Hinotori-C: A Full Polarimetric C Band Airborne Circularly Polarized Synthetic Aperture Radar for Disaster Monitoring

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Abstract— This paper aims to present the design and development work of a full polarimetric Circularly Polarized Synthetic Aperture Radar (CP-SAR) system. The CP-SAR sensor is operating in C band with center frequency of 5.3 GHz, operational bandwidth ranged from 100 MHz to 400 MHz, and transmitting peak power of 280 watt. Four circularly polarized antennas (2 units with left handed circularly polarized and 2 units with right handed circularly polarized) were designed and developed with approximately 22 dBic of gain, and beamwidth of 13° and 6° in range and azimuth direction, respectively. This paper also presents the results from the laboratory test and ground test of the CP-SAR sensor, as well as, the flight test results obtained from the maiden flight of the CP-SAR system using CASA/IPTN CN235-MPA aircraft.

1. INTRODUCTION

Synthetic Aperture Radar (SAR) is a powerful tool in microwave remote sensing due to its capability of all-weather and day-to-night time operation [1, 2]. Over the years, SAR has been widely used in various kind of applications particularly in Earth observation such as disaster monitoring, land deformation observation, oceanography, pollution monitoring, and so on [3]. SAR system uses microwave signal and are robust in the face of unfavorable weather conditions and its cloud cover, haze, and dust and even rain penetration capabilities [4]. There are many airborne and spaceborne SAR sensors that are currently in operation [5]. However, these sensors are operating with Linear Polarization (LP) (HH, VV, HV, and VH) electromagnetic (EM) waves and LP EM waves is sensitive to Faraday rotation effect (higher polarization loss compared to circular polarized) in ionosphere [6].

Currently, Josaphat Microwave Remote Sensing Laboratory (JMRSL) from Center for Environmental Remote Sensing (CEReS), Chiba University is developing airborne and spaceborne Circularly Polarized Synthetic Aperture Radar (CP-SAR) sensors with the aim to retrieve the physical information of Earth surface, especially to monitor the cryosphere, global vegetation and disaster area [7, 8]. This paper presents the design and development work of a C band full polarimetric CP-SAR system named as *Hinotori-C*. Section 2 presents the technical specifications of the SAR system and Section 3 shows the laboratory and ground test performed. Meanwhile, the maiden flight of the CP-SAR sensor (Hinotori-C2) was in March 2018 at Makassar, Indonesia, and the outcomes are discussed in Section 4. The paper is concluded in Section 5.

2. HINOTORI-C CP-SAR SYSTEM

The Hinotori-C CP-SAR is a pulse compression SAR system. The detailed specifications of the system are tabulated in Table 1. At glance, the system operates in C band, with carrier frequency of 5.3 GHz (C band), adjustable bandwidth ranged from 100 MHz to 400MHz, adjustable pulse width ranged from 0.5 µs to 100 µs, adjustable Pulse Repetition Frequency (PRF) ranged from 100 Hz to 10 kHz, and peak transmit power of 280 watt.

Hinotori-C CP-SAR system is composed of 4 major sub-systems, namely the Radio Frequency (RF) sub-system, the Baseband and Control Unit (BCU), the Power Distribution Unit (PDU), and the Inertial Navigation Unit (INU). Figure 1 depicts the top level architecture of Hinotori-C CP-SAR system. The hardware system is developed in 12 months time, starting with the system level

Table 1. Specifications of hinotori-C CP-SAR system.

Parameter	**Value**
Mode of Operation	Stripmap
Carrier Frequency	5.3 GHz (C Band)
Modulation Format	Pulsed-LFM
Slant Range Resolution	1.5 m–0.375 m
Bandwidth	100 MHz–400 MHz
Pulse Width	0.1 µs–100 µs
Pulse Repetition Frequency	100 Hz–10 kHz
Peak Transmit Power	280 W
Receiver Gain	50 dB
Receiver NF	2.5 dB
Antenna Polarization	Full Circular (LL, RR, LR, RL)
Antenna Isotropic Gain	22 dBic
Antenna Beamwidth	13° (Range) 6° (Azimuth)
Antenna Length	0.5 m
Incident Angle	25°–60°
Platform Height	500 m–4000 m
Observation Time	65.536 s

design which outlines the technical specifications of each sub-system, followed by development of each sub-system, and performance test and fine tuning of each sub-system. The tested sub-systems are integrated into a complete CP-SAR system and the performance of the complete system is examined through laboratory tests, ground tests, and flight test. Figure 2(a) shows the snapshot of the circular polarized antennas (2 RHCP and 2 LHCP) and Figure 2(b) shows the major electronics hardware of the CP-SAR system.

