Utilizing Versatile Transmission Waveforms to Mitigate Pulse-Compression Range Sidelobes With the HIWRAP Radar

Matthew L. McLinden, James Carswell, Lihua Li, Gerald Heymsfield, Amber Emory, Jaime I. Cervantes, and Lin Tian

***Abstract*—The NASA Goddard Space Flight Center (GSFC) High-altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) is a solid-state dual frequency Doppler radar funded by the NASA Instrument Incubator Program. It uses direct-digital-synthesizer devices to generate versatile waveforms including conventional pulses and linear frequency modulation (LFM) chirps. This letter describes a waveform used by the GSFC and the Remote Sensing Solutions to address the critical limitations of range sidelobes and blind ranges in airborne pulse-compression radar. By utilizing a frequency diversity waveform consisting of two pulses and an LFM chirp at each transmit cycle, this system provides the improved sensitivity and range resolution benefits of pulse compression on targets within the middle and high altitudes while maintaining conventional pulsed data near the radar and the surface. The data obtained by the HIWRAP during the NASA Midlatitude Continental Convective Clouds Experiment using this waveform scheme are presented.**

***Index Terms*—Pulse-compression methods, pulse-compression radar, radar, remote sensing.**

I. Introduction

PULSE-compression radars offer a number of advantages over traditional high-power short-pulse radars, such as reducing the need for high-power and high-voltage electronics, allowing compact and lightweight systems, and improving range resolution and reliability. However, range sidelobes associated with pulse compression have brought a particular challenge for airborne or spaceborne near nadir-pointing cloud and precipitation radar, since surface returns detected by pulse-compression range sidelobes may mask the returns from nearby clouds or precipitation. Significant effort has been put into reducing range sidelobes for this purpose, but current algorithms have not been shown to be ideal for near-nadir-pointing weather radars.

To achieve ultralow range sidelobes, it is necessary to use a waveform with a large pulsewidth_bandwidth product. The pulsewidth_bandwidth product of airborne pulse-compression weather radar is limited by a number of parameters such as system sensitivity requirements (sensitivity is reduced with increased bandwidth), the transmitter maximum duty cycle, the maximum blind range near the radar, and the minimum unambiguous Doppler velocity. For example, for pulse compression using a linear frequency modulation (LFM) chirp with a bandwidth of 4 MHz and a pulsewidth of 40 μs, the maximum range sidelobe reduction will be approximately $-20\ \log(\mathrm{BT}) - 3 = -47$ dB, where BT is the pulsewidth_bandwidth product, while on the order of -70 dB, sidelobe reduction is required for surface-contamination free operation at Ka and Ku frequencies. While low range sidelobes (-55 dB) have been demonstrated by Tanner *et al.* [1] using an LFM chirp with amplitude tapering, such results have only been demonstrated with high pulsewidth_bandwidth products. These techniques (along with others utilizing non-LFM chirps) introduce significant sensitivity loss through aggressive amplitude tapering, driving the power amplifier in a linear regime, and decreasing the range resolution per noise bandwidth by broadening the main lobe.

To mitigate the range sidelobe effect associated with airborne nadir-pointing weather radars, a new waveform was implemented and tested on the NASA Goddard Space Flight Center (GSFC) High-altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) radar. This waveform scheme utilizes conventional pulses after and before an LFM chirp for detecting targets near the radar and the surface, respectively. To avoid the loss of system sensitivity experienced by earlier radars when switching between multiple modes, the HIWRAP uses the frequency diversity waveform technique to allow the simultaneous receiving of both pulse compressed and conventional pulse data [2]. This technique allows the full benefits of a conventional pulsed radar near the radar and the surface, while retaining the sensitivity benefit of pulse compression at all other ranges.

II. System Description

The GSFC HIWRAP is a dual-frequency (Ku and Ka bands) solid-state Doppler radar capable of flying in either a dual-looking-angle conical scanning mode on the NASA Global Hawk unmanned aerial system or in a nadir-pointing mode on the NASA ER-2 [3]. The system transmits frequency-diverse waveforms while simultaneously receiving and separating the different channels to improve sensitivity and range resolution. The HIWRAP system has flown on the NASA Global Hawk in support of the NASA Genesis and

Manuscript received June 25, 2012; revised December 5, 2012 and October 3, 2012; accepted December 9, 2012. Date of publication March 7, 2013; date of current version October 10, 2013. This work was supported by the NASA Global Precipitation Measurement Ground Validation.

