PULSE COMPRESSION WEATHER RADAR WITH IMPROVED SENSITIVITY, RANGE RESOLUTION, AND RANGE SIDELOBE

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1. INTRODUCTION

In recent years, solid-state weather radar (SSWR) using microwave semiconductor devices, such as GaAs or GaN HEMT, has largely replaced weather radar that uses an electron tube, namely a klystron or a magnetron, for a transmitter, and has become mainstream.

The many advantages of SSWRs compared with klystron or magnetron radar include high-accuracy, small size, easy maintenance, low lifecycle cost and low spurious emission.

Pulse compression, a signal processing technique commonly used by radar, sonar and so on, is a key technology for SSWR from the viewpoint of securing the desired transmission energy and range resolution.

In pulse compression with frequency modulation, two principal methods are used, both of which are well known: Linear Frequency Modulation (LFM) in which the instantaneous frequency varies linearly with time and Non-Linear Frequency Modulation (NLFM) in which the instantaneous frequency varies non-linearly.

LFM is advantageous in that a range sidelobe can be effectively suppressed to a low level by applying the Blackman-Harris window function and raised cosine amplitude taper (Nakagawa et al. 2005).

Therefore, LFM is widely used in current SSWR systems, although radar sensitivity is sacrificed for the mismatch loss by the window function.

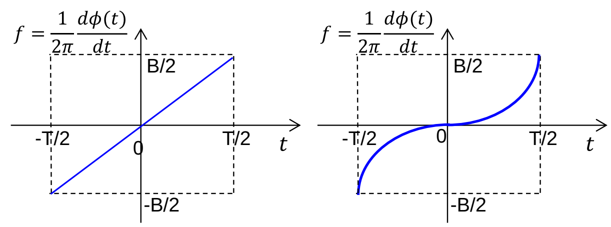
Otherwise, for higher sensitivity, application of NLFM to SSWR has been investigated in recent weather radar development (Kurdzo et al. 2014; Pang et al. 2015), because no lossy window function is needed in NLFM.

Toshiba has been developing NLFM in cooperation with the Advanced Radar Research Center of Oklahoma University (Anraku et al. 2013).

This paper shows quantitatively the performance of our recently developed NLFM and compares it with that of current LFM.

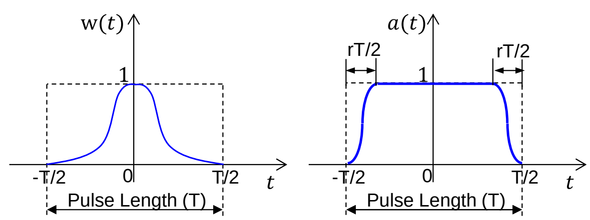
2. PULSE COMPRESSION TECHNIQUE

Fig. 1 shows schematic drawings of LFM and NLFM, where T is a pulse length, and B is a frequency bandwidth. Fig. 2 shows schematic drawings of a window function $w(t)$ and amplitude taper $a(t)$.



(i) LFM (ii) NLFM

Fig. 1: Schematic Drawings of LFM and NLFM



(i) Window Function (ii) Amplitude Taper

Fig. 2: Schematic Drawings of Window Function and Amplitude Taper

The pulse compressed output $y(t)$ in the simplified condition with neither Doppler shift and nor time delay, can be calculated as the following cross-correlation function, where $x(t)$ and $r(t)$ represent a modulated signal, a reference signal, respectively.

$$y(t) = \int_{-\infty}^{+\infty} x(\tau) \cdot r^{*}(\tau - t) d\tau \ , \quad x(t) = a(t) \cdot e^{j\phi(t)}$$

In the case of LFM : $r(t) = w(t) \cdot e^{j\phi(t)}$

In the case of NLFM : $r(t) = x(t) = a(t) \cdot e^{j\phi(t)}$

No mismatch loss occurs in NLFM, because the reference signal functions as the matched filter.

And then, a range sidelobe is suppressed by the non-linear frequency response and amplitude taper.