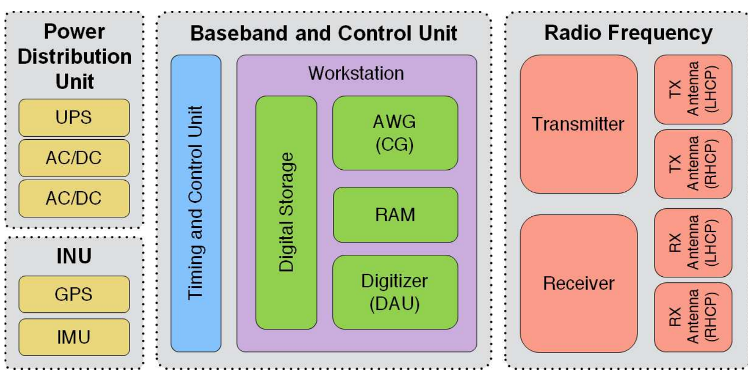


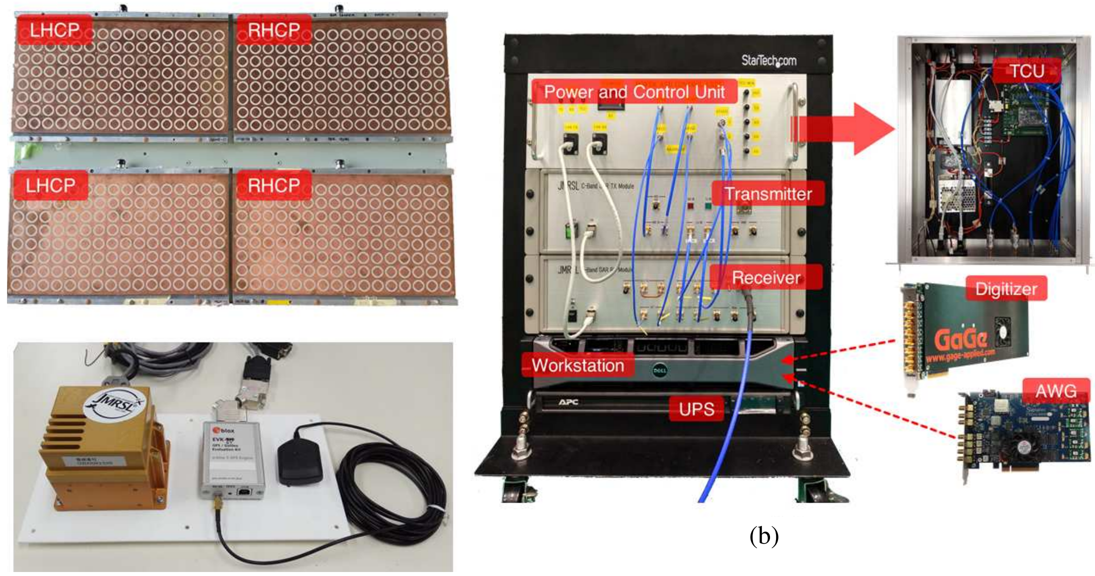
Figure 1. Top level architecture of hinotori-C CP-SAR.

The radio frequency sub-system is composed of a transmitter, a receiver, and four circular polarized antenna with two in left handed circular polarization (LHCP) and two in right handed circular polarization (RHCP). The transceiver adopts two-stage superheterodyne architecture with its Intermediate Frequency (IF) is chosen at 2850 MHz. The measured peak output power of the transmitter is 280 W with total gain of 58 dB in the transmitter chain. Meanwhile, the receiver has total gain of 50 dB with noise figure of 2.5 dB.

