RADI’s Airborne X-SAR with High Resolution: Performance, Characterization and Verification

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Abstract. X-SAR is an airborne multi-mode synthetic aperture radar (SAR) system with high-resolution, interferometer and full-polarization, developed by the Institute of Remote Sensing and Digital Earth (RADI), Chinese Academy of Sciences (CAS), funded by the CAS Large Research Infrastructures. Since 2009, the first developed stage of X-SAR system was successfully implemented to an operational SAR with high resolution (up to 0.5 meter). In May 2013, the imaging verification on flights test was carried out. The data calibration on the laboratory measurements were completed at the end of 2015. Many valuable results of imaging verification and data calibration have emphasized the quantitative microwave measurement capabilities. This paper presents the results of X-SAR system performance, characterization, optimization, and verification as carried out during the flight trials and laboratory measurement. The system performance and calibration parameters are presented such as transmitter amplitude accuracy, phase noise, system gain change with temperature variation, long-term radiometric stability. The imaging verification of the key performance parameters is discussed, including target-response function, target pairs discrimination, image noise and radiometric resolution. The example imagery of radiometric enhanced products for intensity change detection is also described.

1. Introduction

From 2009, RADI has implemented to develop an airborne multi-mode SAR system to investigate the potential for disaster areas of natural hazards such as debris flow, earthquakes and floods. At the end of 2015, the high resolution processing had been achieved to the high-quality multi-look calibrated X-SAR images, using a near real time on ground imaging processing based on GPU architecture. Now, the upgrading radar is being to realize the interferometer and full-polarization capabilities. X-SAR radar is an X-band SAR at a centre frequency of 9.0GHz with 360 MHz maximum bandwidth, housed and operated in CAS’s Cessna Citation II jet. The radar was designed to the dual-channel received with the internal calibrator, which is convenient to configure the interferometer antenna pairs or the polarization switcher. This paper focuses on X-SAR performance, characterization and verification with high resolution, achieving by the flight test and laboratory measurement. Section 2 provides a general description of system overview, architecture and performances. Section 3 describes data calibration results of temperature characterization and long-term radiometric stability measured on the laboratory, while section 4 provides flight test imaging results of the geometric and radiometric measurements, meantime providing an example image of radiometric enhanced products of intensity change detection. Finally, section 5 concludes and presents an outlook on upgrade X-SAR.
2. System overview

X-SAR architecture is divided into modular units or subsystems with controlled interfaces. In this way, each unit can be updated or replaced with minimal need for modification in other units [1]. The six main units are: antenna and servo unit, high power transmitter (HPA), internal calibration unit, radio frequency (RF) subsystem, digital formatting subsystem and monitoring control subsystem. Main operating parameters at high resolution mode are listed in Table1.

Table 1. Main operating parameters at high resolution.

| Parameters                  | Values                      |
|-----------------------------|-----------------------------|
| Operating frequency         | X (9.0 GHz)                 |
| Antenna gain                | >26 dB, HH polarization     |
| Bandwidth (MHz)             | 360                         |
| Pulse length( us)           | 25                          |
| Operating range(km)         | 19~23                       |
| Look angle                  | 63°                         |
| Noise equivalent sigma zero( NESZ) | <-30dB@Max-swath           |

HPA is based on a travelling wave tube amplifier (TWTA) with 4.5 KW/ 400W peak/ average transmitted power. Fig.1 shows the transmitter amplitude stability was less than 0.045 dB, the change values are stable over operational 4 hours and do not results in a measurable effect of the overall system performances.

In RF subsystem, the phase noise of local oscillator signal (7.8GHz) was below -111.65dBc/1kHz, to be minimized the lower phase noise. Meanwhile, the phase noise of transmitting signal (9GHz) was realized to below -102.9dBc/1kHz, which was exceeded -90dBc/1kHz for the design criteria.

In digital formatting subsystem, the sample of received signal data was performed by a 500MHz ADC with a 12-bit capacity, therefore the received dynamic range can be theoretical more than 72dB. Thus, the receiver gain setting is commanded based on an estimated terrain scattering values for each individual scene. No automatic gain control is implemented in X-SAR radar.

3. Data calibration on laboratory measurements

X-SAR radar has been integrated a flexible internal calibrator which can be guaranteed the high radiometric stability of all data products, regardless of operated on board and on laboratory.

3.1. Temperature characterization

The different operational loads onboard are influenced by the cabin’s temperature, which can lead to the total system characterizations dependence on a thermal. The radiometric characterizations with temperature variations can be used by the internal calibration in ground temperature test chamber.
The radiometric stability of transmitted gain (left) and system gain (right) are shown in Fig 2, the root mean square (RMS) values of transmitted gain drifts and system gain drifts are respectively below 0.26dB and 0.82dB for 0–40°C during data acquisition in high resolution up to 0.5 meter, it is no necessary to correct the amplitude change with temperature variations using on-ground characterization data, during data processing steps.

**Figure 2.** Transmitted gain drifts (left) and system gain drifts (right) with temperature variation.

3.2. Radiometric stability characterization

The long-term radiometric stability can be monitored by the evaluation of the internal calibration data [2]. Fig.3 describes the stability curve of system gain and system noise for long-term monitoring as a function of time throughout in 2014. The RMS values of system gain and system noise is respectively below 0.46 dB and 0.31 dB at 0.5 meter spatial resolution, the offsets can be convenient to corrected using on-ground internal calibration data, during data processing steps.