On the other hand, in LFM with a lossy window function like the Blackman-Harris window and slight amplitude taper such as the Tukey window, a range sidelobe can be suppressed to a low level, although about 3 dB power loss occurs. Generally speaking, the range sidelobe level in the already known NLFM tends to be inferior to that in the LFM mentioned above, in the same pulse condition. Moreover, when the NLFM waveform is implemented in a real weather radar system, the range sidelobe property is degraded by the distortion property in the transmitter.

The suppression of the range sidelobe in NLFM is an issue that needs to be resolved, not only in the ideal simulation, but also in real implementation.

3. SIMULATED RESULTS

To suppress range sidelobe in NLFM, the following approaches are attempted in simulation.

- Signal waveform is optimized in frequency and amplitude modulation by use of genetic algorithm.
- The unique amplitude taper model is applied to NLFM signal.
- The characteristics of digital filter are included for an optimization cycle.

Table 1 shows the waveform parameters of LFM and the developed NLFM chirp signal in this simulation and the loopback test shown below.

The goals of an optimization in NLFM are settled as follows.

- Peak Range Sidelobe Level ≤ -60dB
- Range Resolution (3dB) ≤ 150m
- Mainlobe Width (Bottom to Bottom) ≤ 900m

Table 1: Waveform Parameters

Parameter	LFM (current)	NLFM (developed)
Frequency Bandwidth (B)	1.63MHz	←
Chirp Type	Down Chirp	←
Pulse Length (T)	36μs, 72μs, 108μs	←
Amplitude Taper (α(t))	Raised Cosine (Tukey window r=0.16)	Unique Waveform (r=0.16)
Window function (w(t))	Blackman-Harris Window	Same as Amplitude Taper
Digital Filter	Included (BW=1.4MHz)	←
Sampling Frequency	2MHz(Ref), 80MHz(Drive)	←
Center Frequency	0MHz(Ref), 20MHz(Drive)	←

To compare quantitatively the performance of pulse compression between LFM and optimized NLFM, peak range sidelobe level, range resolution (3dB), mainlobe width (bottom to bottom), and power loss are calculated in simulation. Fig. 3 to Fig. 5 show simulated pulse compressed waveform of LFM, and Fig. 6 to Fig. 8 show the optimized pulse compressed waveform of NLFM. The simulated results of LFM and NFLM are summarized in Table 2 and Table 3, respectively.

In the calculation of range resolution, the shape of mainlobe is fitted to a Gaussian function. This approximation makes it possible to calculate the range resolution with high precision, even for low sampling rate data.

Power loss in Table 2 and Table 3 indicates the degradation amount of SNR compared with the ideal case of neither mismatch loss by window function nor signal loss by amplitude taper or digital filter. The difference of SNR between LFM and NLFM can be evaluated by the difference of power loss. About 0.2 to 0.25dB signal loss by digital filter and about 0.45dB signal loss by amplitude taper are included in NLFM's power loss.

From these simulated results, the following are confirmed.

- In each pulse length, peak range sidelobe level of NLFM is lower than that of current LFM with the Blackman-Harris window.
  Very low peak range sidelobe level is obtained in our NLFM.
  (-65.1dB@T=36μs, -67.4dB@T=72μs, -76.2dB@T=108μs)
- SNR of NLFM is about 2.5dB larger than that of current LFM with the Blackman-Harris window..
- Range resolution of NLFM is about 1.2 times lower than that of current LFM with the Blackman-Harris window.

Therefore, from this simulation, it is confirmed that the performance of range sidelobe, SNR, and range resolution may be improved by substituting NLFM for current LFM.

Table 2: Simulated Results of LFM

	T= 36μs	T= 72μs	T= 108μs
Peak Range Sidelobe Level	-50.6dB	-66.1dB	-72.7dB
Range Resolution	178m	178m	178m
Mainlobe Width	900m	900m	900m
Power Loss	3.19dB	3.19dB	3.19dB

Table 3: Simulated Results of NLFM

	T= 36μs	T= 72μs	T= 108μs
Peak Range Sidelobe Level	-65.1dB	-67.4dB	-76.2dB
Range Resolution	148m	145m	149m
Mainlobe Width	900m	900m	900m
Power Loss	0.69dB	0.70dB	0.66dB