M. L. McLinden, L. Li, G. Heymsfield, and A. Emory are with the NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

J. Carswell is with the Remote Sensing Solutions, Inc., Barnstable, MA 02630 USA.

J. I. Cervantes is with the Science Systems and Applications, Inc., NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA.

L. Tian is with Morgan State University, Baltimore, MD 21251 USA.

Digital Object Identifier 10.1109/LGRS.2013.2241729

TABLE I
HIWRAP-ER2 OPERATING PARAMETERS DURING THE 2011 MC3E EXPERIMENT

Parameter	Ku-band	Ka-band
RF Frequency (GHz)	13.9	33.7
Transmitter Peak Power (W)	25	4
Antenna Gain (dB)	34.8	42
3dB Beam Width (^{o})	3	1.2
RF Pulse Width (μs)	Chirp: 20 Pulse: 2	
Receiver Bandwidth (MHz)	Chirp: 2 Pulse: 2	
Unambiguous Doppler Velocity (m/s)	+/- 97	+/- 40
Antenna Angle	Nadir	
Pulse Repetition Frequency (Hz)	4516/3859 (staggered)	
Minimum Detectable Reflectivity (dBZe @ 10 km, 0.5 s avg.)	-0.5	-10.6

Rapid Intensification Processes mission in 2010 and the NASA ER-2 for the NASA Midlatitude Continental Convective Clouds Experiment (MC3E) in 2011. It is scheduled to participate in the NASA Hurricane and Severe Storm Sentinel (HS3) field campaigns from 2012 through 2014. The HIWRAP radar utilizes solid-state power amplifiers to allow for a compact design suitable for conical scanning on high-altitude aircraft. These amplifiers allow for coherent waveforms without limitation of pulse duration or duty cycle. Additionally, the HIWRAP utilizes advanced waveform generation and digital receiving, capable of transmitting and receiving multiple simultaneous frequency-offset waveforms at a staggered Pulse Repetition Frequency. The specifications of the HIWRAP radar during the 2011 MC3E are shown in Table I.

III. WAVEFORM GENERATION

The HIWRAP transmits and receives up to two Ku-band beams and two Ka-band beams simultaneously. The system uses a direct-digital-synthesizer board for each of the Ku and Ka subsystems to generate versatile transmit waveforms, including LFM chirps and conventional pulses for multilooking angles (such as the inner and outer beams on the Global Hawk). Within the same transmit and receive cycles, these chirps and pulses are transmitted with different time delays and different frequency offsets. On the receiving side, the Virtex-5 Field-Programmable Gate Array-based digital receiver developed by the Remote Sensing Solutions (RSS) is capable of receiving data from each subchannel simultaneously. Multimode radars such as the NOAA Millimeter-Wave Cloud Radar [4], the Japan Aerospace Exploration Agency COBRA+ radar [5], and the University of Massachusetts Advanced Multi-Frequency Radar (AMFR) [6] have used multiple waveform modes to overcome limitations in pulse compression but have not done so using frequency diversity to transmit and receive all the waveforms within a single pulse repetition interval. This method of using frequency diversity waveforms allows the benefit of each mode without sacrificing either integration time or pulse averages by switching between modes serially. The technique was implemented by the GSFC and the RSS [2], [7] and has been well examined by Bharadwaj and Chandrasekar [8].

To ensure the radar unambiguous detection in the range and the Doppler velocity while maintaining the system sensitivity and the final data rate within limit, the HIWRAP chirp pulsewidth is set to 20 μs with a 1-MHz bandwidth during the MC3E test and science flights. The pulsewidth_bandwidth selection results in range sidelobes of -29 dB for pulse compression using an LFM chirp. To overcome the limitation of surface sidelobes, the HIWRAP utilizes the technique of transmitting a pulse train of three waveforms at offset frequencies at each beam position to achieve reliable data at all ranges. A 20-μs chirp provides a 9-dB (after pulse-compression algorithm losses) increase in sensitivity. A 2-μs pulse at an offset frequency directly after the chirp allows reflectivity measurements in the pulse-compression blind range near the radar. Finally, a 2-μs pulse is transmitted before the chirp to provide uncorrupted data in 3 km above the surface where the pulse-compression data will be limited by range sidelobes. The use of a pulse transmitted prior to the chirp for this range minimizes the effect of crosstalk between the frequency diversity channels caused by nonlinearities in the transceiver. The strong radar return from the chirp reflecting from Earth's surface occurs only after the critical data near the surface received by the pulse channel. The complete waveform transmitted by a single beam and frequency from the HIWRAP radar is shown in Fig. 1.

