Abstract—Undesired echo from a flying object (aerial clutter) significantly contaminates the received signal of a wind profiler radar (WPR) because it has high intensity and spreads over a wide Doppler velocity range. In this study, results of aerial clutter mitigation obtained by applying adaptive clutter suppression (ACS) to a 1.3-GHz WPR are shown. The 1.3-GHz WPR used in this study has 13 antenna subarrays that consist of the thin antenna (MSAs). Five-element Yagi–Uda antennas were also used as antenna subarrays for detecting clutters from low elevation angles (CSAs). The CSAs were used only in reception and installed so that they covered most of the horizontal directions and the horizontal and vertical polarizations. The directionally constrained minimization of power (DCMP) method was used as the adaptive signal processing to mitigate clutter. By the DCMP method, the weighted sum of the signals collected by 13 MSAs and 11 CSAs was computed so that the power of output signals was minimized under the constraint of constant gain in the antenna beam direction. Results of a case study for an aerial clutter from a low elevation angle at 17:04:37 on October 1, 2020, showed that an overlap of the aerial clutter over a desired echo (i.e., clear-air echo) was solved by decreasing the aerial clutter whose peak intensity was ~24 dB greater than that of the clear-air echo. In a case study at 09:30:27 on September 18, 2020, the effects of the DCMP method on the processed results were discussed.

Index Terms—Adaptive array antenna, clutter, meteorology, radar wind profiler, wind measurement, wind profiler radar (WPR).

I. INTRODUCTION

WIND profiler radar (WPR), also referred to as a radar wind profiler, is an instrument that measures height profiles of wind velocity in the clear air. It detects the echo produced by radio refractive index irregularities of the air (hereafter clear-air echo). Radio refractive index irregularities that bring forth the clear-air echo have a scale half of the radar wavelength (i.e., Bragg scale). Wind velocity is generally measured from Doppler shifts of the clear-air echoes collected in multiple antenna beam directions. Because WPR can measure height profiles of wind velocity in the clear air with high time and vertical resolutions (generally less than ~10 min and several hundred meters, respectively), WPRs have contributed to studying dynamical processes in the atmosphere [1], [2]. Meteorological agencies have been operating WPRs to use the wind velocity profiles that they collect in weather service [3]–[7].

The accuracy of the wind velocity product obtained by WPR (hereafter product accuracy) is important in research and weather service. There are factors that degrade the product accuracy. The thermal noise produced in the receiver and/or the persistent natural noise (i.e., cosmic noise and solar noise) degrade the product accuracy, especially under low signal-to-noise ratio (SNR) conditions. The inhomogeneity of the wind field in or among the sampling volumes of the antenna beams is also a factor that can negatively affect the product accuracy. Effects of these factors depend on the hardware performance of WPR and atmospheric conditions.

Undesired radio waves detected by the antenna also decrease the product accuracy. Undesired echo, referred to as clutter, can cause a misdetection of the clear-air echo when its intensity is comparable to or greater than that of the clear-air echo. Interference from radio sources also obstructs the correct detection of the clear-air echo. The metal fence surrounding WPR (hereafter clutter fence) is a means of mitigating undesired radio waves detected by the antenna. However, the height of a clutter fence cannot be arbitrarily increased without negative effects on the antenna radiation pattern. Therefore, its beneficial effects are limited to undesired radio waves from directions close to the ground. Clutter whose source exists in the air (hereafter aerial clutter) cannot be mitigated well when its source exists at a high altitude at which a clutter fence cannot shield a reception antenna from radio waves scattered by the source of the aerial clutter.

To improve the product accuracy, quality control (QC) is carried out. For example, QC is executed by filtering out undesired signals from the time series [8], by removing undesired signals in the production of the Doppler spectrum [9], [10], by reducing adverse effects of undesired signals on the spectral parameter estimation of the clear-air echo [11], [12], and by examining the consistency of the
spectral parameters and/or the wind vector in time and height [13], [14]. However, because QC methods are generally based on an idea of rejecting unreliable parts of the received signals, they decrease the number of available data points.

Adaptive clutter suppression (ACS), also referred to as adaptive clutter rejection, is a technique that uses antenna subarrays (SAs) in reception. In ACS, the weighted sum of the signals collected by SAs is computed so that clutter contamination from the sidelobe of the reception antenna is mitigated with a constraint that loss of information on the clear-air echo, which is detected by the main lobe of the main antenna, is reduced [15]–[22].

To demonstrate how ACS works to mitigate an aerial clutter from a low elevation angle, case studies of field experiments are presented in this study. In Section II, the SA configuration of a 1.3-GHz WPR in the case studies and the signal processing in ACS are described. The SA configuration is unique in the point that both the SAs of the main antenna and those for detecting clutters from low elevation angles are used in ACS. In Section III, the case studies at 17:04:37 on October 1, 2020 and at 09:30:27 on September 18, 2020 are presented. Conclusions are given in Section IV.

II. INSTRUMENTATION AND METHODOLOGY
A. 1.3-GHz WPR With Antenna Subarrays (LQ-13)

A 1.3-GHz WPR used in this study is installed at the headquarters of the National Institute of Information and Communications Technology in Koganei, Tokyo, Japan. The 1.3-GHz WPR is referred to as LQ-13. Its center frequency and peak transmission power are 1357.5 MHz and 5.2 kW, respectively. The radar wavelength \( \lambda \) is \( \approx 0.22 \) m. Fig. 1(a) shows a photograph of SAs of LQ-13. A phased array antenna installed inside a clutter fence is the main antenna. The gain and half-power width of the main antenna are \( \approx 32 \) dBi and \( \approx 3.6^\circ \), respectively. Beam directions of the main antenna are vertical, northward, eastward, southward, and westward. Zenith angles of the four oblique antenna beams are \( 14^\circ \). The main antenna is linearly polarized and composed of 13 Luneberg lenses. These lenses, which are the SAs of the main antenna, are hereafter referred to as MSAs. Fig. 2 shows their positions. They are aligned hexagonally, and the distance between the centers of two adjacent MSAs is 912 mm. The half-power width of the MSA is \( \approx 17^\circ \).

