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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, 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–μs 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.

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 et al., 2006; Stanley et al., 2004).

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

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

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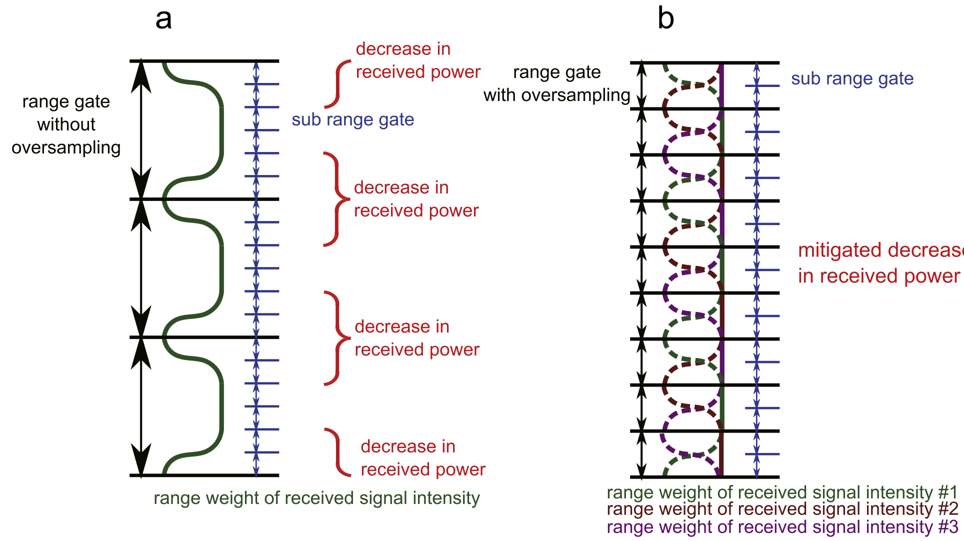

Fig. 1. Schematic of the range-weighting effect of received signals at subgates (a) without oversampling (OS) and (b) with triple OS. The green solid curve in panel (a) and green, purple, and brown dashed curves in panel (b) show the range weight of the received signal intensity for the case without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

clutter 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 Fig. 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 Fig. 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 require 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 used libraries can significantly decrease labor costs and the time for software development not only of the digital receiver for the RIM WPR but also of digital receivers to be developed in future.

In this study, we report the current advantages of the digital receiver. Up to now we have succeeded in implementing RIM and OS capabilities in the 1.3-GHz RIM WPR using the digital receiver. In Section 2, the hardware and software configuration of the digital receiver are described. In Section 3, we demonstrate that the digital receiver, which has the capability of performing the real-time signal processing required for RIM and OS, is useful for measuring fine-scale turbulence with a vertical scale as small as 100 m or finer. Section 4 summarizes the paper.

2. Receiver system

2.1. Requirements and receiver components

The requirements for the development of the digital receiver are the following:

(1) Low hardware purchase cost.
(2) Intermediate frequency (IF) signal sampling which reduces analog circuits.