R&D OF DRONE-BORNE SAR SYSTEM

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ABSTRACT:

DInSAR (Differential Interferometric Synthetic Aperture Radar) is already well-known as an effective application technique of SAR data for the displacement measuring of the ground surface. The authors are developing a drone-borne SAR that can apply DInSAR analysis. In Japan, which has suffered various disasters, the slope stability monitoring for active volcanoes, landslide slopes, open-pit mines, etc., and the maintenance management for aging infrastructures are considered important issues. Therefore, by effectively utilizing the position information and terrain information obtained from the satellite data, we have started an R&D project aiming at practical application of DInSAR technology with drone-borne SAR.

1. PROJECT OUTLINE

The authors are developing a drone-borne SAR system by effectively utilizing the position information and terrain information obtained from the satellite data (Figure 1). The purpose of development is monitoring of slopes and infrastructure. The project has been planned for three years and started in 2018. The implementation items in this project consist of the following five stages;

(1) Development and weight saving of Ku band radar
(2) Position information extraction and accuracy verification of drone using high accuracy GNSS module
(3) Development of synthetic aperture processing technology for drone-borne radar
(4) Development of DInSAR technology using high spatial resolution satellite image
(5) Demonstration test for DInSAR measurement by drone-borne SAR

Currently, stages (3) and (4) are in progress. Our project has been achieved by “Coordination Funds for Promoting AeroSpace Utilization”, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), JAPAN.

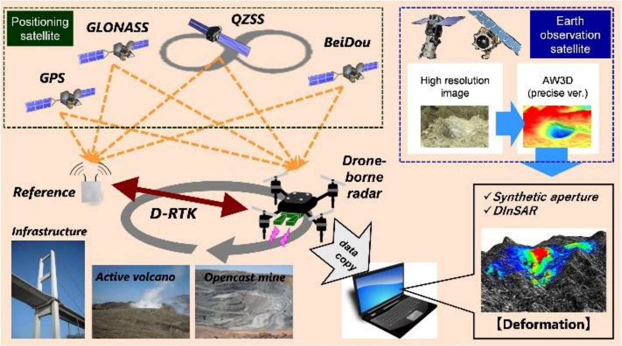

Figure 1. Outline of the R&D of drone-borne SAR system

2. DEVELOPMENT OF FM-CW RADAR MOUNTED ON DRONE

2.1 Hardware development

As the ranging technology by radar, it was decided to adopt the Frequency Modulated Continuous Wave (FM-CW) method which was applied to the collision prevention radar of the car. The FM-CW radar utilizes a frequency difference between a transmission wave linearly modulated with respect to time and a reception wave reflected and returned from a target. From the similarity relationship between the frequency difference and the modulation wave (Figure 2), it is possible to measure the time required for the radio wave to reciprocate the distance between the radar and the object, and the distance measurement should be realized.

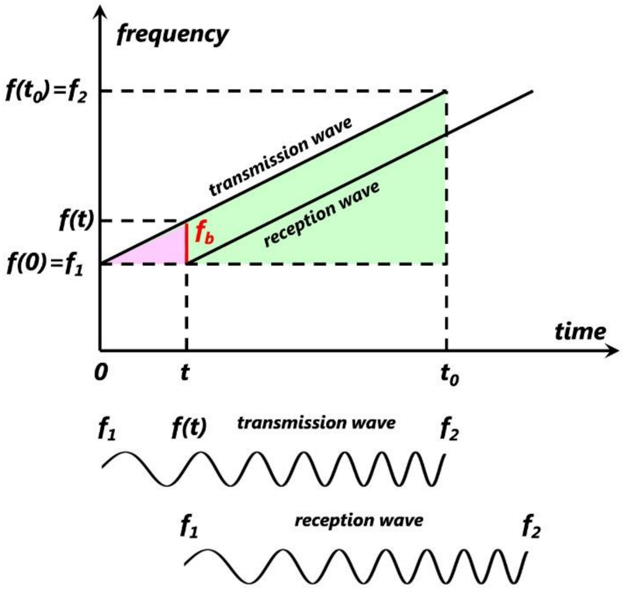

Figure 2. Conceptual diagram of FM-CW radar

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$$R = \frac{c \times t_0 \times f_b}{2 \times \Delta f} \quad (1)$$

where R = Measurement distance by FM-CW
c = velocity of light (= 299,792,458 m/s)
Δf = bandwidth (= f_2-f_1)
t_0 = modulation period
f_b = frequency difference

