Development of a digital receiver for range imaging atmospheric radar

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Abstract

In this paper, we describe a new digital receiver developed for a 1.3-GHz range imaging atmospheric radar. The digital receiver comprises a general-purpose software-defined radio receiver referred to as the Universal Software Radio Peripheral 2 (USRP2) and a commercial personal computer (PC). The receiver is designed to collect received signals at an intermediate frequency (IF) of 130 MHz with a sample rate of 10 MS s⁻¹. The USRP2 digitizes IF received signals, produces IQ time series, and then transfers the IQ time series to the PC through Gigabit Ethernet. The PC receives the IQ time series, performs range sampling, carries out filtering in the range direction, decodes the phase-modulated received signals, integrates the received signals in time, and finally saves the processed data to the hard disk drive (HDD). Because only sequential data transfer from the USRP2 to the PC is available,

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the range sampling is triggered by transmitted pulses leaked to the receiver. For range imaging, the digital receiver performs real-time signal processing for each of the time series collected at different frequencies. Further, the receiver is able to decode phase-modulated oversampled signals. Because the program code for real-time signal processing is written in a popular programming language (C++) and widely used libraries, the signal processing is easy to implement, reconfigure, and reuse. From radar experiments using a 1- μ s subpulse width and 1-MHz frequency span (i.e., 2-MHz frequency bandwidth), we demonstrate that range imaging in combination with oversampling, which was implemented for the first time by the digital receiver, is able to resolve the fine-scale structure of turbulence with a vertical scale as small as 100 m or finer.

Keywords: atmospheric radar, digital receiver, software-defined radio technique, radar imaging, oversampling, turbulence

1. Introduction

Atmospheric radar, also referred to as wind profiler radar (WPR), is a useful means of measuring vertical profiles of vertical and horizontal wind velocities in the clear air. WPR can measure wind profiles up to altitudes of several kilometers or higher, and the temporal and vertical resolution of the wind profiles can reach less than several minutes and several hundred meters, respectively (Fukao, 2007; Hocking, 2011). In order to improve the accuracy of numerical weather prediction, nationwide atmospheric radar networks monitor wind distributions in countries such as the United States and Japan (Ishihara, 2006; Stanley et al., 2004).

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9 A major source of clear-air echo for WPR is atmospheric turbulence that
10 produces perturbations of the radio refractive index at the Bragg scale (i.e.,
11 half the radar wavelength). Therefore techniques for retrieving turbulence
12 parameters (e.g., dissipation rate, diffusivity) from the clear-air echo have
13 been developed (Wilson, 2004). However, the range resolution determined
14 by their transmitted pulse width is typically greater than 100 m, and this
15 range resolution is often not sufficient for resolving the vertical structure of
16 turbulence. The limitation in the range resolution is a major obstacle to im-
17 proving turbulence parameter retrieval. Range imaging (RIM), which is also
18 referred to as frequency domain interferometric imaging (FII), is a technique
19 that improves the range resolution down to several tens of meters by using
20 frequency diversity and adaptive signal processing (Luce et al., 2001; Palmer
21 et al., 1999; Yamamoto, 2012). Measurements using 50-MHz atmospheric
22 radars have demonstrated that RIM is useful for resolving turbulence and
23 wind perturbations triggered by Kelvin–Helmholtz instability (Mega et al.
24 2010; Luce et al., 2010).

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40 Clutter from the ground and flying objects (aircrafts, birds, insects) de-
41 grade the data quality of atmospheric radars (e.g., Wilczak et al., 1995).
42 Therefore clutter must be mitigated as much possible in order to improve
43 the accuracy of wind and turbulence measurement by atmospheric radars.
44 Though fences are used for mitigating clutter, they do not always suppress
45 clutter sufficiently. Adaptive clutter rejection, which controls side lobes using
46 multiple receivers and adaptive signal processing, is a promising technique
47 that suppresses clutter effectively (Cheong et al., 2006; Kamio et al., 2004;
48 Yamamoto, 2012). Yu et al. (2010) proposed RIM with adaptive clutter
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suppression by using both multiple receivers and multiple frequencies.