The Baseband and Control Unit (BCU) handles several important tasks in the CP-SAR system. It is built from a workstation that consist of, i) an Arbitrary Waveform Generator (AWG), ii) a high-speed digitizer, and iii) two units of high-speed Solid-State Drive (SSD), and, a Timing and Control Unit (TCU). All of the components except the TCU are commercial off-the-shelf hardware

(a)

(c)



(b)

Figure 2. Hinotori-C CP-SAR system: (a) Circular polarized antennas. (b) SAR electronics hardware.

product, whereby the TCU is a custom-designed digital system using Field Programmable Gate Array (FPGA) as its programmable logic core. As a brief functional summary of the BCU, it can, i) generates 2-channel (I & Q) of 1.2 GHz (maximum) bandwidth chirp signal with its pulse width ranged from 0.5 µs to 100 µs, ii) able to digitize 2-channel (I & Q) of 1 GHz (maximum) bandwidth chirp echoes with on-board 4 G-Samples of recording buffer, iii) generate accurate and precise timing and control signals with timing resolution of 10 ns, and iv) synchronize and control the operation of all sub-modules and maintain the clock coherency among the sub-modules.

The CP-SAR antennas are designed and fabricated in-house using NPC NH220A substrate [9]. The fabricated antennas have isotropic gain of 22 dBic, with beamwidth of 13° and 6° in range and azimuth direction, and boresight of 0°. The total dimension of a fabricated antenna is 42.4 mm in width, 65.6 mm in length, and 3.3 mm in thickness, with weight of 2.28 kg. Figure 2(a) shows the snapshot of four panels of the fabricated antenna installed on a mounting structure, ready to mount to the aircraft for flight test.

Inertial Navigation Unit (INU) is important in recording the flight attitude of the aircraft during the actual mission. These flight information is essential for SAR image formation post processing to focus the recorded SAR raw data into an useful SAR image for further applications. The INU is composed of a Global Positioning System (GPS) (ublox EVK-5T) and an Inertial Measurement Unit (IMU) (Memsic AHRS440CA-200). The EVK-5T is a cost effective, high-performance u-blox 5 based LEA-5 series of GPS modules with compact 17.0×22.4 mm form factor featuring precision timing and an innovative jamming resistant RF architecture. Meanwhile, the AHRS440CA-200 is a compact standalone attitude and heading reference system that provides roll, pitch and yaw measurement data in both static and dynamic environments.

Power Distribution Unit (PDU) is built from several Uninterruptible Power Supply (UPS) and several AC to DC converters. PDU incorporates several high capacity UPS into a large pool of power source and it is designed to supply a clean and stable AC current source to power up the CP-SAR system for more than 3 hours of continuous operation. The AC to DC converters convert the AC source from the UPS into a few DC sources ($+28V_{dc}$, $+12V_{dc}$, and $+5V_{dc}$) to power up the transmitter, the receiver, the TCU, and the INU.

The controller and processor software is a centralized Graphical User Interface (GUI) software that controls the sub-systems (AWG, digitizer, TCU, transmitter, receiver, and INU) and acquires raw data during laboratory testing, ground test and flight test. The software is written in C# and uses the NET framework from Microsoft®. Figure 3(a) shows the screenshot of the control software, showing, i) the main panel of the software, ii) the waveform generation panel for configuring the chirp parameters and controlling the chirp generation, iii) the TCU panel for configuring the timing information, iv) the data acquisition panel for acquiring large records of echoes, and v) the INU panel for recording the flight attitude information.

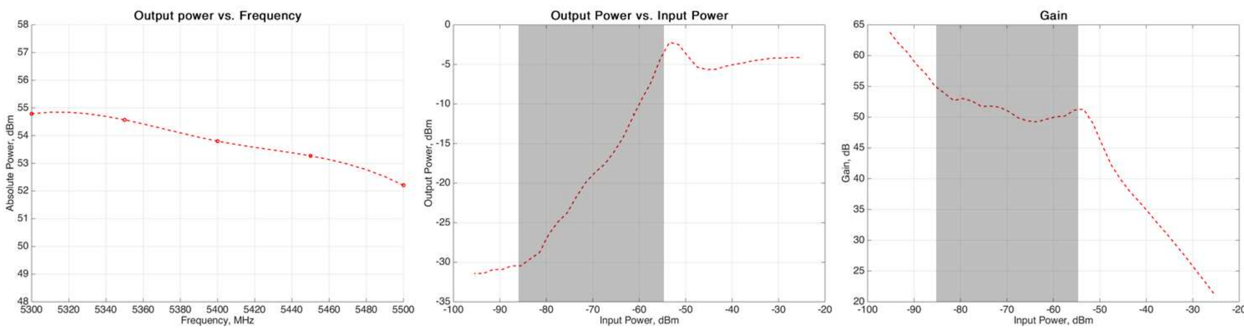
SAR processor is a user friendly image formation software written in Matlab®. The software bundles several function specific signal processing script into a complete solution for focusing Hinotori-C CP-SAR raw data. Figure 3(b) shows the screenshot of some processing modules, showing, i) the main UI that initiates the processing module, ii) the data extration module that loads Hinotori-C2 raw data into the processing environment, iii) the range compression module that compresses the raw data in range direction, iv) the RCMC module that corrects the range cell migration in SAR data, and v) the azimuth compression module that focuses the SAR data in azimuth direction. During the SAR processor development stage, the functionality of each module is tested using a set of simulated point target SAR data.