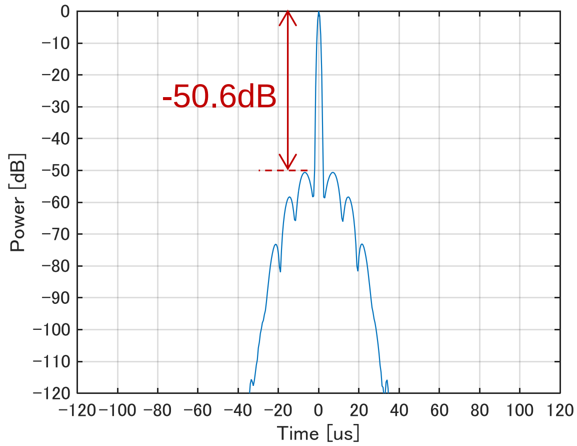


Fig. 3: Pulse Compressed Waveform (LFM T=36μs, Simulated Result)

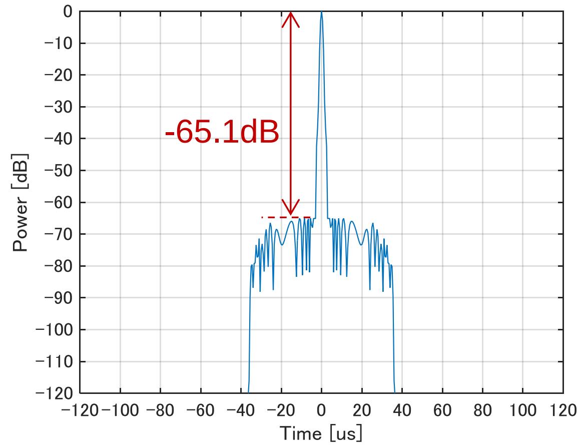


Fig. 6: Pulse Compressed Waveform (NLFM T=36μs, Simulated Result)

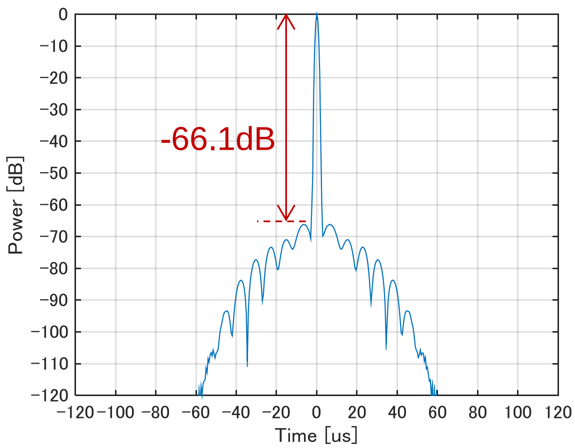


Fig. 4: Pulse Compressed Waveform (LFM T=72μs, Simulated Result)

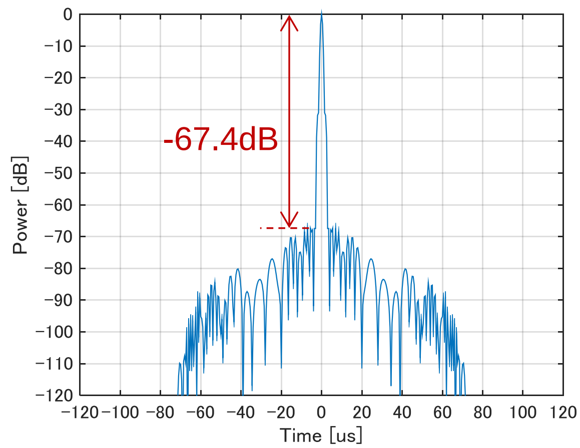


Fig. 7: Pulse Compressed Waveform (NLFM T=72μs, Simulated Result)