However, there are difficulties in improving the measurement accuracy of RIM and implementing adaptive clutter rejection. In order to improve the range resolution, RIM determines subgates within a sample volume in the range direction using a steering vector. RIM performs adaptive signal processing at every subgate to produce time series with high range resolution. When received signals are sampled with an interval that matches the transmitted pulse width, the received signal intensity significantly decreases at the subgates near the edge of the sample volume in the range direction (see Figure 1a). This decrease in the received signal intensity is referred to as the range-weighting effect, and can significantly degrade the accuracy of RIM (Chen and Zecha, 2009). Oversampling (OS) in the range direction, which samples received signals with range intervals smaller than that determined by the transmitted pulse width, overcomes this difficulty. In some cases OS was done by shifting sample points within successive sweeps. However, in the paper, we define OS as the sampling of all the received signals in the range direction within one transmission and reception. Because OS overlaps the sample volumes in the range direction, it is capable of mitigating the range-weighting effect (see Figure 1b). Though OS is useful for RIM, most atmospheric radars do not have the capability of OS. OS was also proposed for improving the range resolution of weather radar through adaptive processing (Yu et al., 2006). In this study, by implementing a new digital receiver on a 1.3-GHz RIM WPR, we prove that OS is useful for unambiguous RIM measurement in the range direction.

Further, the high hardware and development costs for receivers hinder

easy implementation of adaptive clutter rejection. Real-time digital signal processing is one of the major factors that increase the cost. Currently, many radars perform real-time digital signal processing using digital boards that have field programmable gate array (FPGA) and/or digital signal processor (DSP) onboard. Such digital boards requires high hardware cost. Further, software development for the boards is also expensive because it requires expertise in FPGA and DSP. It must be emphasized that because the expertise of vendors varies and the specifications of FPGAs and DSPs change, source code developed for FPGAs and DSPs is difficult to re-use. Therefore software development using popular programming languages and widely used libraries is necessary to ensure the reusability of source code for digital receivers. In conclusion, a new digital receiver that has both low purchase and development costs and a high sample rate is desirable for implementing OS and multiple receivers for atmospheric radars.

In order to overcome the difficulties of improving RIM capability and implementing adaptive clutter rejection, we have been developing a new radar digital receiver (hereafter the digital receiver). The digital receiver uses a general-purpose software-defined radio receiver referred to as Universal Software Radio Peripheral 2 (USRP2) and a commercial personal computer (PC). The purchase price of USRP2 is less than USD 2000. Further, because the program code of real-time signal processing was produced using the C++ language (i.e., a popular programming language) and widely used libraries, the real-time signal processing performed by the digital receiver is easy to test, reconfigure, and reuse. Further, the software development environment is free of charge. These advantages of using the C++ language and widely

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9 used libraries can significantly decrease labor costs and the time for software
10 development not only of the digital receiver for the RIM WPR but also of
11 digital receivers to be developed in future.
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15 In this study, we report the current advantages of the digital receiver. Up
16 to now we have succeeded in implementing RIM and OS capabilities in the
17 1.3-GHz RIM WPR using the digital receiver. In section 2, the hardware
18 and software configuration of the digital receiver are described. In section
19 3, we demonstrate that the digital receiver, which has the capability of per-
20 forming the real-time signal processing required for RIM and OS, is useful
21 for measuring fine-scale turbulence with a vertical scale as small as 100 m or
22 finer. Section 4 summarizes the paper.
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31 **2. Receiver system**

32 *2.1. Requirements and receiver components*

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35 The requirements for the development of the digital receiver are the fol-
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- 41 (1) Low hardware purchase cost.
- 42 (2) Intermediate frequency (IF) signal sampling which reduces analog cir-
43 cuits.
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- 45 (3) High sample rate sufficient for OS.
- 46 (4) Ease of implementation of real-time signal processing.
- 47 (5) Capability of synchronized data collection using multiple receivers.
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53 The USRP2, which is a software-defined radio receiver supplied by Ettus
54 Research, satisfies these requirements for the following reasons:
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- (1) The price of the USRP2 is less than USD 2,000.
- (2) The USRP2 is capable of IF sampling because its basic daughter board (named BasicRX) can sample data with a frequency up to 250 MHz.
- (3) The USRP2 performs digital phase detection to produce complex-valued time series signals (IQ time series) with a maximum sample rate of 25 megasamples per second (MS s^{-1}).
- (4) The USRP2 is controlled from the PC using a Universal Software Radio Peripheral hardware driver (UHD) for the C++ language and development of signal processing software using the C++ language enables easy implementation of real-time signal processing (i.e., range sampling, filtering in the range direction, decoding of phase-modulated received signals, coherent integration, and data storage to the hard disk drive (HDD)).
- (5) Clocks of multiple USRP2s can be synchronized using a 1 pulse per second (pps) input.