In addition to the MSAs, SAs for detecting clutters from low elevation angles were installed outside the clutter fence [see Fig. 1(a)]. Hereafter, they are referred to as CSAs. The CSAs were a Yagi–Uda antenna with five elements, and the polarization of each CSA was determined by its attachment angle to the pole [see Fig. 1(b)]. The Yagi–Uda antenna was designed to have a gain of \( \approx 11 \) dBi, and its half-power widths in a designed value are \( \approx 48^\circ \) in the \( E \)-plane and \( \approx 58^\circ \) in the \( H \)-plane. The CSAs were installed so that they cover most of the horizontal directions and the horizontal and vertical polarizations. The azimuth directions
of six CSAs with horizontal polarization (i.e., CSA01, 03, 05, 07, 09, and 11) had 60° intervals, and those of five CSAs with vertical polarization (i.e., CSA02, 04, 06, 08, and 10) were the same as those of CSA01, 03, 05, 07, and 09 [see Fig. 2]. The elevation angle of the CSAs was 30°, which was determined so that the blockage of the main lobes of the CSAs by the ground was reduced. Note that although a CSA with vertical polarization was installed in the same direction as CSA11, it was not used in the experiments because the available number of receiver channels was limited to 24.

The clutter fence of LQ-13 was designed to have a shielding performance of 36 dB or more. The diameter and spacing of the wire are 0.8 and 6.35 mm, respectively. The height of the clutter fence is ~2.82 m. Below the ~1.51 m height, the clutter fence is vertical, and its width is ~4.77 m. To reduce the edge diffraction at the top of the clutter fence, the clutter fence is slanted outside above the height of ~1.51 m, and a rounded metal cover is installed at the top. Its width at the top is ~5.89 m.

In the experiment shown in this study, an observation mode of the WPRs operated in the Wind Profiler Network and Data Acquisition System (WINDAS) of the Japan Meteorological Agency [5] was used. Note that the WPRs operated in WINDAS do not have a function of ACS. The interpulse period (T_{ipp}) in the observation mode was 100 μs. The number of times of transmissions to collect the time series was 4096, and the beam direction of the main antenna was kept the same during the 4096 consecutive transmissions. Therefore, the duration for collecting the time series from one antenna beam direction was 0.4096 s. To reduce the amount of received signals, the integration of the time series in time (hereafter coherent integration) was executed in real time. The number of times of coherent integrations (hereafter N_{coh}) was 16, and thus, the time series length after the coherent integrations (hereafter N_{data}) was 256. The Nyquist velocity was \((1/(2T_{ipp}N_{coh}))\times 34.5 \text{ m s}^{-1}\). Antenna beam directions were vertical, northward, eastward, southward, and westward, and the duration to cycle the five antenna beam directions was 2.048 s (= 5 × 0.4096 s). In the pulse transmission, the 8-bit optimum binary code [23] was used to enhance the SNR. The subpulse width was 2 μs. The range sampling of received signals started from 300 m. The interval of range sampling was 2 μs, which was the same as the subpulse width and corresponds to the range interval of 300 m. The number of range bins was 40. The above-mentioned measurement parameters are the same as those of the strong wind mode of the WPRs used in WINDAS. The strong wind mode is used in weather conditions with strong wind (e.g., typhoon). The routine measurement mode of the WPRs used in WINDAS is different from the strong wind mode in that N_{coh} is 32. The difference reduces N_{data} to 128 and the Nyquist velocity to 17.3 m s\(^{-1}\) in the routine measurement mode. The Nyquist velocity in the strong wind mode is greater than that in the routine measurement mode, and thus, the strong wind mode was used in the case studies because the greater Nyquist velocity in the strong wind mode was beneficial for measuring the distribution of the aerial clutter in a Doppler spectrum.

### B. ACS Using MSAs and CSAs

Fig. 3 shows a schematic that explains ACS using MSAs and CSAs. The CSAs are directed to a low elevation angle, and the clutter exists in a height where the CSAs have sufficient sensitivity for it. WPR generally uses a high-gain main antenna (generally ~30 dB or greater), and the antenna beams are directed at or near the zenith (i.e., their zenith angles are generally \(\leq 15°\)). Therefore, when ACS is not applied (i.e., the signals collected by the MSAs are summed up with equal weight), the clear-air echo is detected by the main lobe of the main antenna, and the majority of clutters are detected by sidelobes of the main antenna [Fig. 3(a)]. The sidelobe level of the main antenna at low elevation angles is generally small because the main lobe of the main antenna has a large gain and is directed at or near the zenith. Therefore, although small antennas are used as the CSAs, the antenna gain of the CSAs can be greater than the sidelobe level of the main antenna at low elevation angles [Fig. 3(a) and (b)]. Previous studies have shown that CSAs could mitigate clutters from low elevation angles [17, 21, 22]. Because the sensitivity of the CSAs at
or near the zenith (i.e., at high elevation angles) is insufficient to detect the clear-air echo, CSAs do not affect the main lobe pattern of the main antenna [Fig. 3(b)]. The weighted sum of the signals collected by the MSAs and CSAs is computed so that the sidelobe level in the clutter arrival direction decreases [Fig. 3(c)]. As an adaptive signal processing to mitigate clutters detected by sidelobes of the main antenna, the directionally constrained minimization of power (DCMP) method [24]–[26] was used. In the DCMP method, the weighted sum of the time series collected by SAs is computed so that the power of the time series after the weighted summation (i.e., the output power) is minimized with a constraint of constant gain in the beam direction of the main antenna (i.e., in the desired direction).

Signal processing by the DCMP method at a certain range is explained. The wavenumber vector is defined as

$$k = \frac{2\pi}{\lambda} [\sin \theta \sin \phi, \sin \theta \cos \phi, \cos \theta]$$

where \(\theta\) and \(\phi\) are the zenith and azimuth angle of the antenna beam direction, respectively.

Let us represent the time series collected by the \(i\)th MSA as \(m_i(p)\) (\(1 \leq i \leq N_{MSA}\)) and those collected by the \(j\)th CSA as \(c_j(p)\) (\(1 \leq j \leq N_{CSA}\)). \(p\) is an index in time, and \(1 \leq p \leq N_{data}\). \(N_{MSA}\) and \(N_{CSA}\) are the numbers of MSAs and CSAs, respectively. \(m_i(p)\) is normalized by the receiver noise power of the \(i\)th MSA, and \(c_j(p)\) is normalized by the receiver noise power of the \(j\)th CSA. The normalizations for \(m_i(p)\) and \(c_j(p)\) are carried out to correct the noise power difference among the receivers of the MSAs and those of the CSAs.