Figure 3. Hinotori-C CP-SAR Software GUI: (a) Control. (b) Image formation.

3. LABORATORY TEST AND GROUND TEST

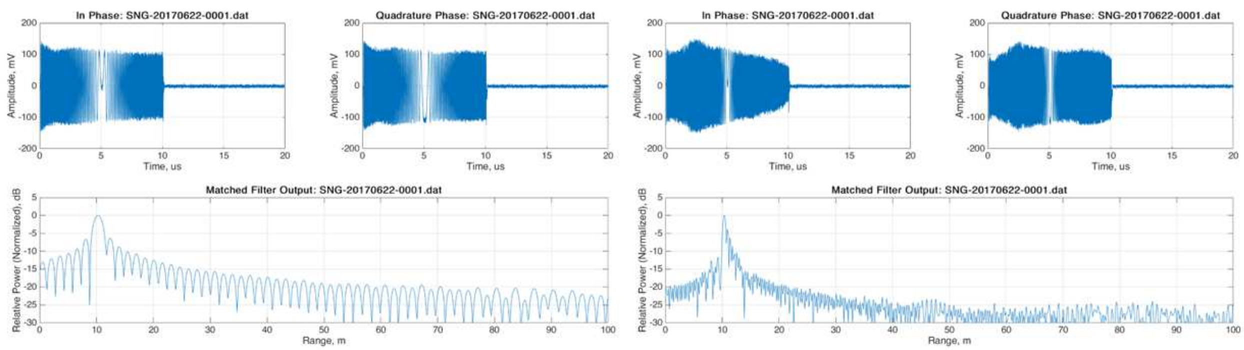
The integrated SAR electronics hardware was tested in laboratory and on the ground to characterize the performance of the CP-SAR system before it can be used for the actual flight mission. From the laboratory tests, the measured peak output power at the output port of the transmitter is approximately 280 watt, as shown in Figure 4(a). Meanwhile, the dynamic range of the receiver falls in the range of −55 dBm to −85 dBm, with approximately 50 dB of gain within the range. In the performed loop-back test, the output of the transmitter was looped to the input of the receiver, with total attenuation of 110 dB in the transmit-receive chain. As shown in Figure 5(b) the recorded loop-back echo can be compressed well, indicating the pulse compression capability of the system.

Further to the laboratory test, a ground test was conducted with the purpose to test the functionality of the entire SAR system, particularly in compressing the echoes in azimuth direction.



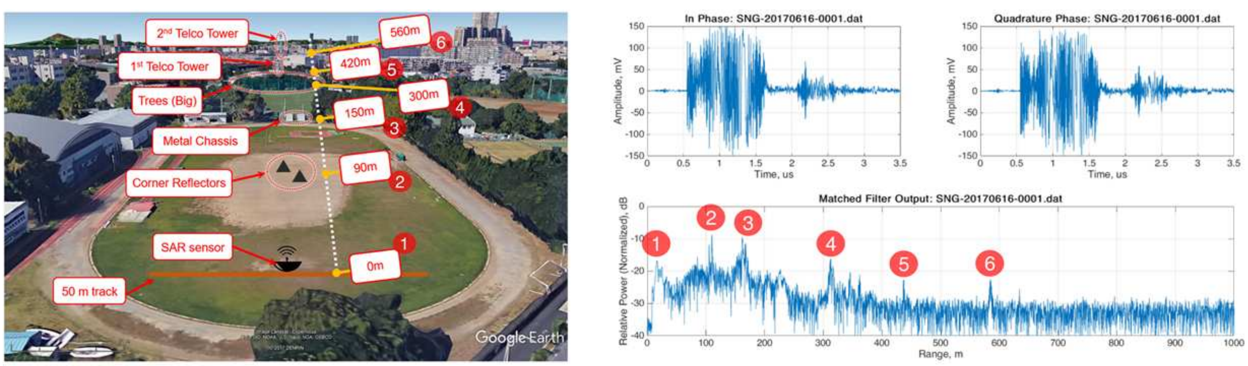
(a) (b) (c)

Figure 4. Hinotori-C laboratory test: (a) Transmitter output power. (b) Receiver dynamic range. (c) Receiver gain.