Therefore we use a combination of the USRP2 and the PC as the digital receiver. However, in this study, we focus on the capability of the digital receiver to carry out the fast real-time signal processing necessary for RIM and OS. Synchronized data collection using multiple USRP2s is under development, and achievements obtained by using multiple USRP2s will be reported in subsequent studies.

2.2. Components of the range imaging wind profiler radar and the digital receiver

Figure 2 shows a system block diagram of the RIM WPR with the digital receiver. The RIM WPR is developed based on the 1.3-GHz WPR referred

to as an LQ-7 (Imai et al., 2007). Figure 3 shows a picture of an LQ-7. It has a phased array antenna composed of seven Luneberg lenses (Sullivan, 2000) with a diameter of 800 mm. The antenna gain is greater than 30 dBi. Each lens has five feeds directed toward the vertical and four oblique directions (north, east, south, and west) with a zenith angle of 14.2° , respectively. The beam direction is electronically switched. Below each lens, a transmission/reception switch and a radio frequency (RF) receiver unit including a low-noise amplifier (LNA) are installed. In the outdoor unit, an RF transmitter comprising a high-power amplifier (HPA) and peripherals, a unit for frequency conversion between RF and IF, and IF units are installed. Because each lens radiates 400-W radio waves, the total peak output power of an LQ-7 is 2.8 kW. The phased array antenna and outdoor unit of the LQ-7 are used for the RIM WPR. In order to switch the frequency for every transmission, five local oscillators, having frequencies of 1227.00, 1227.25, 1227.50, 1227.75, and 1228.00 MHz, are installed. Therefore five RFs of 1357.00, 1357.25, 1357.50, 1357.75, and 1358.00 MHz are available for the RIM WPR.

The signal processing of the LQ-7 does not include the function of IF sampling. Further, the signal processing unit of an LQ-7 does not have the function necessary for real-time processing of RIM (i.e., decoding and integrating each of the received signals collected by the different frequencies) and OS. Therefore we developed a new digital receiver for the RIM WPR that comprises an IF amplifier and filter unit, a USRP2, and a PC. The received IF signals collected from each of the seven antenna elements are synthesized by the combiner. The synthesized signals are amplified, filtered with 3-MHz

bandwidth, and then inputted to the USRP2.

Figure 4 shows a view of the USRP2 interface. As a reference signal, the 10-MHz signal from the GPS receiver is used. In order to synchronize the IF signal produced inside the USRP2, as well as that produced by the analog transmitter/receiver unit, the 10-MHz reference signal is branched into the REF CLOCK terminal and the clock source of the IF oscillator. From the RF1 terminal, the USRP2 collects IF signals, digitizes them, and produces IQ time series by phase detection. From the GB ETHERNET interface, the IQ time series are transferred to the PC through Gigabit Ethernet. The SD MEMORY interface is used to configure the firmware of the USRP2. The firmware needs to be updated when the UHD version is changed. Note that the RF2 and PPS IN terminals are not used for the current receiver configuration. The resolution and maximum input voltage of the analog-to-digital converter of the USRP2 are 14 bits and 2 V peak-to-peak, respectively. The IF amplifier and filter unit were designed to match the input level of the USRP2. The dynamic range of the USRP2 was sufficient for the dynamic range of the LQ-7 (60 dB). Currently the USRP2 is replaced by the newer version (USRP N series). We confirmed that the USRP N210 is also available for the digital receiver (Ettus Research, 2012).