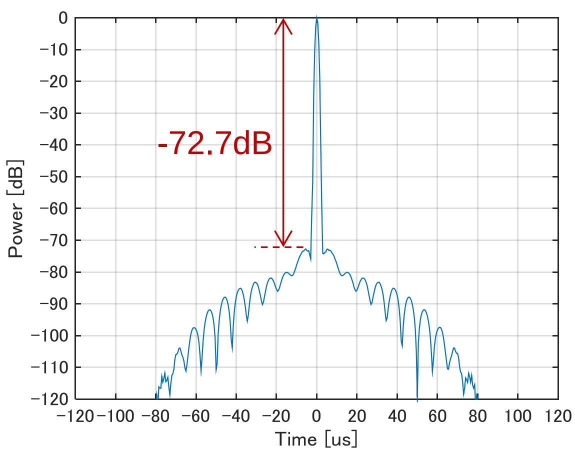


Fig. 5: Pulse Compressed Waveform (LFM T=108μs, Simulated Result)

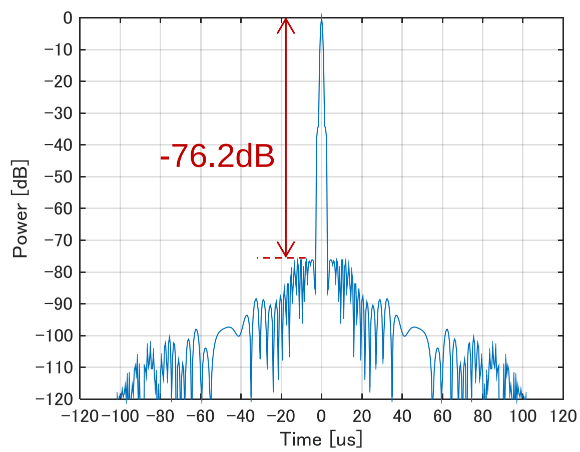


Fig. 8: Pulse Compressed Waveform (NLFM T=108μs, Simulated Result)

4. MEASURED RESULTS OF LOOPBACK TEST

A loopback test was performed with the experimental equipment of C-band SSWR at Toshiba. A photograph of this SSWR system and main specifications of the transmitter are shown in Fig. 9 and Table 4.

The transmitter's output signal is usually distorted in amplitude and phase by a power amplifier. In NLFM, this signal distortion leads to the fatal degradation of range sidelobe and mainlobe width. And so, we make unique high-precision corrections for the distortion property in the transmitter.

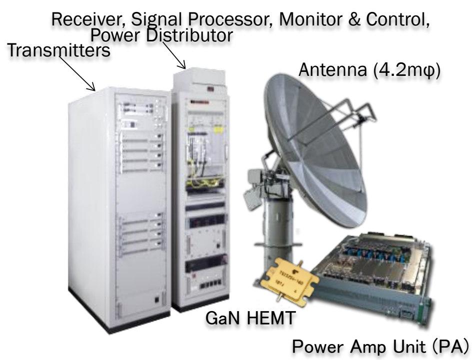


Fig. 9: C-Band SSWR System

Table 4: Specifications of SSWR's Transmitter

Item	Description
RF Frequency	5,600 – 5,850MHz (tunable)
Peak Power	3kW per polarization (6kW max)
Pulse Width (3dB)	0.5μs – 200μs
Power Amplifier's Device	GaN HEMT (by Toshiba)

In this loopback test, the reception IQ signals are pulse-compressed in off-line processing. In the calculation of range resolution and real peak power level of mainlobe, the shape of mainlobe is fitted to a Gaussian function from three points of measured data including the maximum value of mainlobe. The difference of SNR between LFM and NLFM is evaluated by the difference of mainlobe's peak power level in the condition of the same noise floor level between LFM and NLFM. And then, this noise floor level is made to agree with that of each signal before pulse compression.

Fig. 10 to Fig. 12 show pulse compressed waveform of LFM, and Fig. 13 to Fig. 15 show that of NLFM. The measured results of the loopback test in LFM and NFLM are summarized in Table 5 and Table 6, respectively.

From these results of the loopback test, the following are confirmed.

- In each pulse length, peak range sidelobe level of NLFM is lower than that of current LFM with the Blackman-Harris window.
  Peak range sidelobe level is improved to about 2.1dB to 12.8dB lower compared with current LFM.
  Peak range sidelobe level can be suppresed to very low level.
  (-65.7dB@T=72μs, -72.5dB@T=108μs)
  High-precision corrections for the distortion properties in the transmitter are achieved even for NLFM signals with different pulse lengths.
- SNR of NLFM is about 2.5dB larger than that of current LFM with the Blackman-Harris window..
- Range resolution of NLFM is about 1.2 times lower than that of current LFM with the Blackman-Harris window.
- Range resolution and the quantity of improvement of SNR between LFM and NLFM agree well with the simulation result.

