$

It can be found that the phase difference of 10 degrees could induce almost 0.5 % efficiency loss.

For the group delay difference, it implies the difference of signal transmission delay in receiving chain prior to correlation from the antenna. Therefore the impacts of group delay difference on correlator efficiency can be analyzed using same models as the slant delay. The details of analysis can be found in next section.

3. The Configuration of SAIR-2D and Proposed Channel Synchronization Method

To illustrate slant delay of SAIR-2D, the system configuration is discussed briefly. It operates at 34 GHz~34.2 GHz, and consists of 48 8mm-band receiving elements located in a U-shaped geometry. Each elements consists of a pyramid horn antenna and a dual-conversion receiver with IQ demodulator. Figure 3 shows the configuration of SAIR-2D. Each receiver consists of a RF front end and an IF module. To preserve the phase information, coherent LOs are generated by a frequency synthesizer and fed into receivers through a group of dividers. In the Digital Signal Processing (DSP) subsystem, six Data Acquisition Units (DAU) are used to digitize the 200MHz I/Q outputs of receivers. Each DAU consists of 16 ADCs to acquire the raw data of receivers. The complex correlations between signals are calculated in the DSP subsystem. By calculating the IFT of the visibility function samples, a brightness temperature image of the FOV is obtained.

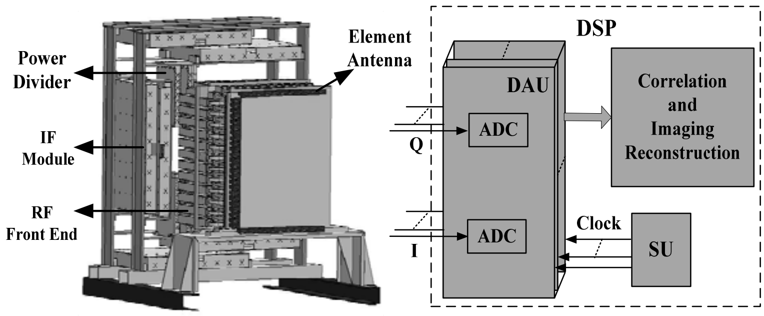


Figure 3. Configuration of the SAIR-2D

According to the systematic requirements, the alias-free FOV of SAIR-2D is ± 11 degrees and ± 20 degrees in horizontal and vertical direction, respectively. Therefore the spacings between elements are 2.62λ and 1.46λ , separately. The longest baseline of SAIR-2D is about 0.4145 m, which leads to an angular resolution of 1.1~1.3 degrees. Thus the maximum slant delay τ_s corresponding to the longest baseline at the edge of the FOV is:

$$\tau_s=\frac{d\cdot\sin\theta}{c}=\frac{0.4145\cdot\sin 20^\circ}{3\cdot 10^8}\approx 473ps \tag{11}$$

To study the impact of FWF on SAIR-2D, the receivers' frequency responses are approximated rectangular. It is equal to unity on the pass-band and equal to zero on the rejection band. Under these assumptions, Equation (3) can be expressed as:

$$\tilde{r}_{12}(\tau_s, \tau_e) = \mathrm{sinc}(B(\tau_s + \tau_e)) \quad (12)$$

Where B is the receiver bandwidth, τ_e is the equivalent delay between channels. For the SAIR-2D, the bandwidth of receivers is 200MHz. Figure 4 shows the dependence of correlator efficiency on total time delay of SAIR-2D. It can be found that the worst correlator efficiency loss is about 1.5% due to the large FOV of SAIR-2D.To meet 5% efficiency loss constraint, the channel equivalent delay should be no more than 380ps. Consequently, according to Equation (12), the efficiency loss due to inter-channel mismatch must be less than 1%.

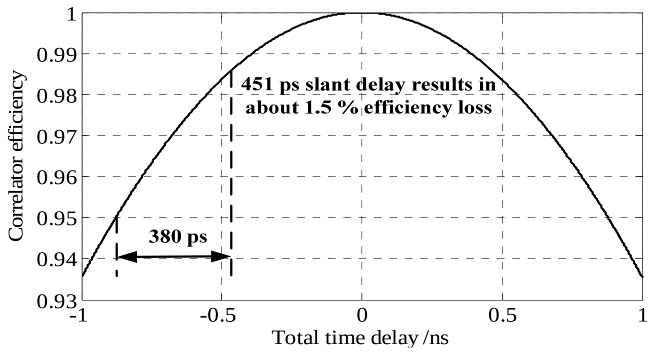


Figure 4. Correlator Efficiency vs Total Time Delay of SAIR-2D

In the DSP subsystem, the DAUs are interconnected through a interconnect board and installed in a standard 6U platform. A Synchronization Unit (SU) is designed to synchronize the sample clock of DAUs. However, owing to different transmission paths from frequency synthesizer to ADCs, the 380ps sample clock delay difference called skew will become a challenge when a large number of channels' analog signals are synchronously digitized. Meanwhile, the <1dB amplitude difference and <10 degrees phase difference can be implemented due to the high-precision manufacture and careful design. Therefore, the clock skew between channels should be corrected to reduce the channel equivalent time delay.