\(s(p)\) represents a column vector containing the time series collected by the MSAs and those collected by the CSAs. \(s(p)\) is expressed as

$$s(p) = [m_1(p), \ldots, m_{N_{MSA}}(p), c_1(p), \ldots, c_{N_{CSA}}(p)]^T$$

where the superscript \(T\) represents the transpose of a vector or matrix. The length of \(s(p)\), represented by \(N_{SA}\), is equal to \(N_{MSA} + N_{CSA}\). The covariance matrix of the received signals \(V\) is expressed as

$$V = \begin{bmatrix} V_{1,1} & V_{1,2} & \ldots & V_{1,N_{SA}} \\ V_{2,1} & V_{2,2} & \ldots & V_{2,N_{SA}} \\ \vdots & \vdots & \ddots & \vdots \\ V_{N_{SA},1} & V_{N_{SA},2} & \ldots & V_{N_{SA},N_{SA}} \end{bmatrix}$$

where \(V_{i,j}\) is defined by

$$V_{i,j} = \sum_{p=1}^{N_{SA}} s_i(p) s_j^*(p)$$

with * being the complex conjugate.

With the weight vector \(w\), the output time series \(y(p)\) is given by

$$y(p) = w^H s(p)$$

where the superscript \(H\) represents the Hermitian transpose (i.e., conjugate transpose) operator. The brightness \(B\) is defined by

$$B = w^H V w.$$  

The problem to be solved is mathematically stated as

$$\min_w B \text{ subject to } e^H w = 1$$

where \(e\) is the steering vector. Elements of \(e\), denoted by \(e_q\), are defined by

$$e_q = \begin{cases} \frac{1}{\sqrt{N_{MSA}}} \exp(j k \cdot D_q), & 1 \leq q \leq N_{MSA} \\ 0, & (N_{MSA} + 1) \leq q \leq N_{SA} \end{cases}$$

where \(D_q\) is the vector representing the position of the \(q\)th MSA. The directional constraint is applied to the time series from the MSAs [i.e., \(e_q = (1/(N_{MSA})^{1/2}) \exp(j k \cdot D_q)\)]. On the other hand, constraints are not applied to the time series from the CSAs (i.e., \(e_q = 0\)) because signals from the CSAs do not contain the clear-air echo [17], [22]. Note that although the signals collected by the CSAs have phase differences caused by the receiver hardware (e.g., cables and receiver components), the phase differences need not be calibrated because signals collected by the CSAs do not contain the clear-air echo. This characteristic contributes to the easy installation of CSAs [22].

The solution for \(w\) has the following form:

$$w = V^{-1} e.$$

In this study, a weight vector composed of the \(w\) elements for the MSAs [i.e., the weight coefficients for \(m_i(p)\)] is expressed by \(w_{MSA}\) and that composed of the \(w\) elements for the CSAs [i.e., the weight coefficients for \(c_j(p)\)] is denoted by \(w_{CSA}\).

In this study, all the values used in the signal processing by the DCMP method were represented by the double-precision floating-point format to ensure their precision and representable range. Note that the time series after real-time signal processing (i.e., after coherent integrations) were stored in the storage device with the single-precision floating-point format. They were processed by the DCMP method after they were converted to the double-precision floating-point format.

Before the DCMP method was applied to the time series collected by the MSAs and CSAs of LQ-13, for every time series, its mean value was removed. The removal of the mean value from the time series (i.e., mean value removal in the time domain) is equivalent to that of the direct current component (hereafter DC component) from the Doppler spectrum (i.e., DC component removal in the frequency domain). The removal of the mean value from the time series collected by the MSAs and CSAs of LQ-13 was executed because the clutter mitigation did not work for the DC component. It is likely that there were many clutter sources that had a mean Doppler velocity of \(0 \text{ ms}^{-1}\) and that their Doppler velocity broadenings were much smaller than the frequency resolution of the Doppler spectrum. Such clutter sources (e.g., buildings) would tightly be fixed on the ground and thus their oscillations by the surface wind had low frequencies. The removal of
Fig. 4. (a) Time series produced by summing up the time series collected by the MSAs with equal weight. (b) Time series computed by the DCMP method. Red and blue curved lines show in-phase and quadrature-phase components, respectively. In the computation by the DCMP method, the time series collected by both the MSAs and CSAs were used. The collection time was 17:04:37 on October 1, 2020, and the antenna beam direction and range were westward and 2.7 km, respectively. The time series collected by each MSA and each CSA are shown in Figs. 7 and 8, respectively.

the DC component did not affect the aerial clutter mitigation described in this study. The DC components of Doppler spectra shown in the figures of this study were interpolated using the adjacent data points on both sides of the Doppler velocity bins.

III. RESULTS AND DISCUSSION

A. Overview of Processed Results

In Section III-A–III-F, the case study at 17:04:37 on October 1, 2020 is presented. Fig. 4(a) shows a time series produced by summing up the time series collected by the MSAs with equal weight. The antenna beam direction and the range of the time series were westward and 2.7 km, respectively. The time series produced by the summation with equal weight is equivalent to that when received signals cannot be collected from each MSA (i.e., signals detected by the MSAs are summed up with equal weight by analog combiners). The oscillatory component that dominated over the time series was an aerial clutter. By using a flight track available from the website of Flightradar24 (https://www.flightradar24.com/), it is estimated that a source of the aerial clutter was a helicopter that flew north of LQ-13 at a height of ∼1430 m. Because the range was 2.7 km, the elevation angle of the aerial clutter was ∼32° (= arctan((1430/27002 − 14302)1/2)). Fig. 5(a) shows a Doppler spectrum of the time series shown in Fig. 4(a). The aerial clutter spread over the Doppler spectrum and had spikes greater than 70 dB. The maximum of the spikes was 96.9 dB at the Doppler velocity of −4.31 ms⁻¹. Due to the dominance of the aerial clutter, it is impossible to distinguish the clear-air echo in the Doppler spectrum.