Also, in a real implementation, it is evident that the performance of range sidelobe, SNR, and range resolution would be improved by substituting our NLFM for current LFM.

Table 5: Measured Results of LFM

	T= 36μs	T= 72μs	T= 108μs
Peak Range Sidelobe Level	-43.5dB	-61.1dB	-70.4dB
Range Resolution	180m	179m	178m
Mainlobe Width	1,050m	1,200 m	1,200m
Peak Power Level	+1.73dBm (=P_1)	+4.62dBm (=P_2)	+6.29dBm (=P_3)

Table 6: Measured Results of NLFM

	T= 36μs	T= 72μs	T= 108μs
Peak Range Sidelobe Level	-56.3dB	-65.7dB	-72.5dB
Range Resolution	148m	145m	149m
Mainlobe Width	1,050m	1,200m	900m
Peak Power Level	P_1+2.52dB (+4.25dBm)	P_2+2.52dB (+7.14dBm)	P_3+2.55dB (+8.84dBm)

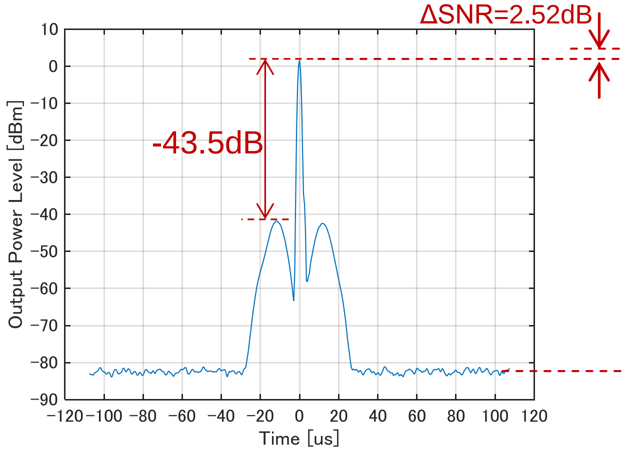


Fig. 10: Pulse Compressed Waveform (LFM T=36μs, Measured Result)

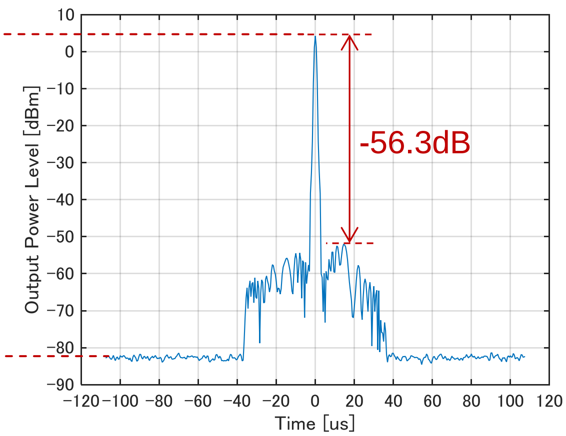


Fig. 13: Pulse Compressed Waveform (NLFM T=36μs, Measured Result)

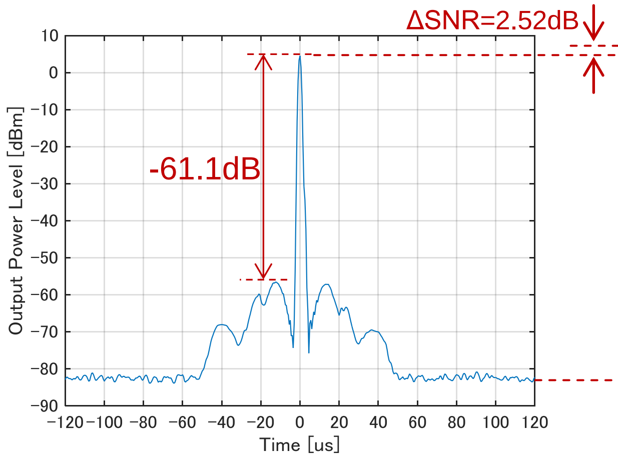


Fig. 11: Pulse Compressed Waveform (LFM T=72μs, Measured Result)