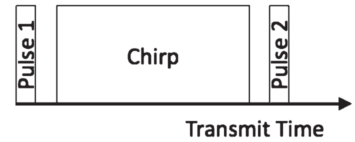

Fig. 1. Illustration of the frequency diversity waveform of the HIWRAP radar. Conventional 2-μs pulses are transmitted on either side of the 1-MHz 20-μs chirp, separated by 5+ MHz. The exact frequencies vary between the Ku- and Ka-band subsystems, as well as between the polarizations or the beams within a frequency band.

A chirp of 20 μs with a 1-MHz bandwidth was chosen as a compromise among the chirp blind range, the sensitivity, and the range resolution. The 20-μs chirp causes blind ranges of 3 km below the aircraft and the possibility of range sidelobes for 3 km above the ground. Increasing the chirp length would increase the sensitivity of the chirp slightly but would reduce the available range with clean pulse-compression data. The 1-MHz bandwidth provides for approximately 200-m range resolution after pulse compression. This level provides sufficient range resolution without sacrificing sensitivity. The waveform was a frequency-modulated chirp with amplitude tapering on receive-only to reduce range sidelobes while maintaining saturated transmit power. This time_bandwidth product of 13 dB provides approximately 9-dB sensitivity improvement over a conventional pulsed waveform with equivalent range resolution. Also, during MC3E, the receiver bandwidths were set as 2 MHz for both the chirp- and pulse-mode channels; thus, the channels were oversampled by a factor of 2 for the chirp mode and a factor of 4 for the pulse modes for better calibration results using the surface as a reference.

By combining these three returns, the radar achieved the sensitivity of a conventional pulsed radar near the radar and the surface while simultaneously benefiting from the increased sensitivity and range resolution by using pulse compression for the middle and high altitudes of each profile. Although this technique does not allow the benefits of pulse compression

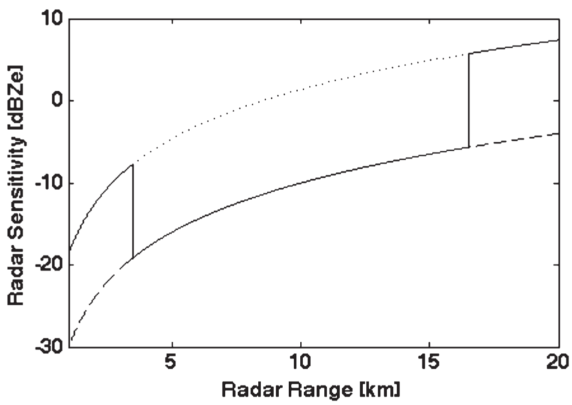

Fig. 2. Sensitivity of the HIWRAP during the 2011 MC3E using a combination of chirp and pulse data. The horizontal axis is the radar range, and the vertical axis is the sensitivity. (Dotted line) Sensitivity of the pulse modes. (Dashed line) Sensitivity of the chirp mode. (Solid line) Combined radar sensitivity with the pulse modes only used during the ground sidelobes and the blind range of the chirp.

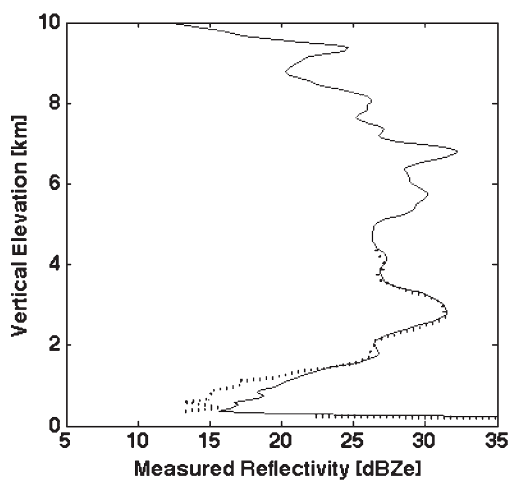

Fig. 3. Single vertical profile of HIWRAP Ka-band data consisting of a chirp and a pulse. (Dotted line) Pulse-mode reflectivity. (Solid line) Chirp-mode reflectivity. The disagreement between the two modes near the surface shows the presence of range sidelobes in the chirp-mode reflectivity.