Fig. 4(b) shows a time series after the time series collected by the MSAs and CSAs were weighted and then summed up by the DCMP method (i.e., the time series obtained by applying ACS). The oscillatory component, which was the aerial clutter, disappeared with the application of the DCMP method [see Fig. 4(a) and 4(b)]. Fig. 5(b) shows a Doppler spectrum of the time series shown in Fig. 4(b). Due to the aerial clutter mitigation by the DCMP method, an echo with a peak of 72.9 dB at the Doppler velocity of 1.35 ms⁻¹ was observed. The Doppler velocity range of the clear-air echo was examined using Doppler spectra when no aerial clutters were found. The Doppler spectrum shown in Fig. 6 is the average of six Doppler spectra measured from 17:03:40 to 17:03:52 on October 1, 2020. The averaging was carried out to reduce random perturbations in the six Doppler spectra. In both the case in which the DCMP method was not applied (black curved line) and that in which the DCMP method was applied (red curved line), the Doppler velocity range of the clear-air echo was ∼1–3 ms⁻¹, which agreed well with that of the echo shown in Fig. 5(b). Therefore, it can be concluded that the echo shown in Fig. 5(b) was the clear-air echo. This agreement in the Doppler velocity range of the clear-air echo can also be confirmed from the Doppler spectrum...
Fig. 6. Black curved line is the average of six Doppler spectra, each of which was computed from the time series produced by summing up the time series collected by the MSAs with equal weight. The six Doppler spectra were collected from 17:03:40 to 17:03:52 on October 1, 2020, and the antenna beam direction and range were the same as those of the Doppler spectra shown in Fig. 5. The red curved line is the same as the Doppler spectrum shown by the black curved line except that each of the six Doppler spectra used in the averaging was computed from the weighted sum of the time series collected by the MSAs and CSAs.

B. Time Series Collected by MSAs and CSAs

Fig. 7 shows the time series collected by each MSA. The collection time, antenna beam direction, and range were the same as those of the time series shown in Fig. 4. Red and blue curved lines show in-phase and quadrature-phase components, respectively.

The polarization of CSA06 was vertical, whereas that of CSA07 was horizontal. Moreover, the beam direction of CSA07 was different by 60° from that of CSA06. Although it is difficult to specify the cause of the arrival direction difference between the detected radio wave with horizontal polarization and that with vertical polarization, metallic structures (e.g., towers, power lines, and buildings) near LQ-13 are possible candidates that generated the arrival direction difference. Metallic structures can induce the multiple scattering and diffraction of radio waves scattered by a clutter source, and polarization characteristics of scattering and diffraction

after the 29 Doppler spectra, including the Doppler spectrum shown in Fig. 5(b), were averaged in time (later shown in Fig. 12).

Fig. 8. Same as Fig. 7 except that the time series were collected by the CSAs.
Fig. 9. Same as Fig. 7 except that the time series were weighted by the DCMP method. The time series collected by both the MSAs and CSAs were used in the weight computation. The amplitude and phase of the weight coefficient for each time series in the complex conjugate form are shown at the top of each panel. Note that the plot range of the amplitude (from $-1$ to $1$) is different from that of Fig. 7 (from $-4$ to $4$).

are expected to differ among metallic structures. The measurement result presented in Fig. 8 shows that the polarization characteristics of clutter are complex.

**C. Signal Weighting**

Fig. 9 shows the weighted time series from the MSAs. The time series collected by both the MSAs and CSAs (i.e., the time series shown in Figs. 7 and 8) were used in the weight vector computation by the DCMP method. The amplitude and phase of each $w_{\text{MSA}}$ element (i.e., the weight for each time series collected by the MSAs) in the complex conjugate form are shown at the top of each panel. The minimum and maximum of their amplitudes were 0.203 (MSA05) and 0.364 (MSA07), respectively. The minimum and maximum of their phases were $-32.3^\circ$ (MSA13) and 27.7$^\circ$ (MSA01), respectively. Fig. 10 shows the weighted time series from the CSAs. The amplitude and phase of each $w_{\text{CSA}}$ element (i.e., the weight for each time series collected by the CSAs) in the complex conjugate form are shown at the top of each panel. The time series from CSA06, 07, 09, and 10 were weighted so that the contributions from them became greater than those from other CSAs. Although the amplitude of the time series from CSA06 was similar to that from CSA07 before the weighting [see Fig. 8], the time series from CSA06 and CSA07 were weighted so that the contribution of the time series from CSA07 became greater than that from CSA06. This measurement result indicates the importance of measuring polarization characteristics in clutter detection using CSAs.

The maximum of the weight amplitudes for the CSAs was 0.195 (CSA09), which was less than the minimum of the weight amplitudes for the MSAs ($= 0.203$). This result indicates that because the CSAs had a higher sensitivity for the aerial clutter than the MSAs [see Figs. 7 and 8], the weight amplitudes necessary for the CSAs to reproduce the time variation of the aerial clutter were smaller than those for the MSAs [see Figs. 9 and 10]. Note that smaller weight amplitudes lead to a smaller noise power increase after applying the DCMP method.

Fig. 11(a) shows a time series produced by summing up the weighted time series from the MSAs [see Fig. 9] and CSAs [see Fig. 10]. Note that Fig. 11(a) is the same as Fig. 4(b). Fig. 11(b) and (c) shows the sum of the weighted time series from the MSAs [see Fig. 9] and CSAs [see Fig. 10], respectively. Because the aerial clutters shown in Fig. 11(b) and (c) were antiphase with each other, the aerial clutter was significantly mitigated in the weighted sum of the time series from the MSAs and CSAs [i.e., the sum of the time series shown in Fig. 11(b) and (c), see Fig. 11(a)]. This indicates that the time series collected by the MSAs and CSAs were weighted so that they worked together to mitigate the aerial clutter by controlling the antenna sidelobes.

The elements of $w$ are the weights for both the MSAs and CSAs [see (7)–(9)], and the square of its norm ($\|w\|^2$) was 1.091 [see Fig. 11(a)]. The square of the norm of
Fig. 11. Time series produced by summing up (a) weighted time series from both the MSAs and CSAs, (b) those from only the MSAs, and (c) those from only the CSAs. The time series in (a) is the same as that in Fig. 4(b). The weighted time series from each MSA and each CSA are shown in Figs. 9 and 10, respectively. The values of $|\mathbf{w}|^2$, $|\mathbf{w}_{\text{MSA}}|^2$, and $|\mathbf{w}_{\text{CSA}}|^2$ are shown on the top of (a)–(c), respectively. For details of $\mathbf{w}$, $\mathbf{w}_{\text{MSA}}$, and $\mathbf{w}_{\text{CSA}}$, see the text.

$|\mathbf{w}_{\text{MSA}}| |w_{\text{MSA}}|^2$ was 1.025 [see Fig. 11(b)] and that of $|\mathbf{w}_{\text{CSA}}| |w_{\text{CSA}}|^2$ was 0.067 [see Fig. 11(c)]. Therefore, the contribution of the CSAs in $|\mathbf{w}|^2 (=|\mathbf{w}_{\text{CSA}}|^2/|\mathbf{w}|^2)$ was 6.1%.