**Figure 3.** The long-term stability of system gain (left) and system noise (right) throughout in 2014.

4. Imaging verification on flight tests

In May 2013, X-SAR performed the first flight tests included data calibration and double side-looking strip imaging verification. We assess the geometric performance of SAR by the observed spatial resolution of corner reflectors using data collected over the calibration site [3]. Fig. 4 shows the X-SAR image (left) obtained during the test flights over the Binhai test sites, near Tianjin. The eight triangular corner reflectors marked by the red rectangular blocks, were deployed for the purposes like target resolution, radiometric and geometric calibration, located in low backscatter areas. Two pairs of rectangular corner reflectors marked by the green rectangular blocks were deployed for the target discrimination in range and azimuth directions.
4.1. Spatial resolutions measurement and target pairs discrimination

Measured on eight triangular corner reflectors having the size of 0.3 meter corresponds to radar cross section (RCS) of 20.6dBm², the values of spatial resolutions in range and azimuth directions are listed in Table 2. The measured values of peak side lobe ratio (PLSR) and integral side lobe ratio (LSLR) are revealed the very low side lobe of the point target response function.

Table 2. Spatial resolutions measurement results.

| Parameters       | Value(Range x Azimuth) |
|------------------|------------------------|
| Spatial resolution (m) | 0.47x0.52 0.88x1.06 1.37x2.03 |
| PSLR (dB)        | -23.7x-22.7 -28.7x-26.2 -32.1x-27.5 |
| LSLR (dB)        | -23.1x-20.4 -24.8x-23.1 -23.8x-22.3 |

The discrimination for target pairs similar to optical line pairs test could be more directly evaluated of the SAR target resolution. Fig.5 describes the distinguished trend calculated curve for spacing of 1.0 meter in range and azimuth directions with target pairs, measured on the SAR image with 0.5 meter resolution in rectangular corner reflectors having the size of 0.3 meter.

4.2. NESZ measurement

NESZ remains the performance parameter to be analyzed and verified, since it does not depend on the scene dependent SNR [4]. The still waters in the red rectangular blocks of Fig. 6 depict the measured NESZ. No masking of waters was applied for a better accordance with the measured NESZ. The mean value of backscatter coefficient for still waters provides the NESZ shown in Table 3. The NESZ performance was to stay below −30 dB at the maximum swath exceeded the design criteria, which was optimized by the balance of the X-SAR radar parameters in Table 3.
Figure 5. Distinguished trend for target pairs of the rectangular corner reflectors.

Figure 6. Measured NESZ on the still water area in the red square.

Table 3. NESZ measurement results.

| Parameters          | Performances |
|---------------------|--------------|
| Bandwidth (MHz)     | 360 180 90   |
| Operating range (km)| 19~23 25~33 31~45 |
| NESZ (dB)           | -35.36 -40.89 -34.89 |

4.3. Radiometric resolution measurement

The radiometric resolution is the important image-quality characteristic for radiometric enhanced images and related to the SNR and the numbers of looks [4]. The multi-look processing can be reduced the speckle noise with SAR image, defined as the equivalent numbers of looks (ENL). The radiometric resolution (RR) is a parameter to measure the terrain distinguishing capability of SAR image, which can be estimated from the measured ENL, mean value $\mu$ and standard deviation $\sigma$ of image intensity, taking into account a distributed target using the following formula:

$$RR = 10\log_{10} \left( \frac{1}{\sqrt{ENL}} + 1 \right) = 10\log_{10} \left( \frac{\sigma}{\mu} + 1 \right)$$

As listed in Table 4, the radiometric resolution in the 360 MHz bandwidth is better for measurement increasing the numbers of looks, beyond a certain threshold will not result in significant improvement in measured radiometric resolution with 180 MHz and 90 MHz bandwidth.

Table 4. Radiometric resolution measurement results.

| Bandwidth (MHz) | Mean value $\mu$ | Standard deviation $\sigma$ | The numbers of looks | Radiometric resolution (dB) |
|-----------------|------------------|----------------------------|----------------------|-----------------------------|
| 360             | -35.2            | 9.48                       | 12                   | 1.08                        |
| 180             | -25.9            | 4.09                       | 40                   | 0.64                        |
| 90              | -33.5            | 5.16                       | 42                   | 0.62                        |

4.4. Radiometric enhanced products of intensity change detection

By the operational ground SAR imaging processor based on GPU architecture, the standard image data products in high resolution (up to 0.5 meter) can be already achieved less than 6 pixels in the image located precision and long-term radiometric stability better than 0.5dB. Therefore, the new radiometric enhanced products of intensity change detection can be operationally implemented. Fig. 7 shows the example imagery of vegetation cover change over Hebei, China, using two X-SAR images in 0.5 meter resolution acquired with a temporal separation of 5 days on 2013-05-21 and 2013-05-25. Approach to change detection is to be preferred by the straightforward comparison of image intensities.
The difference in the reflected radar signals evidently appeared (blue) or disappeared (purple) is particularly vegetation cover, where the most changes occurred in the time between data acquisitions.

Figure 7. X-SAR example imagery of intensity change detection with the multi-looks resolution of 0.5 meter over Hebei, China. The changes with many pieces of the fields have evidently appeared in blue or disappeared in purple with a temporal separation of 5 days on 2013-05-21 and 2013-05-25.

5. Conclusions
As discussed in this paper, the imaging verification and data calibration provide the advanced high resolution quantified images of modern airborne SAR like RADI’s X-SAR. The upgrading X-SAR with interferometer and polarization has been implemented and will be planned to flight test in 2016.

6. References
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Acknowledgments
Authors wishing to acknowledge the whole X-SAR Radar development team supporting the system design, integration and laboratory measurements, special worked on flight campaign and SAR processing for their effort in the development of X-SAR systems.