The frequency of the transmission wave was selected from 12.8 to 12.95 GHz (Ku band), which was easy to obtain a license under the Japanese Radio Law. For this frequency band, an output power of 1 W (EIRP) can be allowed.

The radar device developed in this project is premised to be mounted on a drone. It is necessary to miniaturize the main body of the radar device to a size that can be connected to the drone body. In order to realize long flight of drone, weight reduction is also important. Moreover, in addition to the main body of the radar, the reduction in size and weight of the battery for operating the radar is also inevitable, so power saving of the radar is also an important issue.

The drone used in this study is Matrice 600 pro (hereafter referred as to M600pro) manufactured by DJI. The M600pro is estimated to be capable of about 18 minutes of flight with a payload of 5.5 kg. The size of the developed drone loading radar is 255 × 184 mm (smaller than A4 paper, Figure 3), and the weight is 645 g (including battery), and the power consumption is about 5.76 W.

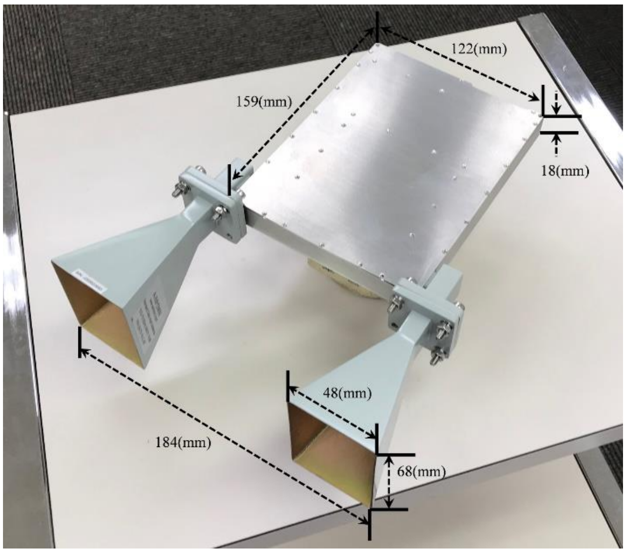


Figure 3. Appearance of drone-borne radar

A commercially available AA battery was used for radar operation, and it was verified that about one hour of operation was possible with four AA batteries.

When connected to a drone, the influence of the electromagnetic noise generated by the drone motor may be concerned. Therefore, the frame case was manufactured by processing an aluminium plate, and electronic circuits were isolated from electromagnetic noise. As a result of actually connecting to the drone and confirming the radar signal using an oscilloscope, the influence of the electromagnetic noise could not be recognized on the monitor of the oscilloscope.

2.2 Performance evaluation test

First, a test was conducted to evaluate the performance of the radar remote detection distance. Figure 4 and Figure 5 show the result of the test conducted around the slope stabilization construction site and the active volcano. Because the radar was fixed to the camera tripod and implemented the demonstration test, the data would be a real aperture recording. In these tests, the possibility of detecting the slope of a construction site about 600 m away and the mountain surface of a volcano about 3 km away was verified.