D. Doppler Spectrum

The aerial clutter spread over the Doppler spectrum and had a peak of 96.9 dB when the DCMP method was not applied [see Fig. 5(a)]. The aerial clutter mitigation by the DCMP method resulted in detecting the clear-air echo with a peak as small as 72.9 dB [see Fig. 5(b)]. The power of the Doppler spectrum was 99.6 dB when the DCMP method was not applied, and it was 83.1 dB when the DCMP method was applied [see Fig. 5(a) and (b)]. From this result, it can roughly be estimated that the aerial clutter mitigation in the received power was $\sim 16.5$ dB, and the clear-air echo whose peak was $\sim 24.0$ dB ($= 96.9$ dB $- 72.9$ dB) less than that of the aerial clutter was successfully detected.

To examine whether or not the aerial clutter mitigation worked continuously, Doppler spectra were averaged in time. The number of averaged Doppler spectra was 29. In the real-time signal processing of the WPRs operated in WINDAS, 29 Doppler spectra are also averaged in time, and then, the averaged Doppler spectrum is stored in a storage device. The thin curved line in Fig. 12 is the average of the 29 Doppler spectra, each of which was computed from the time series produced by summing up the time series collected by the MSAs with equal weight (i.e., the averaged Doppler spectrum when the DCMP method was not applied). The 29 Doppler spectra were measured from 17:04:12 to 17:05:11 on October 1, 2020. Therefore, the Doppler spectrum shown in the solid curved line of Fig. 5(a), which was collected at 17:04:37, was embedded in the 29 Doppler spectra used in the averaging. The thick curved line in Fig. 12 is the average of the 29 Doppler spectra, each of which was computed from the weighted sum of the time series collected by the MSAs and CSAs (i.e., the averaged Doppler spectrum when the DCMP method was applied). The 29 Doppler spectra were measured from 17:04:12 to 17:05:11 on October 1, 2020. Therefore, the Doppler spectrum shown in the solid curved line of Fig. 5(a), which was collected at 17:04:37, was embedded in the 29 Doppler spectra used in the averaging. The thick curved line is the average of the 29 Doppler spectra, each of which was computed from the weighted sum of the time series collected by the MSAs and CSAs (i.e., the averaged Doppler spectrum when the DCMP method was applied using the MSAs and CSAs). The Doppler spectrum shown in Fig. 5(b), which was collected at 17:04:37, was embedded in the 29 Doppler spectra used in the averaging. When the Doppler spectra before the averaging were produced from the equally weighted time series, the aerial clutter extended over the broad range of the Doppler spectrum because of the rapid movement of its source. On the other hand, when the Doppler spectra before the averaging were produced from the time series weighted by the DCMP...
method, the aerial clutter was mitigated sufficiently to detect the clear-air echo that existed in the Doppler velocity range of $\sim 1$–3 m/s$^1$. The Doppler velocity range of the clear-air echo was consistent with that when no aerial clutter was found [see Fig. 6]. The result shown in Fig. 12 indicates that the aerial clutter mitigation continuously worked in time.

E. Results in Absence of CSAs

Fig. 13 shows the weighted time series when the DCMP method was applied to the time series collected only by the MSAs. The minimum and maximum of the weight amplitudes were 0.155 (MSA13) and 0.414 (MSA07), respectively. The range of the weight amplitudes (from 0.155 to 0.414) was greater than that when both the MSAs and CSAs were used in the weight computation by the DCMP method [from 0.203 to 0.364, see Fig. 9]. The minimum and maximum of the weight phases were $-70.7^\circ$ (MSA05) and $32.2^\circ$ (MSA10), respectively. The range of the weight phases (from $-70.7^\circ$ to $32.2^\circ$) was also greater than that when both the MSAs and CSAs were used [from $-32.3^\circ$ to $27.7^\circ$, see Fig. 9]. Fig. 14(b) shows the sum of the weighted time series shown in Fig. 13. The weighted sum of the time series when only the MSAs were used had a greater perturbation than that when both the MSAs and CSAs were used [see also Fig. 4(b)]. Fig. 15(b) shows a Doppler spectrum computed from the time series shown in Fig. 14(b). Although the aerial clutter was significantly mitigated even when only the MSAs were used, a remnant of the aerial clutter, which had a peak of 70.1 dB at the Doppler velocity of $-4.58$ m/s$^1$, was found. The presence of this remnant in the Doppler spectrum indicates that the greater perturbation of the time series shown in Fig. 14(b) was caused by the remnant of the aerial clutter. Because the peak of the clear-air echo was 74.8 dB at the Doppler velocity of 1.35 m/s$^1$, the remnant is comparable to the clear-air echo. Such a remnant of the aerial clutter makes distinguishing the clear-air echo difficult.

F. Main Lobe of Main Antenna

Effects of the time series weighting on the antenna pattern are presented. Because there were many objects on the ground that can scatter radio waves from/to LQ-13 (e.g., towers, power lines, and buildings), it is impossible to reproduce the antenna pattern at low elevation angles where the source of the aerial clutter existed. Therefore, only the main lobe of the main antenna, which was directed near the zenith and could affect the measurement accuracy of wind velocity, is discussed. Fig. 16(a) shows an antenna pattern in reception when the signals collected by the MSAs were equally weighted (i.e., an antenna pattern when the DCMP method was not applied). The zenith angle ranges from 0$^\circ$ to 50$^\circ$. Equal weighting was also used in producing the time series shown in Fig. 4(a) and the Doppler spectrum shown in Fig. 5(a). The sidelobes are hexagonally located due to the disposition of the MSAs [see Fig. 2]. Fig. 16(b) shows an antenna pattern when the signals collected by the MSAs were weighted by the $w_{MSA}$ elements computed using the time series collected by both the MSAs and CSAs (for the values of the $w_{MSA}$ elements...
in the complex conjugate form, see Fig. 9). In addition to the position of the MSAs, \( w_{\text{MSA}} \) was also a factor that determined the array factor. The sidelobe pattern after the weighting by \( w_{\text{MSA}} \) did not cause the detection of clutter other than the aerial clutter [see Fig. 5(b)]. In this case, the main lobe shape was kept well even after the weighting. Fig. 16(c) shows an antenna pattern when signals from the MSAs were weighted by the \( w_{\text{MSA}} \) elements computed using the time series collected only by the MSAs (for the values of the \( w_{\text{MSA}} \) elements in the complex conjugate form, see Fig. 13). The shape of the main lobe became elliptical and extended from the west-southwest to the east-northeast. The comparison of the antenna pattern in Fig. 16(b) with that in Fig. 16(c) indicates that the CSAs contributed to decreasing the distortion of the main lobe.