at all ranges, it alleviates the difficulty in providing pulse compression suitable for both ultralow range sidelobes and high system sensitivity. Fig. 2 shows the HIWRAP Ka-band sensitivity as a function of the distance from the radar. The figure clearly shows the increased sensitivity afforded by the chirped mode. Fig. 3 shows the HIWRAP reflectivity profiles near the surface from the chirp and pulse modes. These nadir-pointing profiles were measured by the HIWRAP on May 24, 2011, during MC3E. Note how the reflectivity values of the chirp and pulse modes agree for most ranges but diverge near the surface. The chirp mode shows higher reflectivity just above the surface due to the presence of range sidelobes, while the pulsed data are clear of this interference. An identical technique is used to provide composite Doppler images uncorrupted by surface range sidelobes.

This algorithm could be further improved by using the pulsed waveform data near the surface only if the ground return is strong enough to warrant it. Oftentimes, with high-frequency radar, attenuation from weather targets will reduce the return of the surface to a level low enough that its sidelobes are

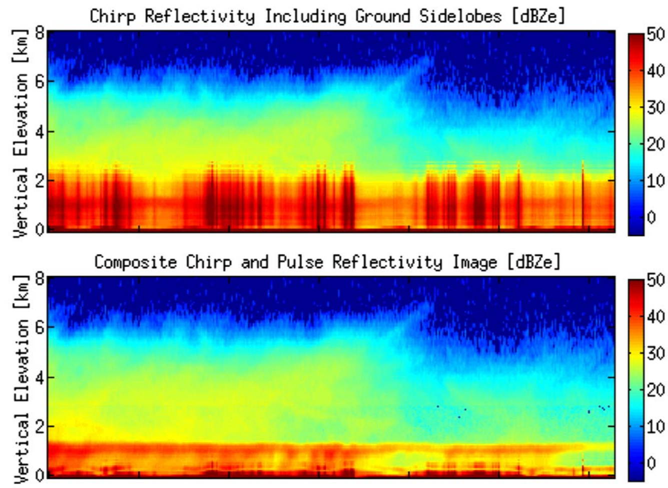

Fig. 4. Vertical slice of a storm measured by the HIWRAP radar at the Ka-band. (Top) Pulse-compression mode alone. (Bottom) Composite of the pulse and chirp modes. In this image, the bottom 3 km is from the conventional pulse data, while the remainder of the image is derived from the chirp data. Note the clear detection of the bright band and other phenomena within 3 km of the surface in the composite image.

significantly below the noise floor. In these cases, it is not necessary to utilize the pulse-mode data. Still, care would have to be taken to avoid unpredictably changing sensitivity in the lower elevations should this technique be used.

IV. Processed Data

Reflectivity data from a storm on May 24, 2011, is shown in Fig. 4 as a representative sample of data produced by this technique. A vertical slice of the storm is shown from both the chirp-only data and the composite data taken from both the chirp and the pulse. The top subplot is the chirp data that clearly show range sidelobes in 3 km near the surface. The bottom subplot incorporates the pulse mode in that region, and while it experiences reduced sensitivity, the measured reflectivity is uncorrupted by range sidelobes. Both the pulse and chirp waveforms are calibrated using the internal calibration loop, with absolute calibration using the ocean as a reference. A slight calibration discrepancy between the channels is removed by fixing the pulse-compression waveform to that of the conventional pulse by comparing the two directly in areas of moderate precipitation.

V. Future Applications

For tube-based radars, such as those common at W-band for cloud profiling, the transmit window and the duty cycle are limited. As the range resolution is often less important than sensitivity, pulsewidth_bandwidth products may be limited to 13 dB or so, similar to those of the HIWRAP during the MC3E campaign. By including an additional short pulse before the chirp, the data near the surface will maintain conventional performance while gaining 6 dB or more sensitivity through pulse compression at higher ranges. Kollias *et al.* has proposed a dual-operation mode for W-band radar for both cloud and precipitation observations by alternating the operation mode in the time domain [9]. The technique discussed in this letter is capable of operating the radar for both cloud and precipitation measurement detection simultaneously without sacrificing system sensitivity. Although the pulse and chirp waveforms will have slightly different range resolutions, it may be possible to utilize them for frequency-diversity Doppler techniques.