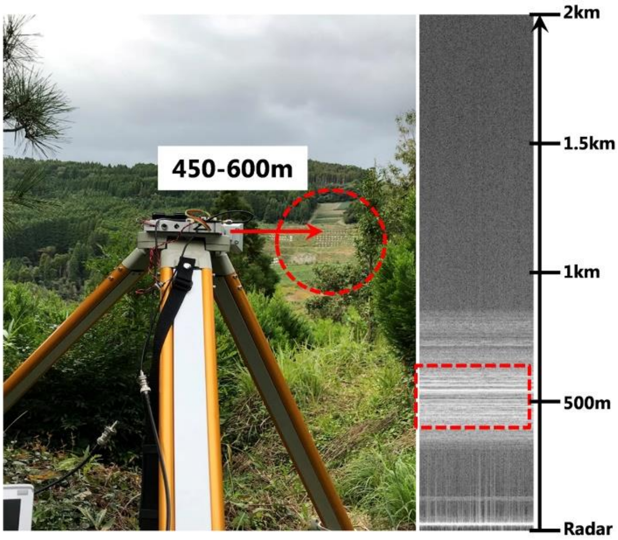


Figure 4. Remote detection distance test conducted around the construction site and its results

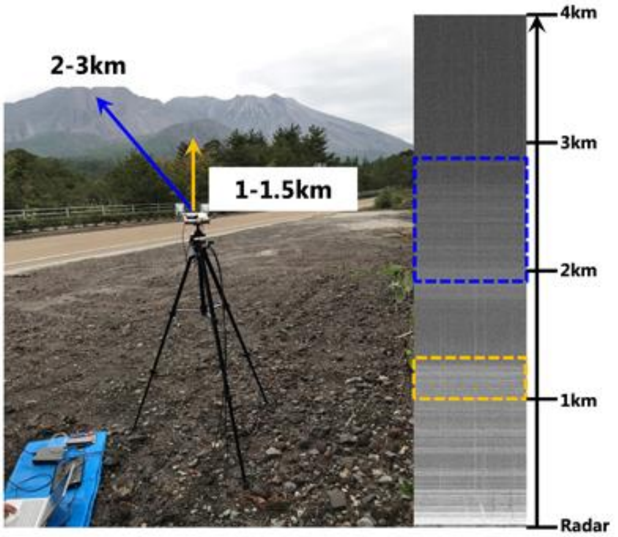


Figure 5. Remote detection distance test conducted around the active volcano and its results

Next, an experiment using a corner reflector was performed to verify displacement measurement accuracy. The corner reflector installed on the stage was slid by 0.1 mm and the movement was measured by radar device. The verification test result of displacement measurement accuracy is shown in Figure 6. The black solid line means the amount of movement of the corner reflector, and the coloured graph (red, orange, blue, and green) is a record of the displacement measured by the radar. A total of 4 measurements were performed in summer and autumn, each measurement accuracy was verified to be 0.7 mm or less. Since remote sensing technique detects fluctuation of vegetation growing on the ground surface, a corner reflector was placed in the grass and the same test was performed in order to consider the effect of vegetation on displacement measurement.

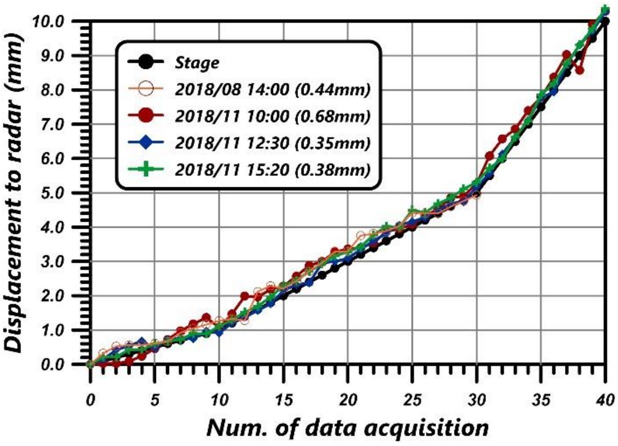


Figure 6. The verification test result of displacement measurement accuracy

The results of three tests in total are shown in Figure 7. Also for this result, the radar could track the movement of the corner reflector with an accuracy of 0.6 mm or less. Based on the above tests, it was shown that the developed radar has the ability to realize highly accurate displacement measurement by remote sensing.