The PC performs real-time signal processing and stores the processed data. It uses an Intel Core 2 Quad Q9450 central processing unit (2.66-GHz operational frequency and 12-MB cache), four PC2-6400 (DDR2-800) memory boards with 2-GB capacity (i.e., 8-GB memory in total), and an ASUS P5K-E motherboard. The PC uses the Ubuntu 10.04 LTS operating system. Ubuntu is one of the major Linux distributions. Software developed

for the digital receiver was written in the C++ language and built using the g++ 4.4.3 compiler, Boost 1.40.0, and UHD 003.003.000. Boost is a free peer-reviewed library for C++, and its website (<http://www.boost.org/>) describes the details. See http://files.ettus.com/uhd_docs/manual/html/ for details of UHD. UHD is also available free of charge. Therefore the software development environment is cost free. The operation system is installed in an internal HDD with 1-TB capacity and 7200 rpm speed, and processed data are stored in the external HDD connected to the PC through the external Serial Advanced Technology Attachment (eSATA) interface.

In order to maximize the signal processing speed by compiler optimization, all the measurement parameters that determine data collection (inter-pulse period, number of samplings in the range direction, transmitted pulse pattern, and so on) are hard-coded as constant values in the program. Because the timing signals used to control the LQ-7 are generated by the timing signal generator of the LQ-7, the same measurement parameters defined in the digital receiver are also assigned to the timing signal generator of the LQ-7. Though the software needs to be rebuilt when the measurement parameters are changed, it takes only a few tens of seconds and hence is not an obstacle to carry out measurements.

2.3. Signal processing

2.3.1. Signal flow

Figure 5 shows the signal flow of the digital receiver. The USRP2 collects received IF signals and produces IQ time series. Then the IQ time series are transferred to the PC. In order to collect the IQ time series and perform other real time signal processing simultaneously, the PC uses multithread-

ing composed of Data Taking and Signal Processing threads. Data Taking collects the IQ time series and performs range sampling. Signal Processing executes filtering in the range direction, decodes phase-modulated received signals, performs coherent integration, and finally saves the processed data in the external HDD. Figure 6 shows a schematic diagram of the thread handling. Boost is used for the thread handling. At the start of data sampling, Data Taking creates Signal Processing. After its creation, Signal Processing waits for the start request from Data Taking. In order to avoid a memory conflict between Data Taking and Signal Processing, the shared memory is divided into two parts (i.e., double buffered; see Figure 5). When the time length of ranging data reaches the magnitude necessary for performing filtering, decoding, and coherent integration, Data Taking requests Signal Processing to obtain the ranging data from the shared memory region that Data Taking accessed (i.e., shared memory #1). After the request, Data Taking collects data from the USRP2, performs range sampling, and stores the sampled data in the shared memory region that Signal Processing does not access (i.e., Data Taking uses shared memory #2). In the subsequent part of the section, the details of signal processing in the USRP2 and the PC are described.

2.3.2. Production of IQ time series

The USRP2 digitizes the 130-MHz IF signals with a sample rate of 100 MS s⁻¹ and a resolution of 14 bits. In order to sample IF signals with a frequency higher than its sample rate (i.e., 100 MS s⁻¹), the USRP2 performs downsampling with a frequency of 30 MHz (= 130 MHz - 100 MHz). The downsampling works with sufficient accuracy for the RIM WPR (later

shown in section 3). The USRP2 produces IQ time series by applying phase detection to the digitized signals. Though the USRP2 is able to produce IQ time series with a rate up to 25 MS s^{-1} , a rate of 10 MS s^{-1} is chosen by both considering the signal processing capability of the PC and the uncertainty in range sampling using the transmitted pulse leaked to the receiver (hereafter the leaked transmitted pulse). The range sampling details are explained in section 2.3.3. The IQ time series produced with a rate of 10 MS s^{-1} are transferred to the PC sequentially. The UHD uses User Datagram Protocol (UDP) for the data transfer and selects the data format of the IQ signals. For the digital receiver, the short integer format is used in order to reduce the amount of data transferred to the PC. Figure 7 shows the packet format used for the data transfer. Each packet contains 362 pairs of IQ signals, and the IQ signals are expressed in the short integer format with a length of 2 bytes. Packets are received by the PC at intervals of $36.2 \mu\text{s}$.