When only the MSAs were used, \(|w|^2\), which was equal to \(|w_{\text{MSA}}|^2\) in this case, was 1.145 [see Fig. 14(b)]. It was only \( \sim 5\% \) greater than that when both the MSAs and CSAs were used \([= 1.091, \text{see Fig. 11(a)}]\). However, when only the MSAs were used, the distortion of the main lobe was significant [Fig. 16(c)], and the remnant of the aerial clutter appeared [see Fig. 15(b)]. These results indicate that aerial clutter mitigation using both MSAs and CSAs has an advantage over the clutter mitigation using only MSAs. Note that the use of CSAs is also useful for mitigating ground clutter \([17], [21], [22]\).

**G. Another Case**

In this section, another case study at 09:30:27 on September 18, 2020, is presented. Fig. 17(a) shows a Doppler spectrum of the time series produced by summing up the time series collected by the MSAs with equal weight (i.e., the Doppler spectrum when the DCMP method was not applied). The antenna beam direction and the range were eastward and 1.2 km, respectively. In the Doppler spectrum, in addition to the clear-air echo observed in the Doppler velocity range of approximately \(-4\)–\(-0\) ms\(^{-1}\), the aerial clutter that had a peak of 98.5 dB at 15.4 ms\(^{-1}\) was detected. At that time, a visual examination observed a small jet plane that flew at a low altitude. Because no other flying objects were found, the small jet plane was the most plausible source of the aerial clutter. Fig. 17(b) shows a Doppler spectrum when the DCMP method was applied using both the MSAs and CSAs. \(|w|^2\), \(|w_{\text{MSA}}|^2\), and \(|w_{\text{CSA}}|^2\) of the weight vector were 2.584, 2.413, and 0.171, respectively. By applying the DCMP method, the aerial clutter was mitigated down to the level comparable to the noise intensity.

Fig. 18(b) shows a Doppler spectrum when the DCMP method was applied using only the MSAs. \(|w|^2\), which was equal to \(|w_{\text{MSA}}|^2\) in this case, was 2.810. When only the MSAs were used, although the aerial clutter was considerably mitigated, a remnant of the aerial clutter was found in the Doppler velocity range of \(\sim 12\)–\(18\) ms\(^{-1}\). The remnant had a peak of 74.3 dB at 15.9 ms\(^{-1}\). The results shown in Figs. 17 and 18 indicate that the source of the aerial clutter flew at a low elevation angle where the sensitivity of the CSAs was sufficient to mitigate the aerial clutter well and that the CSAs contributed to mitigating the aerial clutter as the case at 17:04:37 on October 1, 2020 [see Figs. 5 and 15].
To examine whether or not the aerial clutter mitigation worked continuously, 29 Doppler spectra measured from 09:30:17 to 09:31:17 on September 18, 2020, were averaged in time. The thin curved line in Fig. 19 is the averaged Doppler spectrum when the DCMP method was not applied. In the Doppler spectrum, in addition to the clear-air echo with a peak at $-1.89 \text{ m s}^{-1}$, the peaks caused by the aerial clutter were observed in the Doppler spectrum. The aerial clutter scattered in the averaged Doppler spectrum because its source moved with time. Note that the Doppler spectrum shown by the thick curved line in Fig. 17(a), which was measured at 09:30:27, was embedded in the 29 Doppler spectra used to produce the averaged Doppler spectrum when the DCMP method was not applied. The thick curved line in Fig. 19 is the averaged Doppler spectrum when the DCMP method was applied. The power of the aerial clutter in the averaged Doppler spectrum decreased to the level buried in the noise intensity because the aerial clutter mitigation worked continuously in time as that measured from 17:04:12 to 17:05:11 on October 1, 2020 [see Fig. 12]. Note that the Doppler spectrum shown in Fig. 17(b), which was measured at 09:30:27, was embedded in the 29 Doppler spectra used to produce the averaged Doppler spectrum when the DCMP method was applied.

In the averaged Doppler spectrum shown in Fig. 19, the clear-air echo was clearly distinguished after the DCMP method was applied. On the other hand, the peak of the clear-air echo decreased by 8.4 dB (from 86.5 to 78.1 dB) and the noise power increase of $\sim 6.3$ dB (from $\sim 54.1$ to $\sim 60.4$ dB) was observed. Fig. 20 shows the average of the ten Doppler spectra measured from 09:31:20 to 09:31:41 on September 18, 2020. The antenna beam direction and range were the same as those of the Doppler spectrum shown in Figs. 17–19, and no aerial clutters were found during the period. Although the clear-air echo was clearly distinguished after the DCMP method was applied, the peak of the clear-air echo decreased by 7.8 dB (from 87.5 to 79.7 dB) and the noise level increased by $\sim 6.9$ dB (from $\sim 53.9$ to $\sim 60.8$ dB) by applying the DCMP method. These results indicate that the power decrease of the clear-air echo and the noise power increase occurred regardless of the presence of the aerial clutter. The minimization of the output power by the DCMP method explains the power decrease of the clear-air echo and the noise power increase [18].

In the cases shown in Figs. 19 and 20, the DCMP method worked so that the power decrease of the clear-air echo contributed more than the noise power increase in minimizing the output power. Both the power decrease of the clear-air...
Fig. 19. Same as Fig. 12 except that Doppler spectra used in the averaging were collected by the eastward antenna beam from 09:30:17 to 09:31:17 on September 18, 2020. The range was 1.2 km. Each of the 29 Doppler spectra used in producing the averaged Doppler spectrum shown by the thick curved line was computed from the weighted sum of the time series collected by the MSAs and CSAs. See text for more details.

Echo and the noise power increase cause the decrease in SNR, and the decrease in SNR is the tradeoff of clutter mitigation by using the DCMP method when the power of the clear-air echo is significant compared with the total received power. Note that because the SNR decrease is evident only when the power of the clear-air echo is significant compared with the total received power, the SNR decrease was not evident in the case measured from 17:03:40 to 17:03:52 on October 1, 2020 [see Fig. 6].