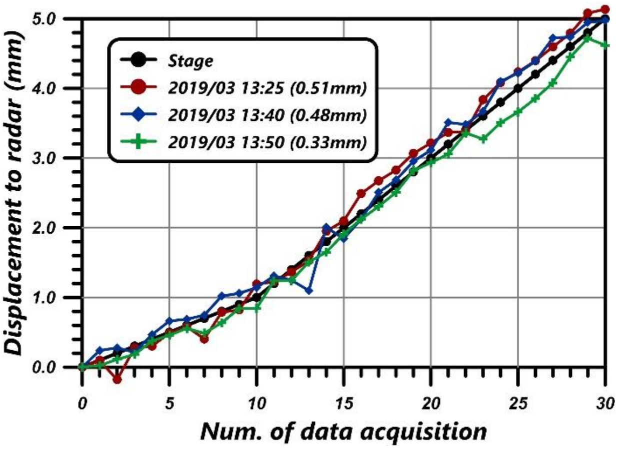


Figure 7. The verification test result of displacement measurement accuracy when the corner reflector was installed in the grass field

3. FLIGHT CONTROL ACCURACY VERIFICATION TEST OF DRONE

In DInSAR technique, the surface displacement is measured by calculating the phase difference between data acquired in two period. The drone has to regress the track with high repeatability in each observation. Therefore, in order to realize highly practical displacement measurement by DInSAR, it is required to control the position of the drone with high accuracy. The critical baseline length can be mentioned as an index for objectively evaluating the allowable deviation of the track. It is generally known that as the track-to-track distance in each measurement deviates, the correlation of the phase information deteriorates and the measurement accuracy decreases. The maximum track-to-track distance at which the correlation of the phase information becomes zero is called "critical baseline" and is described by the following equation (Gatelli et al., 1994).

$$B_c = \frac{\lambda \times \rho \times tan\theta}{2 \times R_{res}} \qquad (1)$$

where Bc = critical baseline
λ = wavelength
ρ = range distance
θ = incidence angle
f_b = frequency difference

Assuming that an object 500 m apart is observed at an incident angle of 45 degrees, the critical baseline is calculated to be about 5.8 m. The critical baseline means the limit value at which arithmetic measurement by DInSAR cannot be performed. It is empirically known that the baseline length representing the limit of practical measurement is about 1/7 to 1/10 of the critical baseline. Consequently, the ability to control the position of the drone with an accuracy of 1 m or less is required. In order to achieve this goal, drone position information must be acquired with an accuracy of 1 m or less, which is a difficult level with ordinary independent positioning by GNSS.

The authors decided to apply RTK technology that enables high precision positioning of a centimeter class. In RTK positioning, when the distance to a reference point whose coordinates are accurately surveyed is D, the positioning accuracy is described by "1cm+2ppm*D". If the reference point is set near the drone, the theoretical positioning accuracy is 1 cm. D-RTK is available as an optional product for M600pro. Autopilot was implemented combining M600pro and D-RTK, and a total of 10 flight logs were acquired to verify the repeatability of the drone track. The average deviation distance was calculated to be about 7.3 cm for the linear track assigned to the autopilot route. Although this result does not reach theoretical RTK positioning accuracy, it can be evaluated that it has sufficient accuracy to perform practical DInSAR measurement.

4. EXPERIMENTAL DATA ACQUISITION

4.1 Flight and data acquisition

The developed Ku band radar and D-RTK were mounted on M600pro (Figure 8), and data acquisition was carried out targeting a corner reflector (15 cm on a side) approximately 100 m apart (Figure 9).