2.3.3. Range sampling

Data Taking collects the IQ time series sequentially transferred from the USRP2 and performs range sampling. The operation system sets the buffer memory for the data transfer from the USRP2 to the PC, and the size of the buffer memory is set to 200 MB by the `sysctl` command of the Linux operation system. In order to determine the start timing of the range sampling, a leaked transmitted pulse is used. Figure 8 shows an example of a leaked transmitted pulse detected by the digital receiver. Because the intensity of the leaked transmitted pulse is much greater than that of the receiver noise and returned signals, it is safe to determine the onset of transmission using the leaked transmitted pulse. The threshold for determining the onset is set

to 8×10^7 . Figure 9 explains the detection of the leaked transmitted pulse. In order to eliminate the false detection caused by impulse noise, the leaked transmitted pulse was verified at its onset, at the center of the first subpulse, and at the center of the last subpulse.

Because the USRP2 transfers IQ time series continuously with a fixed packet length (see Figure 7), the packets have three states;

- Neither the leaked transmitted pulse nor the signals to be sampled in the range direction are present in the packet (TX_WAIT).
- The leaked transmitted pulse needs be verified in the next packet sent to the PC (TX_VERIFY).
- The signals to be sampled are present in the current packet (RX_WRITE).

Figure 10 shows the state change diagram of Data Taking determined by the packet states. The state changes of Data Taking are defined as follows:

- (1) Data Taking finds neither the leaked transmitted pulse nor signals to be sampled in the current packet and hence tries to find a leaked transmitted pulse in the next packet.
- (2) Data Taking detects the signal increase, which can be caused by a leaked transmitted pulse, and verifies whether a leaked transmitted pulse is present in the next packet or not.
- (3) Data Taking judges that the signal increase found in the packet was impulse noise and hence tries to find a leaked transmitted pulse again.
- (4) Data Taking detects the end of the leaked transmitted pulse in the current packet and starts data sampling in the range direction.

- (5) Data Taking continues the data sampling in the next packet.
- (6) Data Taking completes the data sampling and tries to find a new leaked transmitted pulse.

The data sampled in the range direction are stored in the shared memory (see Figure 5). Because we use a sample rate of 10 MS s^{-1} , the range sampling can have an offset of 15 m. However, the offset is sufficiently small that it can be ignored compared with the range uncertainties caused by signal delays in the transmitter, receiver, and cables.

The RIM WPR measurements confirmed that fluctuations in the leaked transmitted pulses were negligibly small for the range sampling (shown in Figure 13).

2.3.4. Filtering in the range direction, decoding, time integration, and data storage

Using the data sampled in the range direction, Signal Processing performs digital filtering in the range direction to limit the frequency bandwidth of the sampled signals. The length and coefficients of the filter can be configured arbitrarily. After the filtering, Signal Processing decodes the phase-modulated signals. Because the receiver has the capability of data sampling with 15-m range spacing (i.e., a sample rate of 10 MS s^{-1}) at any reception time, the phase-modulated received signals collected at every transmission and reception have range intervals less than that determined by the transmitted pulse width. On the other hand, in order to decorrelate the phase-modulated received signals in the range direction, they must have range intervals equivalent to that determined by the transmitted subpulse

width. Therefore, interleaving is performed for the oversampled signals. Figure 11 shows a schematic diagram of the interleaving for the case of triple OS. Because decoding has to be done for signals with an interval equivalent to the transmitted subpulse width (e.g., $1\ \mu\text{s}$ or $150\ \text{m}$ for a $1\text{-}\mu\text{s}$ subpulse width), the received signals are interleaved into three parts each of which has an interval equivalent to the subpulse width. After the decoding, the interleaved signals #1~#3 are merged and sorted again to restore the original order in the range direction. The digital receiver is designed to decode any pulse patterns with binary phase (0° or 180°) and subpulse length. The subpulse width must be multiples of $0.1\ \mu\text{s}$ (e.g., $1.0\ \mu\text{s}$, $2.0\ \mu\text{s}$) because we use the fixed sampling rate of $10\ \text{MS s}^{-1}$. The subpulse width constraint can be solved by varying the sample rate of the USRP2, and this sample rate variation function will be implemented in the future.

