Performance Evaluation of a Modified SweepSAR Mode for Quad-Pol Application in SAR Systems

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Abstract

Efficient earth observation using spaceborne synthetic aperture radar (SAR) requires the analysis of high-resolution wide-swath (HRWS) systems, which have a fine resolution and a short revisit time through wide-area observation, and quadrature-polarimetric (quad-pol) systems, which can obtain a quad-pol image and have many applications. The operational method of SAR generally affects system performance involving the system parameters and antenna patterns, and thus analyzing HRWS quad-pol SAR systems is essential to the system design. In this paper, an extension of the modified SweepSAR technique to a quad-pol observation scenario is performed and a comparison to ScanSAR and conventional SweepSAR is provided for a simulated scenario. On the basis of the system requirements, we selected the optimal parameters and designed a reflector antenna suitable for a wide-swath quad-pol SAR system. As a result of comparing the wide-swath quad-pol SAR operation modes, the modified SweepSAR mode demonstrated advantages in terms of system performance, such as the ambiguity ratio and swath width, and reflector antenna design for a spaceborne SAR system.

Key Words: High-Resolution Wide-Swath (HRWS), Quadrature-Polarimetric (Quad-Pol), Reflector Antenna, Synthetic Aperture Radar (SAR).

I. INTRODUCTION

A spaceborne synthetic aperture radar (SAR) is a sensor that is mounted on a satellite and utilizes radio waves to enable high-resolution and all-weather Earth observation. However, conventional spaceborne SAR has some limitations in use because it has a trade-off relationship within the main system parameters. In addition, it obtains information from the Earth's surface by transmitting and receiving only a single polarization.

In Earth observation using spaceborne SAR, an efficient observation requires a short revisit time by observing wide areas [1].

For this purpose, wide-swath SAR operation modes, such as ScanSAR and TOPSAR (terrain observation with progressive scans SAR), were introduced and studied [2, 3]. However, these two modes observe the sub-swaths sequentially and this operational method worsens the resolution in the azimuthal direction of the SAR system. Therefore, obtaining a wide-swath and fine resolution at the same time is difficult for a conventional wide-swath SAR system. To overcome this constraint, many operation modes are currently being studied as high-resolution wide-swath (HRWS) systems. Among these systems, we are interested in HRWS systems using a reflector antenna [4–6]. Generally,

Manuscript received March 13, 2020 ; Revised May 25, 2020 ; Accepted June 8, 2020. (ID No. 20200313-034J)

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reflector antennas have high gain and moderate bandwidth and can be made light-weight by using composite material or with a mesh-type design. In addition, digital beam forming (DBF) can be performed by on/off operation of the feed elements. One of the operation modes analyzed as a reflector-based HRWS system is SweepSAR [4], which is a SAR operation mode of obtaining a high-resolution image using a broad beam to transmit and a narrow beam to receive based on the SCORE(scan-on-receive) method using DBF. However, this operation mode requires the use of a low pulse repetition frequency (PRF) to obtain an unambiguous wide swath. For this reason, a modified mode of SweepSAR using dual channels, which is called M-SweepSAR, was examined for a single polarization (single-pol) SAR system [6].

Generally, the SAR system employs only a single transmitting/receiving polarization and obtains one type of polarization information. In contrast, in polarimetric SAR, such as dual-polarimetric and quadrature-polarimetric (quad-pol) approaches, various information can be obtained using multiple transmitting and receiving polarizations, and it has been utilized this way in many fields [7, 8]. However, for a SAR system operating in a quad-pol mode, interleaving transmitting pulses of different polarizations impacts the design of the SAR system. Therefore, accurately analyzing this effect, as done in [9, 10], is necessary to design an appropriate quad-pol SAR system.

In the current paper, the reflector antenna and the performance of the proposed quad-pol system operating in M-SweepSAR mode are designed and analyzed, respectively. We also compared wide-swath quad-pol SAR systems in terms of system performance and antenna design.

II. PERFORMANCE OF THE WIDE-SWATH QUAD-POL SAR SYSTEM

Generally, a SAR system can be characterized by performance indicators, such as the ambiguity-to-signal ratio and resolution. These indicators are strongly related to the system parameters, antenna patterns, and SAR operation modes.