Effects of the time series weighting on the antenna pattern in the case at 09:30:27 on September 18, 2020, are presented. Fig. 21(a) shows an antenna pattern in reception when signals collected by the MSAs were equally weighted. Fig. 21(b) shows an antenna pattern when the signals collected by the MSAs were weighted by the $w_{MSA}$ elements computed using the time series collected by both the MSAs and CSAs, and Fig. 21(c) shows an antenna pattern when the signals collected by the MSAs were weighted by the $w_{MSA}$ elements computed using the time series collected only by the MSAs. Although the antenna beam pattern was significantly changed by the DCMP method, the clear-air echo was clearly distinguished even after the DCMP method was applied [see Figs. 17 and 18]. The clear-air echo was also clearly distinguished in the averaged Doppler spectra shown in Figs. 19 and 20 because the directional constraint of the DCMP worked to retain the Doppler velocity information in the desired direction (i.e., the beam direction of the main antenna) and because the output power minimization by the DCMP controlled the antenna pattern so that the contribution of echoes from undesired directions was minimized. Therefore, in the case that the DCMP method using both the MSAs and CSAs mitigated the aerial clutter well, the contribution of echoes from undesired directions was not significant compared with the noise power increase [see Figs. 17 and 19]. Although the information on the Doppler velocity of the clear-air echo was retained, caution is necessary in interpreting the echo power and the spectrum width of the clear-air echo because the DCMP method significantly changed the main lobe. Other than the DCMP method, signal processing methods for ACS have been proposed [17], [18], [21]. Investigation on ACS using the signal processing methods other than the DCMP method will be carried out in the future.
IV. CONCLUSION

In this work, case studies of aerial clutter mitigation were presented by using the measurement results obtained by the 1.3-GHz WPR referred to as LQ-13. LQ-13 has 13 SAs of the main antenna (MSAs), and 11 SAs for detecting clutters from low elevation angles (CSAs) were installed so that they covered most of the horizontal directions and the horizontal and vertical polarizations [Figs. 1 and 2]. A case study at 17:04:37 on October 1, 2020, was presented in detail. The time series collected by the MSAs and CSAs were weighted by using the DCMP method so that they worked together to mitigate the aerial clutter [Figs. 7–11]. The aerial clutter that spread over the Doppler spectrum was mitigated by the DCMP method, and the clear-air echo whose peak was around 24.0 dB less than that of the aerial clutter was successfully detected [Fig. 5]. When only the MSAs were used in the DCMP method, the remnant of the aerial clutter appeared in the Doppler spectrum [Fig. 15]. Moreover, the distortion of the main lobe was more significant than that when both the MSAs and CSAs were used in the DCMP method [Fig. 16].

Another case study at 09:30:27 on September 18, 2020, also showed that the aerial clutter was mitigated well by the DCMP method using both the MSAs and CSAs [see Figs. 17 and 19]. In this case, because the power of the clear-air echo was significant compared with the total received power, the antenna beam pattern significantly changed due to the output power minimization by the DCMP method [Fig. 21]. Although the information on the Doppler velocity of the clear-air echo was retained after the DCMP method was applied, caution is necessary in interpreting the echo power and the spectrum width of the clear-air echo because the antenna beam pattern was changed significantly by the DCMP method. The decrease in SNR is the tradeoff of ACS when the power of the clear-air echo is significant compared with the total received power [Figs. 19 and 20]. Investigation on ACS using the signal processing methods other than the DCMP method will be carried out in the future.

Results obtained using the MSAs and CSAs of LQ-13 showed that multiple scattering caused by scatterers other than the clutter source and movement of the clutter source can affect the characteristics of a clutter from a low elevation angle [Figs. 7–10]. Therefore, when SAs dedicated to detecting undesired signals from the sidelobes of the main antenna (i.e., SAs to reject undesired signals from the sidelobes of the main antenna, hereafter SSAs) are used in an adaptive array system, it is suggested that the following should be considered so that SSAs can reproduce the characteristics of undesired signals detected by the sidelobes of the main antenna: 1) the SSA configuration that can measure both horizontal and vertical polarizations and 2) using directional antennas as SSAs so that undesired signals from different directions can be separated. Because examples of signal processing using the adaptive array technique are not abundant for radars used to measure the properties of the atmosphere, this study provides practical information on how an adaptive array works in rejecting undesired signals.

As shown in this study, ACS is useful for mitigating clutter that cannot be suppressed well by other means. However, ACS can mitigate clutter well only when ACS sufficiently decreases the sidelobe level in the arrival direction of clutter to reduce the power of clutter comparable to or below the noise power. Sidelobe control by ACS has limitations due to the radiation pattern and the position of SAs, and clutters detected by the main lobe of the main antenna cannot be mitigated well due to the directional constraint. QC to remove undesired signals from Doppler spectra is a means to remove remnants of clutters after ACS is applied. Even when ACS cannot mitigate all the clutters sufficiently, clutter mitigation by ACS can contribute to enhancing the performance of QC to remove undesired signals from Doppler spectra. A study to evaluate the combination of ACS and QC at stages later than ACS will be carried out in the future.