The degree of OS is limited by the sample rate of the IQ time series (i.e., $10\ \text{MS s}^{-1}$). For the $1\text{-}\mu\text{s}$ subpulse width, 10 times, 5 times, double, and no OS can be performed. Reducing the degree of OS helps to both reduce the amount of data saved in the external HDD and extend the upper limit of the range coverage. We confirmed that the digital receiver works for the following measurement parameters: 10 times OS, 220 stored range gates, $65\text{-}\mu\text{s}$ interpulse period, $1\text{-}\mu\text{s}$ subpulse width, 8-bit pulse compression, five frequencies, and without range filtering. By using the updated PC (Dell Precision T7500 with Xeon E5620 central processing unit (2.40-GHz operational frequency and 12-MB cache), 12-GB memory comprising six 2-GB PC3-10600 (DDR3-1333) memory boards, and internal solid state drive with 256-GB capacity), we further confirmed that the digital receiver also works for the measurement

parameters: 10 times OS, 390 stored range gates, 100- μ s inter-pulse period, 2- μ s subpulse width, 8-bit pulse compression, five frequencies, and 35-point range filtering.

After the filtering and decoding, Signal Processing performs coherent integration to reduce the amount of data. Finally, Signal Processing stores the processed data in the external HDD, and then waits for the next start request from Data Taking.

It is noted that the synchronization between the digital receiver and the transmitter unit of the LQ-7 is ensured by using the leaked transmitted pulse. In addition to the ranging data, Data Taking transfers the sampled leaked transmitted pulse to Signal Processing through the shared memory. By verifying that the pulse pattern of the leaked transmitted pulse matches the pattern that is expected to be detected, Signal Processing confirms that Data Taking has correctly detected the onset of transmission (see Figure 9). The verification confirmed that the digital receiver is able to make continuous measurements over several days or longer.

3. Measurement results

In this section, we demonstrate that the OS capability of the digital receiver is useful for unambiguous RIM measurement in the range direction. Measurement using a 1- μ s subpulse width, the 8-bit optimum binary code of Spano and Ghebrebrhan (1996), five frequencies (1357.00, 1357.25, 1357.50, 1357.75, and 1358.00 MHz), 10-MS s⁻¹ sampling in the range direction, and the vertical beam was carried out at Shigaraki MU Observatory (34°51'N, 136°06'E, 385 m above the sea level).

From the viewpoint of the receiver capability, it is possible to improve range resolution by using short transmitted pulse widths down to $0.1 \mu\text{s}$. However, owing to radio-frequency licensing allocation, we need to achieve range resolution improvement with a limited frequency bandwidth. Therefore we used range imaging with a $1\text{-}\mu\text{s}$ subpulse width and five frequencies with a 1-MHz span. Owing to the range-weighting effect, RIM using the $1\text{-}\mu\text{s}$ subpulse width causes a significant decrease of the received signal intensity every 150-m range interval, and the decrease hinders the accurate detection of turbulence with a small vertical scale (see the explanation in section 1 and Figure 1a). In order to overcome the difficulty of the range-weighting effect, we used OS (see Figure 1b). In order to compare a case with OS and that without OS, data without OS were produced using the original sample data collected with OS. In the production of data without OS, the original data are taken every 10 range gates so that the range interval of data without OS matches the range resolution determined by the subpulse width of $1 \mu\text{s}$ (i.e., the range interval was changed to 150 m). RIM was carried out at subgates with 5-m range intervals. For adaptive signal processing of RIM, we used the Capon method (Capon, 1969). In order to achieve the best range resolution with minimal range sidelobe effects, the Capon method solves the constrained optimization problem in which the brightness (i.e., received signal intensity produced using RIM) is minimized with the constraint of constant gain at the desired subrange (Palmer et al., 1999; Yamamoto et al., 2012). Because the Capon method satisfies both high range resolution and simple calculation, it is widely used for adaptive signal processing of RIM.

Figures 12a and 12b show an example of the RIM Doppler spectra for

the case without OS and with OS, respectively. For the brightness profile without OS, the locations of the center of the range gates are 0.60, 0.75, 0.90, 1.05, and 1.20 km. It is clear that the Doppler spectra without OS show discontinuity at the edges of the sample volume (i.e., 0.675, 0.825, 0.975, and 1.125 km). On the other hand, because OS overlaps the sample volumes in the range direction, such discontinuity was not observed in the Doppler spectra with OS. Further, at the edges of the sample volume, the echo spectrum intensity without OS was 5–10 dB smaller than that with OS because of the range-weighting effect (Chen and Zecha, 2009; see Figures 1a and 1b). Figure 12c shows the height profiles of brightness for the case with and without OS. Compared with the brightness with OS, the brightness without OS decreased from 5 to 10 dB at the edges of the sample volume (i.e., 0.675, 0.825, 0.975, and 1.125 km). The decrease of brightness without OS is explained by the fact that the echo spectrum intensity without OS decreases at the edges of the sample volume (see Figure 12a). However, because the overlap of sample volumes by OS significantly mitigated the range-weighting effect, the effect was not evident in the brightness profile with OS (see Figures 1b and 12b).