The ambiguity-to-signal ratio, which comprises the range ambiguity-to-signal ratio (RASR) and azimuth ambiguity-to-signal ratio (AASR), is the ratio of undesired signals to the desired SAR signal. It is calculated through the transmitting/receiving antenna pattern, $G_t(\theta)/G_r(\theta)$; backscattering coefficient, σ^0 ; slant range, ρ ; range ambiguous slant range, ρ_{RA} ; incidence angle, θ_I ; Doppler processing bandwidth, PB ; and the angles at which the ambiguity signal occurs in the range and azimuth directions, θ_A and θ_{AZ} , respectively [9, 11]. The resolution, which is the degree of distinguishing the main target from other objects, in the azimuthal direction (ρ_a), is calculated

through the beam footprint velocity (V_g), Doppler bandwidth (Δf_{dop}) and wavelength (λ) [12, 13]. The range resolution is related to the bandwidth of the transmitted pulse and is not directly associated with other performance indicators.

$$RASR = \frac{\sum_{n \neq 0} \int_{PB} \frac{\sigma^0(\theta_I(n)) G_t(\theta_A(n), \theta_{AZ}) G_r(\theta_A(n), \theta_{AZ})}{\rho_{RA}^3(n) \sin(\theta_I(n))} d\theta_{AZ}}{\int_{PB} \frac{\sigma^0(\theta_I(0)) G_t(\theta_A(0), \theta_{AZ}) G_r(\theta_A(0), \theta_{AZ})}{\rho^3 \sin(\theta_I(0))} d\theta_{AZ}} \quad (1)$$

$$AASR = \frac{\sum_{n \neq 0} \int_{PB} G_t(\theta_{AZ}(n)) G_r(\theta_{AZ}(n)) d\theta_{AZ}(n)}{\int_{PB} G_t(\theta_{AZ}(0)) G_r(\theta_{AZ}(0)) d\theta_{AZ}(0)} \quad (2)$$

$$\rho_a = \frac{0.886 V_g}{\Delta f_{dop}} = \frac{0.443 \lambda}{PB} \quad (3)$$

We dealt with the wide-swath and quad-pol operation modes and designed the antenna, which is one of the most important parts of the SAR system, to conduct a proper performance analysis.

1. Wide-Swath SAR System

The swath width of the spaceborne SAR system is affected by the SAR system parameters, such as the PRF, pulse width, altitude of the satellite, and incidence angle. Moreover, the swath width is also related to noise and the resolution performance. As a representative operation mode, ScanSAR, the most widely used wide-swath SAR operation mode, uses multiple beams to sequentially observe sub-swaths, which are designed according to the position of the blind ranges determined by the PRF and pulse width.

However, as the sub-swaths are observed sequentially, the dwell time of each sub-swath is decreased, and the azimuth resolution is degraded in proportion to the number of sub-swaths [2]. In contrast, SweepSAR continuously observes the total swath width by using a broad transmitting antenna beam and narrow receiving antenna beams through a DBF method, whereas ScanSAR uses the same transmitting/receiving pattern for each sub-swath. However, due to the azimuth ambiguity performance and blind range, conventional SweepSAR requires a low PRF and a large reflector antenna.

Alternatively, M-SweepSAR, which is examined in this paper, can overcome this constraint by using two channels, so that this operation mode can reduce the reflector size than SweepSAR. M-SweepSAR uses two rows of linear-array feed antennas, with each of the two channels corresponding to a row. Each channel forms a transmitting/receiving pattern in the same way as the DBF method of SweepSAR. Unlike SweepSAR, however, an area which overlaps the blind range of one channel can be observed by using the other channel. In other

words, each channel operates simultaneously with different PRFs. Two channels continuously observe the total swath with one of the two frequency bands within the total available bandwidth and filtering is performed to reduce interference [6, 14]. The operational concepts of the three wide-swath modes (ScanSAR, SweepSAR, and M-SweepSAR) are shown in Fig. 1.

In this way, the required antenna conditions depend on the SAR operation mode. The selection of the SAR system parameters, such as the PRF, is also affected in meeting the system requirements.