(a) (b)

Figure 5. Hinotori-C loop-back test: (a) 400 MHz chirp bandwidth, 10 µs chirp pulse width, (b) 100 MHz chirp bandwidth, 10 µs chirp pulse width.



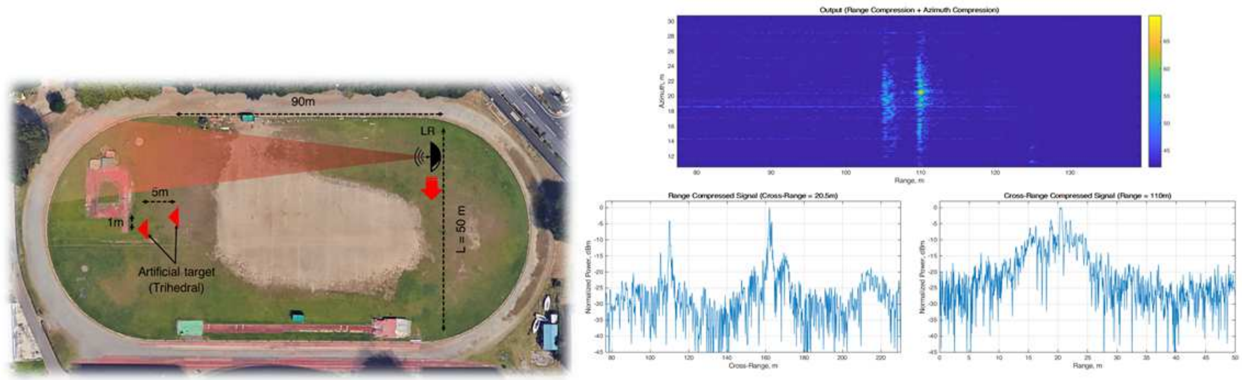
(a) (b)

Figure 6. Range test: (a) Test setup. (b) Results.

Two tests were performed in the test, which were the range test, and the ground based imaging test. In the range test, as illustrated in Figure 6(a), the CP-SAR system was placed at the edge on an empty field and both the transmitting and receiving antenna were pointing to the other edge of the field. Two trihedral corner reflectors were setup at the middle of the field (90 meters away from the antennas), with their pointing direction were heading to the CP-SAR system. Then, the echoes were recorded and the the recorded data was further processed. Figure 6(b) shows the range compressed plot from the test. The plot shows that the CP-SAR system can precisely detects the trihedral corner reflectors (Point 2), also some permanent scatterers that are located behind the reflectors, such as the metal enclosure (Point 3), large trees (Point 4), and telecommunication towers (Point 5 and Point 6) that are located approximately 400 meters and 560 meters away from the CP-SAR system.

After the range test, ground based imaging test was conducted to test the imaging capability of the SAR system. Figure 7(a) shows the test setup on the same field. In the imaging test, a

50 meters rail was assembled on the field and the SAR system was placed at the left end of the rail. The antennas were elevated to 2 meters height above the ground and were pointing toward the scene. Then, using a 1-axis robot, the system moved 50 cm toward the right end of the rail, stopped, scanned, and the echoes were recorded. The measurement was repeated for 1001 times (Stop-N-Go, 1001 azimuth points, 50 m total azimuth length) so that the scan covers more than one synthetic length for targets that are located at the middle of the field. The collected 2-dimensional data was processed and the acquired SAR image is shown in Figure 7(b).