The overlap of sample volumes by OS also contributes to the better estimation of the Doppler velocity. Owing to the range weight, scatterers closer to the range center contribute more to the brightness than those farther from it (see Figure 1a). Therefore the Doppler spectra calculated at subranges can be distorted. The distortion of the Doppler spectra can become significant at subranges near the edges of the sample volume, where the range weight rapidly decreases as the distance from the range center increases. The dis-

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tortion of the Doppler spectra explains the Doppler velocity discontinuity at some edges of the sample volume (0.825, 0.975, and 1.125 km) for the case without OS (Figure 12a). On the other hand, because RIM in combination with OS is able to overlap the sample volumes, it can use only the subgates near the range center at which Doppler spectra distortion due to the range-weighting effect is neglected. The results provide evidence that RIM in combination with OS achieves unambiguous RIM measurement in the range direction, and hence is useful for improving the accuracy of RIM measurement.

In order to demonstrate that RIM in combination with OS is useful for measuring fine-scale wind and turbulence structure, a measurement result around the top of the boundary layer is presented. Figure 13 shows a time range plot of brightness, vertical air velocity, and spectrum width from 09:20:00 to 09:40:00 on 8 July 2012. The spectrum width is defined by half-power full width in m s^{-1} . Signals with lower intensity than the noise level are not plotted. Note that the broadening effects in the spectrum width are not removed because horizontal wind measurement was not carried out. The vertical air velocity showed an oscillatory structure with a period of approximately 2 min at 1.3–1.5 km (Figure 13b), and the brightness layer around 1.3–1.4 km ascended (descended) in association with the upward (downward) air motion. Though the broadening effects in the spectrum width are not removed, it is clear that the spectrum width shows a marked contrast below and above 1.5 km; it is greater than 0.84 m s^{-1} below 1.5 km and less than 0.84 m s^{-1} above 1.5 km. Note that though some received signals were below the noise level, most had an intensity greater than the noise level. Further,

the spectrum width increased to 1.68 m s^{-1} or greater where the direction of the vertical air velocity changed from upward to downward (e.g., at 1.3–1.4 km around 09:22, 09:23, 09:29, 09:31, 09:33, and 09:37 and 1.2–1.4 km around 09:35). The enhancement occurred probably owing to the enhanced mixing at the interfaces between the upward and downward winds. It is stressed that because the vertical scale of the perturbation was as small as 100 m, its structure cannot be measured without RIM in combination with OS, which is able to measure wind and turbulence without the range-weighting effect. The development of the digital receiver is successful in showing that the OS function can be implemented with low hardware and development costs. Further details of the measurement results with the RIM WPR will be presented in separate studies.

The future plan to develop the digital receiver is described. When data collection using multiple receivers is performed, the onset timing of a leaked transmitted pulse is not synchronized among the receivers. Therefore, in order to realize data collection using multiple receivers, we are trying to input the transmission trigger signal to the USRP2 by using the RF2 terminal (see Figure 4). Because the method as shown in Figure 10 can be applied for robust detection of transmission trigger signals, future implementation of the range sampling function using transmission trigger signals is promising. Further, clocks of multiple USRP2s can be synchronized using a 1 pps input (see Figure 4). Based on these ideas, we continue the development of the digital receiver necessary for synchronized data collection using multiple receivers.