2. Quad-Pol SAR System

In the quad-pol SAR operation, H/V polarization is transmitted and received alternately within the given intervals, and the PRF is doubled that of the single-pol SAR. Therefore, the quad-pol SAR can obtain four types of information: HH, HV, VH, and VV. However, the increase in the PRF causes a decrease of the receiving interval and performance degradation in the RASR.

Fig. 1. Operational concepts of the wide-swath SAR systems: (a) ScanSAR, (b) SweepSAR, and (c) M-SweepSAR. Dashed line is transmitting operation; colored region is receiving operation. Adapted from Lim [13].

Moreover, the behavior of backscattering coefficients in different polarizations [15, 16] needs to be considered for the prediction of the quad-pol SAR performance. Due to the interleaving of the transmitting pulses of different polarizations, two types of signals with different transmitting polarization channels but the same receiving polarization channels are considered as range ambiguities. Since cross-polarized backscatter levels are typically lower than the co-pol ones and the first-order ambiguities, in Eq. (1), dominate the range ambiguity levels when considering the antenna radiation pattern, poorer RASR performance is expected for cross-pol in a conventional quad-pol SAR system [9]. For these reasons, when we assume the same effective channel PRF, the quad-pol mode obtains about half the swath width of the single-pol mode.

Therefore, the considerable effects of the use of the quad-pol mode on the SAR system performance need to be analyzed. In addition, performance degradation should be compensated with the selection of appropriate parameters based on the relation between the SAR system parameters and the system performance [17, 18]. The increase in the PRF leads to the degradation of the RASR performance while improving the AASR performance. PB, which is the reliable range in the azimuthal direction, also affects ambiguity performances. It is especially important in the AASR characteristics, which are related to the azimuth resolution, rather than to the RASR.

3. Design of the SAR Reflector Antenna

For satisfying the required performance of a SAR system, a proper antenna should be considered and designed depending on the polarization. In other words, it is necessary to design an antenna that considers quad-pol performance because there is a limit to achieving sufficient quad-pol performance by appropriately selecting the system parameters while using an antenna that had been considered for only single mode in its design [18]. According to a brief comparison between two systems employing the single-pol mode and the quad-pol mode, the ambiguity performance of the single-pol mode is better than that of the quad-pol mode. In terms of resolution, the characteristic of the quad-pol mode is better than that of the single-pol because ScanSAR, which has a trade-off relation between resolution and the number of sub-swaths, covers less swath width due to the increase of the PRF and the RASR performance degradation, especially at the far region, in the quad-pol mode. Therefore, the antenna should be designed to match the ambiguity ratio of the quad-pol mode and the resolution of the single-pol mode.

The relation among the size of the reflector antenna, ambiguity ratio, and resolution of the SAR system is as follows. Increasing the reflector length in the azimuthal direction improves the azimuth ambiguity performance and degrades the resolution regardless of the operation mode. Increasing the reflector width

in the range direction improves the range ambiguity performance in ScanSAR. However, as the beamwidth decreases, the space between the feeds becomes narrower considering the beam deviation factor (BDF) to ensure a continuous total swath width, and the resolution performance is degraded because it leads to an increased number of sub-swaths. The *BDF* of an offset reflector antenna is derived from the beam scan angle, θ_B ; feed tilt angle, θ_F ; focal length, F ; and parent reflector, D_p ; as shown in the following [19]:

$$BDF = \frac{\theta_B}{\theta_F} = \frac{1 + 0.36 \left(4 \frac{F}{D_p} \right)^{-2}}{1 + \left(4 \frac{F}{D_p} \right)^{-2}} \quad (4)$$

As SweepSAR and M-SweepSAR continuously observe the full range of the swath width, improving the range ambiguity ratio by increasing the reflector width does not affect the resolution. However, as the reflector width increases, the space between the feeds becomes narrower and the minimum space is limited by the size of the feed antenna. Therefore, RASR and AASR require an increase in the reflector size, but the resolution and the size of the feed antenna must be considered as the upper bound of the reflector width [13, 20].