For the purpose of reducing the skews between ADCs, a clock synchronization module is implemented. The block diagram of the synchronization module is illustrated in Figure 5. It consists of a Precision Clock Conditioner (PCC) and a Clock Distributor (CD) in each DAU. Firstly, the clocks are transmitted to PCCs in DAUs from SU. The functions of the PCC are to adjust the sample clock phase difference due to different transmission delay in interconnect broad. With this device, the skew can be corrected with 100ps step by step and the sample clock jitter can be cleaned, which can meet the signal to noise ratios requirement. Then, the sample clocks are fed into ADCs through the CD in DAU. To minimize the transmission delay in DAUs, the equal signal paths of all clocks from the CD to the ADCs are designed.

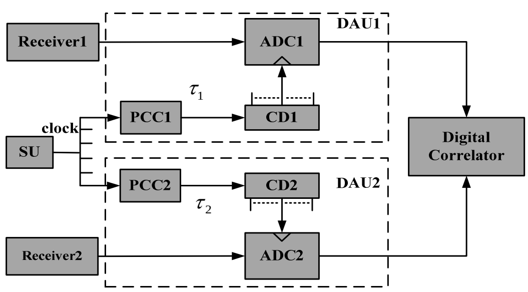
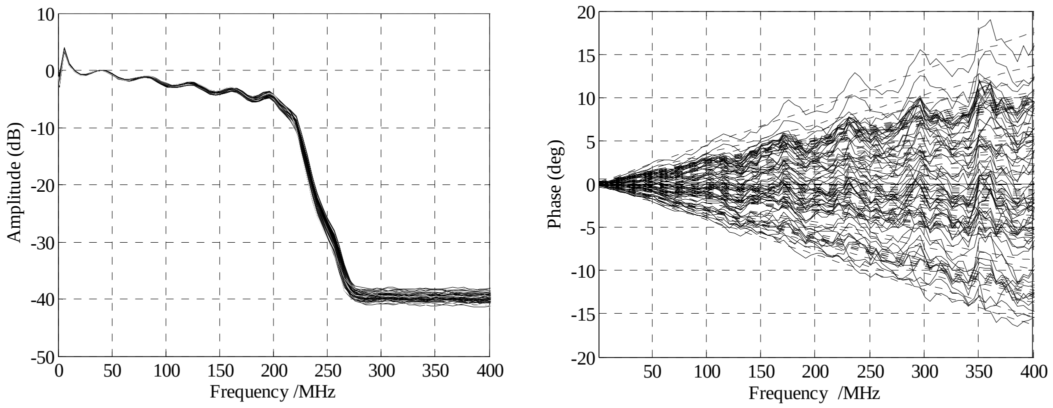


Figure 5. Block Diagram of the Synchronization Module

4. Results and Discussion

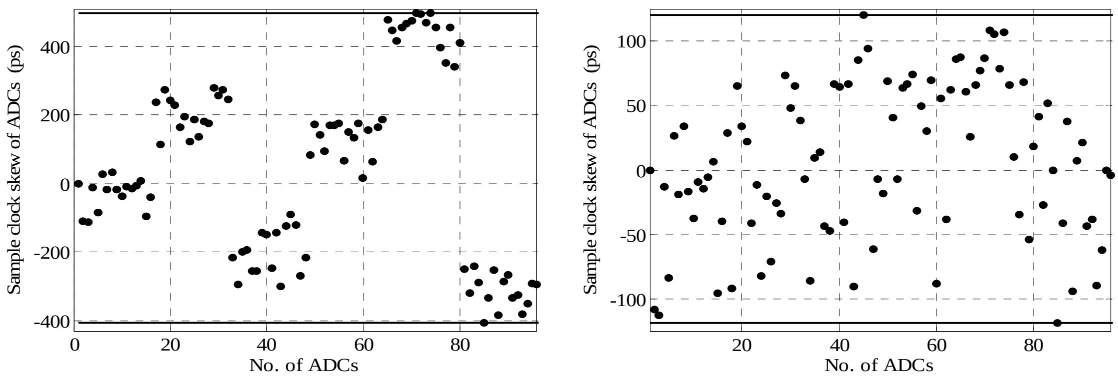
Several experiments have been carried out to verify the performance of SAIR-2D. Firstly, the amplitude frequency responses and phase differences of 96 channels are measured. The measurements (only I-channels) are shown in Figure 6.



(a) (b)

Figure 6. (a) Measured amplitude frequency responses of channels. (b) Measured phase differences of channels (solid line), the linear regression of phase differences with the first channel as reference (dotted line)

As is expected, the amplitude and phase differences between channels are below 1dB and 3 degrees in pass band. The raw sample clock skews between channels are also measured and shown in Figure 7(a) we can see that the raw skews are almost ±500ps. According to Equation (7) and Equation (10), the effects of amplitude and phase differences on correlator efficiency can be ignored for SAIR-2D compared with loss caused by group delay difference. After correcting by means of the proposed channel synchronization method, as is shown in Figure 7(b) the skews are strongly reduced to about ±120ps. Based on the analysis of above, the ±120 ps skew will results in below 0.4% correlator efficiency loss.