REFERENCES

[1] S. Fukao, “Recent advances in atmospheric radar study,” J. Meteorol. Soc. Japan., vol. 85B, pp. 215–239, Jul. 2007, doi: 10.2151/jmsj.85B.215.
[2] W. K. Hocking, “A review of mesosphere–stratosphere–troposphere (MST) radar developments and studies, circa 1997–2008,” J. Atmos. Solar-Terrestrial Phys., vol. 73, no. 9, pp. 848–882, Jun. 2011, doi: 10.1016/j.jastp.2010.12.009.
[3] S. G. Benjamin, B. E. Schwartz, E. J. Szoke, and S. E. Koch, “The value of wind profiler data in US weather forecasting,” Bull. Amer. Meteorol. Soc., vol. 85, no. 12, pp. 1871–1886, Dec. 2004, doi: 10.1175/BAMS-85-12-1871.
[4] A. J. Illingworth et al., “Exploiting existing ground-based remote sensing networks to improve high-resolution weather forecasts,” Bull. Amer. Meteorol. Soc., vol. 96, no. 12, pp. 2107–2125, Dec. 2015, doi: 10.1175/BAMS-D-13-00283.1.
[5] M. Ishihara, Y. Kato, T. Abo, K. Kobayashi, and Y. Izumiwaka, “Characteristics and performance of the operational wind profiler network of the Japan meteorological agency,” J. Meteorol. Soc. Japan., vol. 84, no. 6, pp. 1085–1096, Dec. 2006, doi: 10.2151/jmsj.84.1085.
[6] B. K. Dolman, J. M. Reid, and C. Tingwell, “Stratospheric tropospheric wind profiling radars in the Australian network,” Earth, Planets Space, vol. 70, no. 1, pp. 1–10, Oct. 2018, doi: 10.1186/s40623-018-0944-z.
[7] B. Liu, J. Guo, W. Gong, L. Shi, Y. Zhang, and Y. Ma, “Characteristics and performance of wind profilers as observed by the wind radar wind profiler network of China,” Atmos. Meas. Tech., vol. 13, no. 8, pp. 4589–4600, Aug. 2020, doi: 10.5194/amt-13-4589-2020.
[8] V. Lehmann and G. Teschke, “Advanced intermittent clutter filtering for radar wind profiler: Signal separation through a Gabor frame expansion and its statistics,” Ann. Geophys., vol. 26, no. 4, pp. 759–783, May 2008, doi: 10.5194/angeo-26-759-2008.
[9] T. L. Wilfong, D. A. Merritt, R. J. Latatis, B. L. Weber, D. B. Wuertz, and R. G. Strauch, “Optimal generation of radar wind profiler spectra,” J. Atmos. Ocean. Technol., vol. 16, no. 6, pp. 723–733, Jun. 1999, doi: 10.1175/1520-0426(1999)016<0723:OGORWP>2.0.CO;2.
[10] D. A. Merritt, “A statistical averaging method for wind profiler Doppler spectra,” J. Atmos. Ocean. Technol., vol. 12, no. 5, pp. 985–995, Oct. 1995, doi: 10.1175/1520-0426(1995)012<0985:ASAMFW>2.0.CO;2.
[11] E. E. Clothiaux, R. S. Perc, D. W. Thomson, T. P. Ackerman, and S. R. Williams, “A first-guess feature-based algorithm for estimating wind speed in clear-air Doppler radar spectra,” J. Atmos. Ocean. Technol., vol. 11, no. 4, pp. 888–908, Aug. 1994, doi: 10.1175/1520-0426(1994)011<0888:AFBASA>2.0.CO;2.
[12] L. B. Cornman, R. K. Goodrich, C. S. Morse, and W. L. Ecklund, “A fuzzy logic method for improved moment estimation from Doppler spectra,” J. Atmos. Ocean. Technol., vol. 15, no. 6, pp. 1287–1305, Dec. 1998, doi: 10.1175/1520-0426(1998)015<1287:AFMGME>2.0.CO;2.
[13] B. L. Weber, D. B. Wuerzt, D. C. Welsh, and R. McPeek, “Quality controls for profiler measurements of winds and RASS temperatures,” J. Atmos. Oceanic Technol., vol. 10, no. 4, pp. 452–464, Aug. 1993, doi: 10.1175/1520-0426(1993)010<0452:QCPRMO>2.0.CO;2.

[14] “Experience of the Japan Meteorological Agency with the operation of wind profilers,” Instrum. Observing Methods Rep., World Meteorological Org., Geneva, Switzerland, Tech. Rep., 2012, pp. 20–35, no. 110.

[15] B. L. Cheong, M. W. Hoffman, R. D. Palmer, S. J. Frasier, and F. J. López-Dekker, “Phased-array design for biological clutter rejection: Simulation and experimental validation,” J. Atmos. Ocean. Technol., vol. 23, no. 4, pp. 585–598, Apr. 2006, doi: 10.1175/JTECH1867.1.

[16] H. Hashiguchi, T. Manjo, and M. Yamamoto, “Development of middle and upper atmosphere radar real-time processing system with adaptive clutter rejection,” Radio Sci., vol. 53, no. 1, pp. 83–92, Jan. 2018, doi: 10.1002/2017RS006417.

[17] T. Hashimoto, K. Nishimura, and T. Sato, “Adaptive sidelobe cancellation technique for atmospheric radars containing arrays with nonuniform gain,” IEICE Trans. Commun., vol. E99-B, no. 12, pp. 2583–2591, Dec. 2016, doi: 10.1587/transcom.2016EBP9047.

[18] T. Hashimoto, K. Nishimura, M. Tsutsumi, K. Sato, and T. Sato, “A user parameter-free diagonal-loading scheme for clutter rejection on radar wind profilers,” J. Atmos. Ocean. Technol., vol. 34, no. 5, pp. 1139–1153, May 2017, doi: 10.1175/JTECH-D-16-0058.1.

[19] T. Hashimoto, K. Nishimura, M. Tsutsumi, and T. Sato, “Meteor trail echo rejection in atmospheric phased array radars using adaptive sidelobe cancellation,” J. Atmos. Ocean. Technol., vol. 31, no. 12, pp. 2749–2757, Dec. 2014, doi: 10.1175/JTECH-D-14-00035.1.

[20] W. K. Hocking, J. Röttger, R. D. Palmer, T. Sato, and P. B. Chilson, Atmospheric Radar. Cambridge, U.K.: Cambridge Univ. Press, 2016, pp. 301–305, doi: 10.1017/9781316556115.

[21] K. Kanio, K. Nishimura, and T. Sato, “Adaptive sidelobe control for clutter rejection of atmospheric radars,” Annales Geophysicae, vol. 22, no. 11, pp. 4005–4012, Nov. 2004, doi: 10.5194/angeo-22-4005-2004.

[22] M. K. Yamamoto, S. Kawamura, and K. Nishimura, “Facility implementation of adaptive clutter suppression to an existing wind profiler radar: First result,” IEICE Commun. Exp., vol. 6, no. 9, pp. 513–518, Sep. 2017, doi: 10.1587/comex.2017XBL0075.

[23] E. Spano and O. Ghebrebrhan, “Sequences of complementary codes for the optimum decoding of truncated ranges and high sidelobe suppression factors for ST/MST radar systems,” IEEE Trans. Geosci. Remote Sens., vol. 34, no. 2, pp. 330–345, Mar. 1996, doi: 10.1109/36.485311.

[24] J. Capon, “High-resolution frequency-wavenumber spectrum analysis,” Proc. IEEE, vol. 57, no. 8, pp. 1408–1418, Aug. 1969, doi: 10.1109/PROC.1969.7278.

[25] R. D. Palmer, S. Gopalam, T.-Y. Yu, and S. Fukao, “Coherent radar imaging using Capon’s method,” Radio Sci., vol. 33, no. 6, pp. 1585–1598, Nov. 1998, doi: 10.1029/98RS02200.

[26] K. Takao, M. Fujita, and T. Nishi, “An adaptive antenna array under directional constraint,” IEEE Trans. Antennas Propag., vol. AP-24, no. 5, pp. 662–669, Sep. 1976, doi: 10.1109/TAP.1976.1141411.