III. CHARACTERISTIC ANALYSIS AND COMPARISON OF THE QUAD-POL M-SWEEPSAR SYSTEM

In this research, we selected a spaceborne SAR system with a C-band center frequency operating at an altitude of 505 km with a total swath width of 150 km for a single-pol mode at an incidence angle of 20° – 35° [6]. In this case, we assumed that the SAR system performance, which involves an ambiguity ratio in each direction and the resolution should be under the conditions of -20 dB and 10 m, respectively.

The required SAR antenna beamwidth was determined by the swath width and the number of sub-swaths, which help in selecting the optimum reflector antenna depending on the operation mode. This paper suggests a reflector length for the offset reflector antennas of 4 m, 13.5 m, and 6 m for ScanSAR, SweepSAR, and M-SweepSAR, respectively. These antennas had a reflector with $F/D_p = 0.409$ and a feed array linearly placed in the range direction with one row. Only M-SweepSAR had a feed array with two rows. The radiation patterns of the reflector antenna by several elements at one row of the feed array for the M-SweepSAR system are presented in Fig. 2. These patterns were simulated using the FEKO EM simulation tool. The transmitting pattern in the elevation direction was broad enough to cover the overall swath using additional feed antennas at both ends of each row of the feed array. The receive-

Fig. 2. Antenna radiation patterns used for the quad-pol M-SweepSAR system: (a) elevation patterns and (b) azimuth patterns.

ing patterns were tilted in the elevation direction, so that each feed received echoes from each sub-swath.

The reflector antenna of each SAR system had a feed antenna according to the number of sub-swaths in the single-pol mode. However, SAR systems use fewer feed antennas in the quad-pol mode to meet the requirements (except for the M-SweepSAR system). In quad-pol M-SweepSAR, the PRF and signal acquisition areas of each channel were determined based on the timing diagram shown in Fig. 3. M-SweepSAR had 14

Fig. 3. Timing diagram of the quad-pol M-SweepSAR system. Red lines are blind range; black lines, nadir return; dashed region, channel PRF selection; colored segments, sub-swaths corresponding to each feed element.

sub-swaths in the quad-pol mode with PRFs of 5,250 Hz and 5,400 Hz in each row of the feed array, which maintained an PB of 0.16° and had 14 sub-swaths in a single-pol mode. As shown in Fig. 3, each row of the feed array transmits the signal to sub-swath (sw) 1–14, with one row receiving echoes from sw 5–7 and 11–12, and the other row receiving echoes from sw 1–4, 8–10, and 13–14. ScanSAR had three sub-swaths in the quad-pol mode, with three PRFs of 10.15, 10, and 9 kHz and a PB of 0.44° , and 6 sub-swaths in the single-pol mode. SweepSAR had 13 sub-swaths in the quad-pol mode, with a PRF of 3,400 Hz and PB of 0.26° , and 24 sub-swaths in the single-pol mode. All of the information for the three wide-swath operation modes working in the quad-pol mode is shown in Table 1.

Based on the simulation results of the three quad-pol SAR systems for wide-swath, the SAR performances, including reflector antenna size, ambiguity ratio, resolution, and swath width, were analyzed and compared with the use of the backscattering coefficients assumption, which was suggested by Ulaby and Dobson [16]. In our previous work [18], we had conducted a comparison between our calculation results and data in [9] to verify our analysis procedure on quad-pol SAR systems. Generally, the RASR for the co-pol (HH and VV) was about 10 dB lower than that for the cross-pol (HV and VH). Therefore, we present only the RASR for HV in Fig. 4.

From Table 1 and Fig. 4, the reflector length for SweepSAR was the largest in order to meet the required performance in the single-pol and quad-pol modes while maintaining the required swath width obtained in the single-pol mode because of the

characteristics of the SweepSAR operation mode. Conversely, the reflector lengths of M-SweepSAR and ScanSAR were half that of SweepSAR and the smallest, respectively. Quad-pol SweepSAR had the largest reflector antenna but was best in terms of total ambiguity ratio, which means the sum of RASR and AASR. Quad-pol ScanSAR and quad-pol M-SweepSAR had similar levels in ambiguity within the incidence angle range of 20.0° – 27.5° . However, it can be conjectured from Fig. 4 that quad-pol M-SweepSAR had better characteristics than quad-pol ScanSAR and satisfied the requirements on the overall incidence angle range.