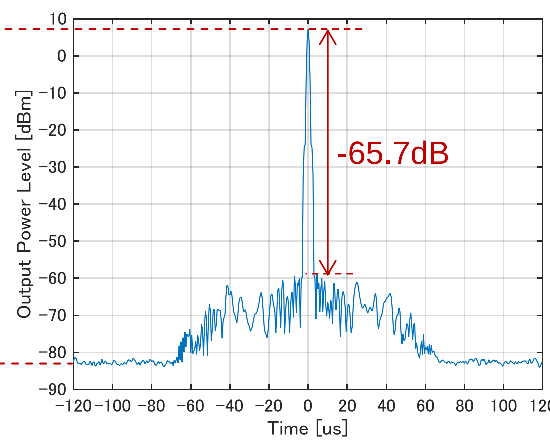


Fig. 14: Pulse Compressed Waveform (NLFM T=72μs, Measured Result)

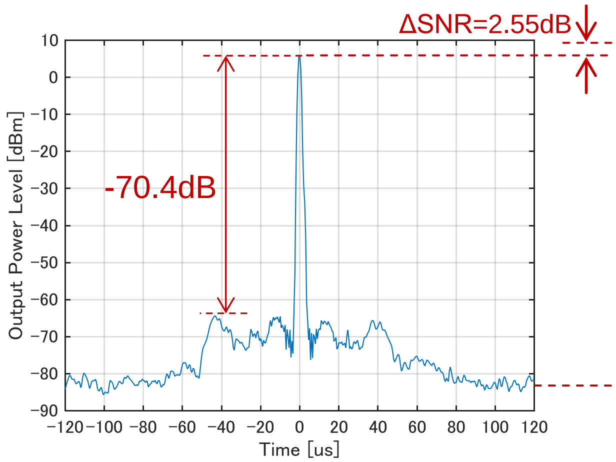


Fig. 12: Pulse Compressed Waveform (LFM T=108μs, Measured Result)

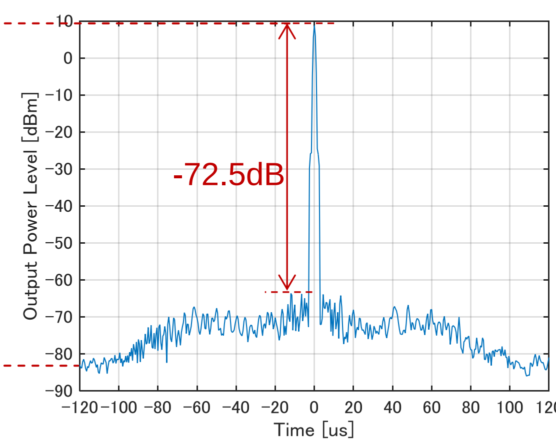


Fig. 15: Pulse Compressed Waveform (NLFM T=108μs, Measured Result)

5. RESULTS OF WEATEHR OBSERVATION

Using C-band SSWR installed at the Meteorological Research Institute (MRI) facility in Tsukuba, we observed weather phenomena with current LFM and the developed NLFM.

Fig. 16 shows the appearance of this C-band SSWR at the MRI facility and Table 7 shows the major specifications of C-band SSWR installed at the MRI facility.

This parabolic dish-type C-band SSWR installed in 2007 was developed jointly by Toshiba Corporation and MRI, in order to study the efficacy of a weather radar system using a solid-state transmitter (Wada et al. 2009). It was the first SSWR system used in Japan, and through observation at MRI, C-band SSWR has contributed to useful research results in weather studies.