For spaceborne precipitation and cloud radars, the challenge with pulse-compression range sidelobes and performance will be particularly difficult due to the wide Doppler spectral width associated with the spacecraft's motion and beamwidth. These instruments [such as the Global Precipitation Measurement (GPM) Dual-Frequency Precipitation Radar (DPR)] often have power amplifiers capable of transmitting pulse-compression waveforms but do not do so in part because of the range sidelobe effects. The technique detailed in this letter provides an alternative approach to mitigate the pulse-compression range sidelobe issue near the surface while fully taking advantage of pulse compression at middle and high altitudes where better system sensitivity is essential to detect weaker targets such as clouds.

A similar technique can be used with frequency diversity waveforms to increase sensitivity and the number of independent samples, as with the ELDORA radar [10]. By transmitting multiple frequency diversity pulses or chirps and receiving them separately then averaging, the sensitivity is improved, as is the number of independent samples. In this case, care must be taken to minimize the frequency rolloff of each pulse into neighboring frequency channels so as to avoid artifacts similar to pulse-compression sidelobes.

VI. Summary

The technique of transmitting simultaneous waveforms to compensate for range sidelobes will allow a partial benefit of pulse compression in situations where corrupted data would otherwise disqualify the technology. This decreases the risk associated with the spaceborne pulse-compression radar and allows pulse compression to be used without the sensitivity and range resolution loss of aggressive range sidelobe suppression.

The HIWRAP successfully demonstrated this technique, producing high-quality science data both at high altitudes and near the surface as an airborne nadir-pointing weather radar. It is hoped that this technique will hasten the adoption of pulse compression in future airborne and flight radar missions.

Acknowledgment

The authors would like to thank M. Perrine, G. McIntire, M. Vega, and M. Coon at the NASA Goddard Space Flight Center for their effort in developing and preparing the High-altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) instrument for the Midlatitude Continental Convective Clouds Experiment (MC3E).

References

[1] A. Tanner, S. L. Durden, R. Denning, E. Im, F. K. Li, W. Ricketts, and W. Wilson, "Pulse compression with very low sidelobes in an airborne rain mapping radar," *IEEE Trans. Geosci. Remote Sens.*, vol. 32, no. 1, pp. 211–213, Jan. 1994.

[2] J. Carswell, S. Bidwell, and R. Meneghini, "A novel solid-state dual-polarized, dual-wavelength precipitation Doppler radar/radiometer," in *Proc. IEEE IGARSS*, Jul. 7–11, 2008, vol. 4, pp. IV-1014–IV-1017.

[3] L. Li, G. Heymsfield, J. Carswell, D. Schaubert, M. McLinden, M. Vega, and M. Perrine, "Development of the NASA high-altitude imaging wind and rain atmospheric profiler," in *Proc. IEEE Aerosp. Conf.*, Mar. 5–12, 2011, pp. 1–8.

[4] K. Moran, B. E. Martner, M. J. Post, R. A. Kropfli, D. C. Welsh, and K. B. Widener, "An unattended cloud-profiling radar for use in climate research," *Bull. Amer. Meterol. Soc.*, vol. 79, no. 3, pp. 443–445, Mar. 1998.

[5] K. Nakagawa, H. Hanado, K. Fukutan, and T. Iguchi, "Development of a C-band pulse compression weather radar," in *Proc. 32nd Conf. Radar Meteorol.*, Albuquerque, NM, USA, 2005, pp. 38–62.

[6] N. Majurec, "Advanced multi-frequency radar: Design, preliminary measurements and particle size distribution retrieval," Ph.D. dissertation, Univ. Massachusetts Amherst, Amherst, MA, USA, 2008.

[7] L. Li, G. Heymsfield, J. Carswell, D. Schaubert, J. Creticos, and M. Vega, "High-altitude imaging wind and rain airborne radar (HIWRAP)," in *Proc. IEEE IGARSS*, Jul. 7–11, 2008, vol. 3, pp. III-354–III-357.

[8] N. Bharadwaj and V. Chandrasekar, "Wideband waveform design principles for solid-state weather radars," *J. Atmos. Ocean. Technol.*, vol. 29, no. 1, pp. 14–31, Jan. 2012.

[9] P. Kollias, W. Szyrmer, I. Zawadzki, and P. Joe, "Considerations for spaceborne 94 GHz radar observations of precipitation," *Geophys. Res. Lett.*, vol. 34, no. 21, p. L21803, 2007.

[10] H. Hildebrand, C. L. Frush, and C. Walther, "Design of the ELDORA airborne Doppler radar," NCAR, Boulder, CO, USA, NCAR Tech. Note, NCAR/TN325+EDD, 1988.