The azimuth resolution depends on the Doppler bandwidth, and in the case of ScanSAR, it is also affected by the number of sub-swaths. As shown by the simulation results, quad-pol ScanSAR had the largest PB with the smallest antenna size, but its resolution was the worst. In addition, quad-pol SweepSAR had the best resolution among the three operation modes, even though it had the largest antenna size because quad-pol M-SweepSAR had a narrower PB for the azimuth ambiguity performance.

In terms of the swath width under the conditions of less than -20 dB RASR and AASR, quad-pol ScanSAR was limited in

Table 1. Comparison of the wide-swath quad-pol SAR operation modes

Operation mode	ScanSAR	SweepSAR	M-SweepSAR
Reflector length (m)	4	13.5	6
Number of feeds	6	26 (Tx: 26, Rx: 24)	32 (Tx: 16×2 , Rx: 14×2)
Number of sub-swaths	3	13	14
Swath width (km) (incidence angle, $^\circ$)	70 (20–27.5)	75 (20–28.1)	150 (20–35)
PRF (Hz)	10,150 10,000 9,000	3,400	5,250 (Ch. 1) 5,400 (Ch. 2),
PB ($^\circ$)	0.44	0.26	0.16
Azimuth resolution (m)	9.7	5.4	8.9
RASR/AASR (dB)		< -20

Fig. 4. Comparison of the ambiguity performance of the quad-pol SAR system according to the operation mode: (a) RASR and (b) AASR.

obtaining a wide swath width because of the ambiguity performance degradation over a large incidence angle range. As the PRF increased, and the receiving interval was reduced for the quad-pol mode, quad-pol SweepSAR was also limited in obtaining a continuous total swath width because of the blind range. Therefore, the two modes had half of the total swath width in comparison with the single-pol mode. On the contrary, quad-pol M-SweepSAR could obtain a swath width almost like that of the single-pol mode within the required performance levels. In other words, M-SweepSAR used two PRFs, and this characteristic was advantageous in obtaining a wider swath width than SweepSAR. In addition, M-SweepSAR had a better ambiguity performance than ScanSAR; it was also advantageous in obtaining a wider swath width than ScanSAR.

Most of the differences in the performance indicators discussed in this chapter arose from the differences in antenna patterns, which were determined on the basis of the required performance. Therefore, if the requirements change, the antenna size, which determines the achievable range of the SAR system performance, should be changed. As a result of confirming the performance changes derived from the size of the reflector antenna in each operation mode, increasing the reflector size for the ScanSAR improves the ambiguity performance but worsens the resolution [20]. Conversely, SweepSAR and M-SweepSAR have the advantage of maintaining resolution in comparison with ScanSAR even when the reflector size increases, and M-SweepSAR can reduce the reflector size in comparison with SweepSAR, as mentioned in Chapter II. In other words, for the ScanSAR system to obtain a wider swath width in the quad-pol, a larger reflector must be required to improve the ambiguity ratios, which does not satisfy the resolution requirement. However, we can design a reflector antenna for the M-SweepSAR and achieve a wider swath width in the quad-pol, although it uses a larger reflector than ScanSAR.

IV. CONCLUSION

In this paper, the performance analysis of the proposed quad-pol M-SweepSAR system was conducted. To determine the validity of our analysis, we designed, analyzed, and compared the ScanSAR, SweepSAR, and M-SweepSAR systems. The result of the analysis and comparison of the three operation modes based on the properly designed systems indicated that M-SweepSAR is expected to be highly recommended as the HRWS spaceborne SAR system because it is advantageous in satisfying the required ambiguity ratio and resolution in both the single-pol and the quad-pol modes with an appropriate reflector antenna size and obtains a wider swath width in the quad-pol mode than the conventional wide-swath operation mode. However, as the feed array has two rows, the system

must have dual channels and operate two center frequencies in the available bandwidth. Therefore, filtering for interference suppression should be considered for practical implementation.

This work was performed for the Development of Radar Payload Technologies for Compact Satellite in Korea Aerospace Research Institute, funded by the Ministry of Science and ICT.

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