(a) (b)

Figure 7. (a) Raw skews of ADCs' channel. (b) Corrected skews of ADCs' channel with the first ADC channel as reference

To further test the inter-channel mismatch of SAIR-2D, the FWF shape is approximated by 3-delay Method. For easier implementation, the FWFs of 6 channels are measured. The measurement configuration is shown in Figure 8(a). Figure 8(b) illustrates the normalized modulus of FWF, which is computed from the measurements. We can see that the correlator efficiency loss introduce by the inter-channel mismatch is below 1%. Thus it can meet the specifications of SAIR-2D.

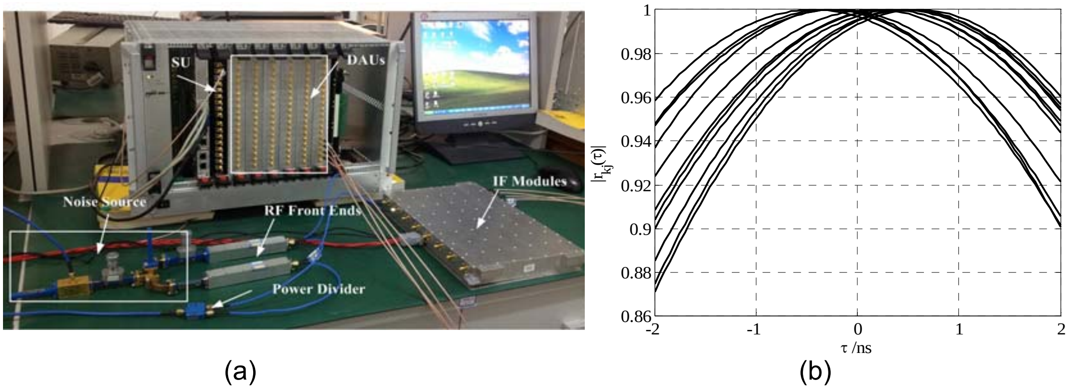


Figure 8. (a) Measurement configuration of FWF, (b) Normalized modules of FWFs of 6 channels in SAIR-2D

5. Conclusion

In this paper, the impacts of inter-channel mismatch on correlator efficiency of SAIR have been theoretically studied. Based on the analysis, the impacts of amplitude and phase differences are relatively small compared to group delay difference between channels. To reduce the difference, a channel synchronization method including an adjustable PCC module and a CU for each DAU is adopted. Experimental results have shown these differences are well below system specification: 1dB for the amplitude, 3 degrees for phase, ±120ps for sample clock skew after correction. The experimental results of FWFs presented in this paper have shown the correlator efficiency loss due to inter-channel mismatch is below 1%. Consequently, the worst case of the loss is less than 5% at the edge of FOV. It can satisfy the requirements for the SAIR-2D.

References

[1] CS Ruf, CT Swift, AB Tanner, DM Le. Vine. Interferometric synthetic aperture radiometry for the remote sensing of the earth. *IEEE Transactions on Geoscience and Remote Sensing*. 1988; 26: 597-611.

[2] Vladimir G Kolinko, Shiow-Hua Lin, Alex Shek, Will Manning Chris Martin, Max Hall, Oskar Kirsten, Joshua Moore, David A Wikner. A passive millimeter-wave imaging system for concealed weapons and explosives detection. *SPIE, Optics and Photonics in Global Homeland Security*. 2005; 5781: 85-92.

[3] Ding H. Application of Wireless Sensor Network in Target Detection and localization. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2013; 11(10).

[4] C Zheng, X Yao, A Hu, J Miao. A passive millimeter-wave imager used for concealed weapon detection. *Progress in Electromagnetics Research B*. 2013; 46: 379-397.

[5] R Butora, M Martin-Neira, A Rivada. Fringe-Washing Function Calibration in Aperture Synthesis Microwave Radiometry. *Radio Science*. 2003; 38(2).

[6] I Corbella et al. On-Ground Characterization of the SMOS payload. *IEEE Transactions on Geoscience and Remote Sensing*. 2009; 47: 3123-3133.

[7] MA Fischman, AW England, CS Ruf. How Digital Correlation Affects the Fringe Washing Function in L-Band Aperture Synthesis Radiometry. *IEEE Transactions on Geoscience and Remote Sensing*. 2003; 40: 671-679.

[8] A Camps, F Torres, J Bara, I Corbella, F Monzon. Automatic Calibration of Channels frequency response in interferometric radiometers. *Electronics Letters*. 1999; 35: 115-116.

[9] S Jing, SUH Zhang. The Study and Achieving of Highprecision Data acquisition Based on ΔΣADC. *TELKOMNIKA Indonesian Journal of Electrical Engineering*. 2013; 11(8).