4. Summary

In this study, we described the digital receiver developed for the 1.3-GHz range imaging wind profiler radar (RIM WPR). The digital receiver uses a general-purpose software-defined radio receiver referred to as the USRP2 and a commercial personal computer (PC), and the purchase price of the USRP2 is less than USD 2000. Because the program code of real-time signal processing is written in the C++ language, the real-time signal processing executed by the digital receiver was easy to develop. Multithreading composed of Data Taking and Signal Processing threads are used to execute data collection from the USRP2 and other signal processing at the same time (Figures 5 and 6). The low hardware cost and ease of software development of real-time signal processing greatly contributed to the realization of the RIM WPR. Further, the high-speed sampling capability of the USRP2 was used for the 10-MS s^{-1} oversampling (OS) capability of the digital receiver. In order to decorrelate oversampled signals, interleaving is carried out so that the interleaved signals have a range interval equivalent to the subpulse width (see section 2.3.4 and Figure 11). It is noted that OS for phase-modulated signals can be applied for other wind profiler radars if their signal processing is can be changed so that it carries out the decoding method we described. Because only sequential data transfer from the USRP2 to the PC is available, we implemented the range sampling function on the PC. Transmitted pulses leaked to the receiver are used as the trigger signal of range sampling. The robustness of triggering is secured by checking the signal level at three points (i.e., onset of the leaked transmitted pulse, first subpulse, and last subpulse) and by verifying the phase change of subpulses (Figures 8, 9 and 10). Using

the measurement results from the RIM WPR, we showed that a combination of RIM and OS is useful for significantly mitigating the range-weighting effect of RIM (Figures 1 and 12). Finally, we demonstrated that high range resolution measurement using both RIM and OS resolves the fine-scale turbulence with a vertical scale as small as 100 m or finer (Figure 13).

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Figure 1: Schematic of the range-weighting effect of received signals at subgates (a) without oversampling (OS) and (b) with triple OS. The green solid curve in panel (a) and green, purple, and brown dashed curves in panel (b) show the range weight of the received signal intensity for the case without OS. The weight is determined by the shape of the transmitted pulse. The solid curves in panel (b) show the range weight of the received signal intensity for the case with triple OS.

Figure 2: System block diagram of the 1.3-GHz range imaging wind profiler radar (RIM WPR) equipped with the digital receiver.

Figure 3: Picture of the (a) antenna, (b) outdoor unit, and (c) power supply unit of the RIM WPR.

Figure 4: A view of the USRP2 interface.

Figure 5: Signal flow of the digital receiver.

Figure 6: Thread handling in the PC. NBEAM, NFREQ, NPSEQ, NCOH, and NDATA indicate the number of radar beams, number of frequencies, number of phase-modulated pulse sequences, number of coherent integrations, and number of time series stored in the HDD in one record, respectively. Note that NPSEQ is not counted in NCOH.

Figure 7: Data format of a packet transferred from the USRP2 to the PC.

Figure 8: Example of a transmitted pulse that was leaked to the reception line and sampled by the digital receiver. Top, middle, and bottom panels show the signal intensity computed by I^2+Q^2 , the amplitude of the I and Q components, and the phase computed by $\arg(\frac{Q}{I})$, respectively. The horizontal axis indicates a sample number in time. The sampling interval is $0.1 \mu\text{s}$ (i.e., sampling rate is 10 MS s^{-1}). The length of a subpulse and the number of subpulses are $1 \mu\text{s}$ and 8, respectively.

Figure 9: Schematic diagram that explains the detection of a leaked transmitted pulse.

Figure 10: State change diagram of Data Taking. See text for the details of the states (1)–(6).

Figure 11: Schematic diagram of the interleaving used to decode the oversampled signals. A case of triple oversampling is shown. τ_{tx} indicates the subpulse width.

Figure 12: Height profile of RIM Doppler spectra (a) without OS and (b) with OS collected from 14:11:00 to 14:11:02 on 22 June 2012. Black circles are the Doppler velocity. (c) Height profile of brightness without OS (black) and with OS (blue) during the same period as that of panel (a) and (b).

Figure 13: Time range plot of (a) brightness, (b) vertical air velocity, and (c) spectrum width from 09:20:00 to 09:40:00 on 8 July 2012. Contours colored green in panel (b) and (c) indicate the brightness of 122 dB.

Figure1

Figure2

Figure3

Figure4

Figure5

Figure6

*Request is executed when number of ranged samples reaches $N_{\text{BEAM}} \cdot N_{\text{FREQ}} \cdot N_{\text{PSEQ}} \cdot N_{\text{COH}} \cdot N_{\text{DATA}}$ (i.e., number of ranged samples per record).

Figure7

Figure8

Figure9

Figure10

Figure11

*After the decoding, the interleaved signals are sorted in the original ranging order again.

Figure12

Figure13