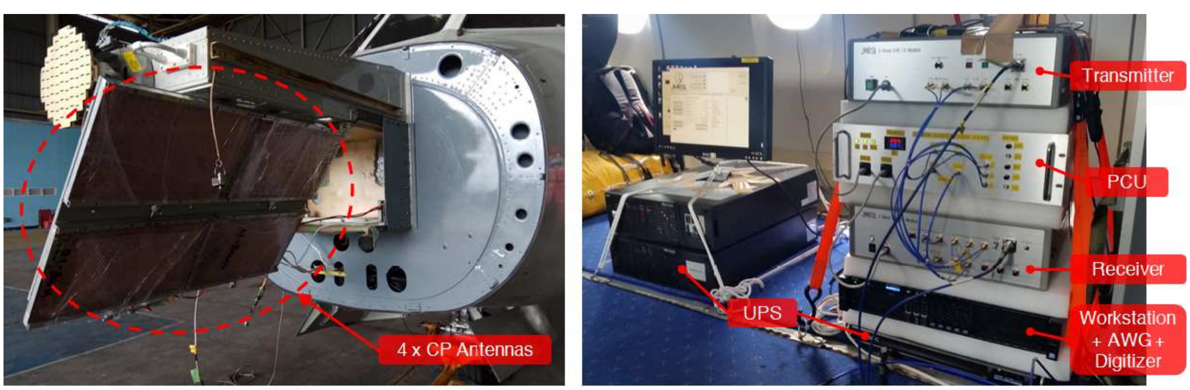


(a) (b)

Figure 7. Ground based imaging test: (a) Test setup. (b) Results.

4. FIRST CP-SAR FUNCTIONAL FLIGHT TEST

The performance of the CP-SAR system was further tested in JMRSL Hinotori-C2 flight mission. The mission was held from 3 March to 16 March 2018, in Makassar, Indonesia using CASA/IPTN CN235-MPA aircraft as the carrier. The main objective of the flight test was to verify the functionality of the Hinotori-C CP-SAR system and to acquire full polarimetric circularly polarized SAR images that cover different types of natural and artificial targets such as calibration reflectors, man-made buildings, water body, homogeneous rainforest area. Figure 8 shows the installation of Hinotori-C CP-SAR system to the aircraft. Four CP antennas (2 units of LHCP and 2 units of RHCP) were installed in nose cone of the aircraft (with final incident angle of 56°) while the CP-SAR electronics hardware were firmly seated in the cabin area.



(a) (b)

Figure 8. Installation of Hinotori-C CP-SAR System: (a) Antennas in the nose cone of the aircraft, (b) CP-SAR electronics hardware system in the cabin.

Before the takeoff, point target calibration was carried out and Figure 9 shows the plots obtained from the test. From the plot, the CP-SAR system can accurately detects the trihedral corner reflectors that were placed at 650 m away from the CP-SAR system. Other than that, the CP-SAR system can also spots the buildings in the housing estate that are located at more than 2.2 km away from the system.

In the flight mission, three rounds of flight test were successfully completed. The flight were carried out with different flight altitude ranged from 1000 m to 1500 m above the sea level. Figure 10 shows the world's first acquired full polarimetric CP-SAR images imaged using Hinotori-C CP-SAR system. The acquired high quality SAR images has proven that Hinotori-C CP-SAR system is working well.