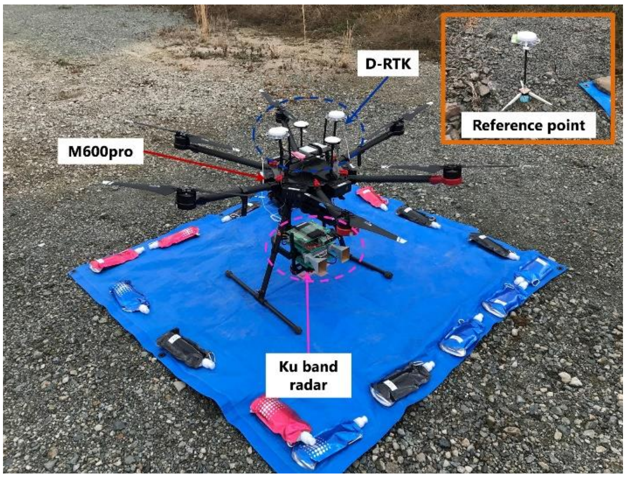


Figure 8. The developed drone-borne SAR system

The test site was in the open-cast limestone mine in operation in Japan. A signal received by the radar is stored in a small personal computer via an AD converter. The AD converter used in this study is TUSB-0212ADM2Z manufactured by Turtle Industrial Co., Ltd. with 12-bit resolution. LattePanda Windows 10 Mini PC was used as a small personal computer. The flight distance was about 106 m, the flight speed was 1 m/s, the sampling rate for AD conversion was 2 MHz, and the sampling rate of data acquisition was 10 Hz.

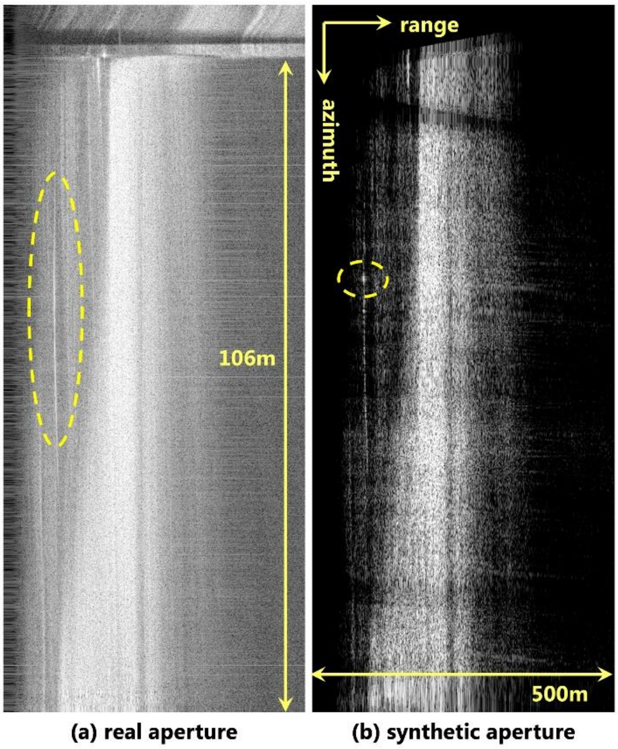
Figure 9. Data acquisition test targeting a corner reflector

4.2 Synthetic aperture processing

Radio wave emitted by the radar propagates toward the target object with a spread determined by the beam width of the antenna. Therefore, in order to make a radar image, it is necessary to perform a compression process to improve the image resolution in the range and azimuth direction (Cuelander et al., 1991 and Soumekh, 1999). The developed radar does not need to apply range compression processing because the distance measuring is performed using the FM-CW method. Signal processing required for imaging is azimuth compression, so-called synthetic aperture processing. In the case of a real aperture radar, the beam width of the antenna corresponds to the azimuth resolution. The synthetic aperture radar realizes a high resolution in the azimuth direction by creating a reference signal for a point target and calculating the cross-correlation between the received signal and the reference signal.

Calculation of cross-correlation in the time domain requires a huge amount of computation time. In the case of the space-borne radar, since the orbit can be linearly approximated and the reference signal becomes invariant with respect to the time axis, the fast Fourier transform (FFT) can be applied to reduce the processing time. However, in the case of drone-borne radar, the track fluctuates due to the influence of the wind, and the flight speed also changes irregularly. In addition, since the attitude of the drone also becomes unstable, the signal processing applied to the data of the satellite-borne radar cannot be applied. Here, the method of recalculating the reference signal for every pixel in the azimuth direction using the position and attitude information of the drone was adopted. In this case, application of FFT is impossible, and signal processing is performed in the time domain at the sacrifice of computation time.