Fig. 16: C-Band SSWR Installed at MRI Facility

Table 7: Specifications of C-Band Solid-State Weather Radar Installed at MRI Facility

Item	Description
Observation Range	230km or more in radius
RF Frequency	5,370MHz
Pulse Width (3dB)	1μs – 129μs (variable)
Peak Power	3.5kW per polarization (Power Devices: GaAs FET)
Receiver Dynamic Range	110dB
Radome Diameter	7m or less
Antenna Diameter	4m or less
Antenna Gain	42dBi or less
Beam Width	1deg or less
Radar Products	Reflectivity (Z_H, Z_V)
	Differential Reflectivity (Z_{DR})
	Doppler Velocity V (m/s)
	Spectrum Width W (m/s)
	Differential Phase Φ_{DP}(deg)
	Specific Differential Phase (K_{DP})
	Correlation Coefficient (ρ_{HV})
Manufacture	Toshiba Corporation

In the present study, we compared the received power obtained by current LFM and by the developed NLFM.

In NLFM, the corrections of the distortion property are revised for the distortion property in this SSWR's transmitter. Incidentally, the pulse lengths of LFM and NLFM signal are changed to 67μs on account of the continuation of the observation condition.

Fig. 17 and Fig. 18 show the results of received power by LFM and by NLFM, respectively. The time difference in the two experiments is less than 60 sec.

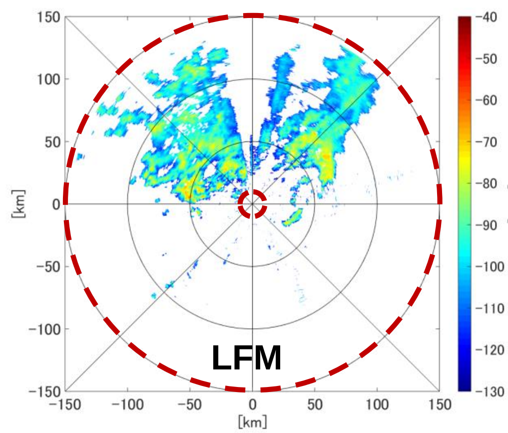


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Fig. 17: Received Power by LFM

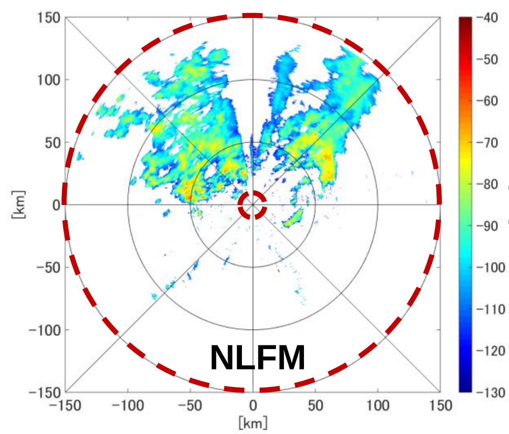

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Fig. 18: Received Power by NLFM

The results show that received power by NLFM is a little stronger than that by LFM.

In addition, an area integral calculus level of the received power is compared between LFM and NLFM. As a result of this calculation, about 2.8dB improvement of SNR is confirmed in the developed NLFM, compared with current LFM using the Blackman-Harris window function.

So, we confirmed more than 2.5dB improvement of SNR (Figs. 10-15) can be expected not only for the point target, but also for the distributed weather target.

6. CONCULUSION AND FUTURE WORK

In conclusion, we developed a pulse compression weather radar with improved sensitivity, range resolution, and range sidelobe, by use of proposed NLFM.

Compared with current LFM using the Blackman-Harris window function, developed NLFM is superior as follows.

- SNR is more than 2.5dB larger.
  This is confirmed from both the results of the loopback test and the actual weather observation.
- Range resolution (3dB) is approximately 1.2 times lower as a result of the optimization of NLFM signal by use of genetic algorithm.
- Peak range sidelobe level is about 2.1dB to 12.8dB lower, as a result of the above-mentioned approaches in simulation and high-precision corrections for the distortion properties in the transmitter.
  Peak range sidelobe level is suppressed to a very low level.
  (-65.7dB@T=72μs, -72.5dB@T=108μs)

We are conducting further evaluations of the developed NLFM in weather observations and plan to make practical use of NLFM with SSWR within the next few years.

ACKNOWLEDGEMENT

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