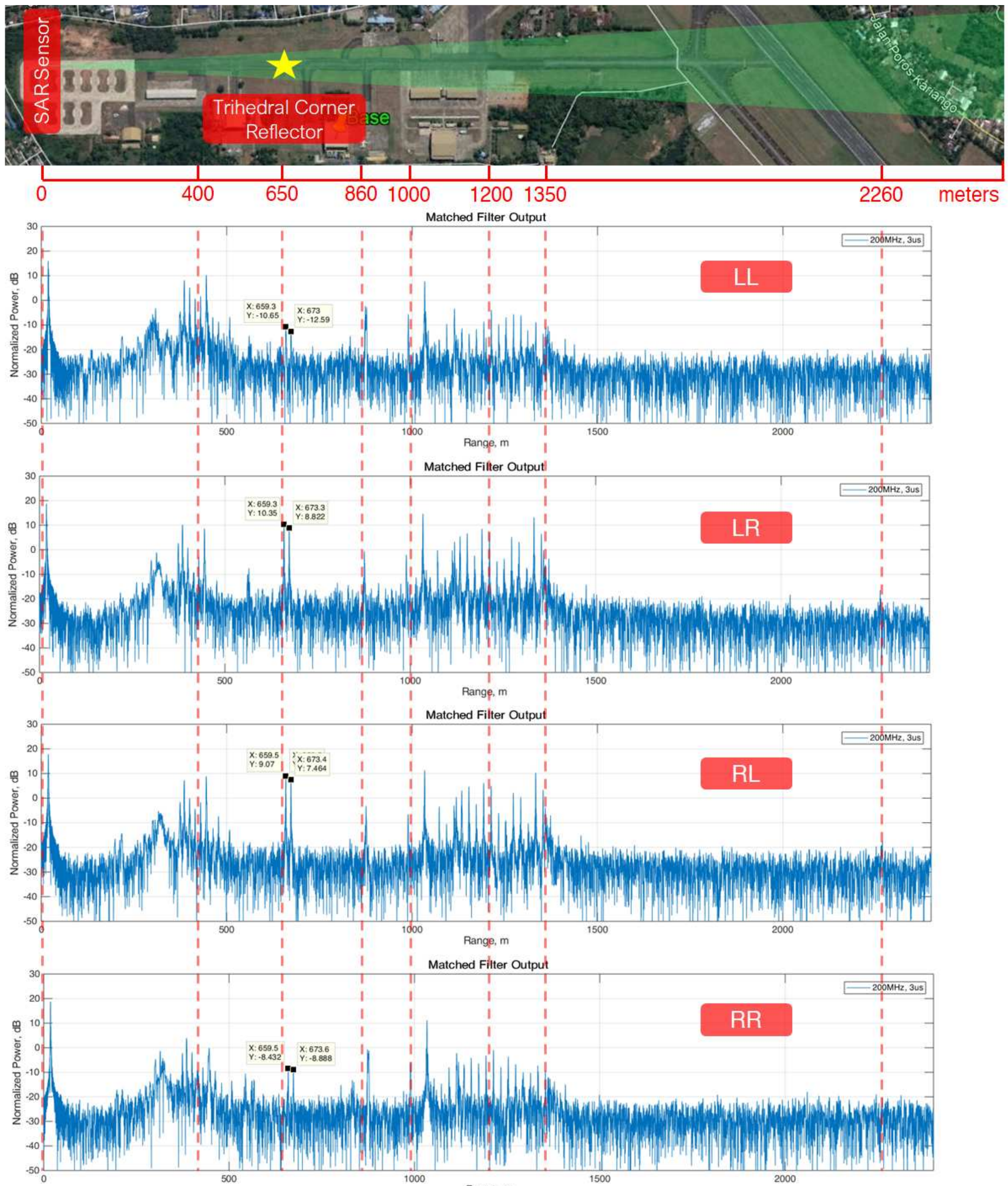


Figure 9. Full polarimetric point target calibration using 2 trihedral corner reflectors (650 m away from the CP-SAR system).

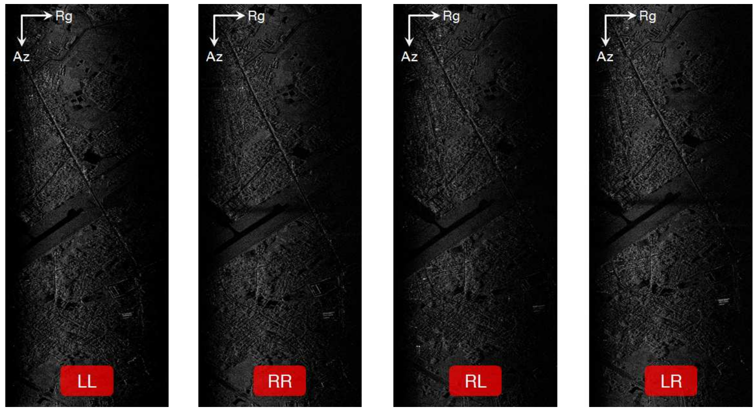


Figure 10. World first full polarimetric circularly polarized SAR images from Hinotori-C (First letter: Received polarization, Second letter: Transmit polarization).

5. CONCLUSION

A full polarimetric circularly polarized airborne SAR (CP-SAR) system has been designed and developed. The CP-SAR system operates in C band and has finest resolution of 37.5 cm. The performance of the system is validated through a series of laboratory tests, ground tests, and flight tests. The test results show that the CP-SAR system is able to produce high resolution and high quality circularly polarized SAR images. In future, more studies will be conducted using the CP-SAR images for advanced remote sensing applications.

ACKNOWLEDGMENT

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