Figure 10 shows the result of applying synthetic aperture processing to actual data acquired targeting a corner reflector. In the case of a real aperture radar, the reflected signal from the corner reflector spreads to about 35 m in the azimuth direction. On the other hand, the azimuth resolution of the reflected signal was improved to about 1.5 m by applying the synthetic aperture processing. This result means that the azimuth resolution has been improved by about 23 times.



(a) real aperture (b) synthetic aperture

Figure 10. An example of focusing by synthetic aperture processing

However, the 3dB beam width of the horn antenna attached to the radar device is approximately ±9 degrees (Figure 11), and the resolution improvement effect by synthetic aperture processing should be about 350 times theoretically. The reason why the improvement effect rate was lower than the theoretical value is that the acquisition speed may be slow considering the flight speed. In such a case, aliasing will occur at both ends of the beam width. In this test, the beam width which could be used for the actual signal processing without aliasing remained at ±1.5 degrees. Accordingly, 80% or more of the synthetic aperture time corresponding to the 3dB beam width may have been wasted.

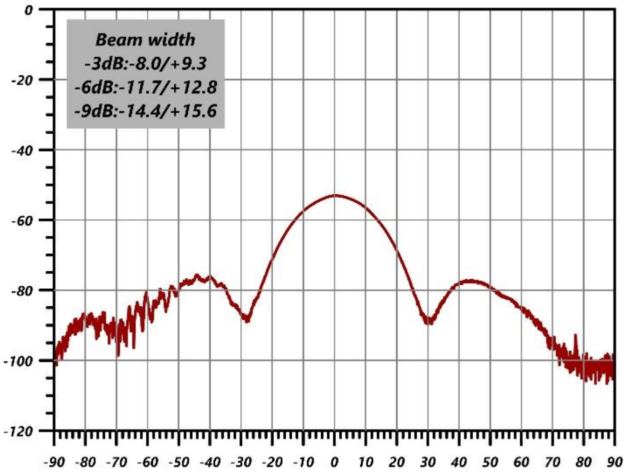


Figure 11. Antenna pattern of the developed Ku band radar

In order to make full use of synthetic aperture time, speeding up of data acquisition rate is desired. The numerical target for speeding up is estimated to be 60 to 65 Hz. System improvement will be one of the most important issue for the future. In addition, we plan to acquire actual measurement data targeting slopes in mines, etc., and work on the application of DInSAR processing.

5. SUMMARY AND FUTURE WORKS

After the tests up to now, the performance of the developed radar and the characteristics of M600pro and D-RTK are clarified, and it can be evaluated that the actual measurement stage has been reached. However, the effect of high resolution by synthetic aperture radar has not been fully utilized. The task is to upgrade the system to improve the speed of data acquisition and maximize the benefits of synthetic aperture processing. Moreover, we will develop to DInSAR processing technology using AW3D high-resolution version of terrain data which stores elevation value in a pixel of 1 m, and displacement measurement accuracy verification with synthetic aperture system.

In the final FY2020, the authors plan to conduct demonstration and verification tests at the limestone mine, the active volcano, and the construction site to prevent the slope collapse. Through this stage, the monitoring business related to ground deformation measurement using drone-borne SAR led by the private sector is expected to create.

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REFERENCES

Cuelander, J. C. and Mcdonough, R. N., 1991. Synthetic aperture radar systems and signal processing. John wiley & sons, inc., ISBN 0-471-85770-X.

Gatelli, F., Guarnieri, A. M., Parizzi, F., Pasquali, P., Prati,C., and Rocca,F., 1994. The wavenumber shift in SAR interferometry. IEEE Transactions on Geoscience and Remote Sensing, vol.32, pp.855-865.

Soumekh, M., 1999. Synthetic aperture radar signal processing with MATLAB algorithms. John wiley & sons, inc., ISBN 0-471-29706-2.