一般社団法人　電子情報通信学会
THE INSTITUTE OF ELECTRONICS,
INFORMATION AND COMMUNICATION ENGINEERS

信学技報
IEICE Technical Report
SANE2012-68(2012-10)

Evaluation of Millimeter wave Radar using Stepped Multiple Frequency Complementary Phase Code modulation

Masato WATANABE and Takayuki INABA

Graduate School of Electro-Communications, The University of Electro-Communications

1-5-1 Chofugaoka, Chofu-shi, Tokyo, 182-8585 Japan

E-mail: watanabe.masato@inabalab.ee.uec.ac.jp, inaba@ee.uec.ac.jp

Abstract This paper describes a development of Millimeter wave Radar for automotive and railway safety monitoring system. The radar is based on Stepped multiple-frequency CPC(complementary phase code) that is proposed radar signal modulation to obtain high range resolution even with the narrowband receiver in our previous study. In this paper, it experimentally confirmed low range sidelobe after the CPC pulse compression is added and high range resolution even with narrowband receiver using millimeter wave radar in anechoic chamber. As an example of the application of millimeter-wave radar, the measurement results which human detection in crossing and platform is shown. Furthermore, the measurement results for the Millimeter wave Radar equipped in front of railway train is introduced.

Key words Radar, Pulse Compression, Complementary Phase Code, Step Frequency

1. Introduction

In recent years, the short range radar is expected to be applied for the automotive radar, and the railway safety monitoring system which detects the human having fallen onto tracks from a platform and the obstacles in the railway crossing. In case of millimeter wave automotive radar, it is required to provides driver assistance such as Adaptive Cruise Control (ACC) (detection distance of 150m or more) and Stop or Go or distance control or active safety systems[1]. The automotive Radar must be developed in accordance with the law, known as specified low power radio stations of the millimeter wave[2]. In general, FMCW(Frequency Modulated Continuous Wave) modulation which provide high range resolution with less signal processing complexity compared to the pulse compression radar is adopted for millimeter wave automotive radar[3]. Although FMCW has the above advantage that high distance resolution is achieved by low signal processing. Nevertheless, it has the following problem. Since using CW for transmit signal, the reflected waves are observed simultaneously from all range. In particular, when there are undesired objects with small range attenuation at short range (the undesired objects is called clutter), the clutter, and a leakage from the transmit antenna into the receive antenna, and also interference from other radars, are received as undesirable signals. On the other hand, Pulse compression has excellent clutter reduction performance and interference rejection performance[3]. But, high speed AD and the signal processing system is required to obtain the required range resolution in the automotive radar. In the range corresponding to the transmit pulse width, the range estimation is also difficult. In addition, the performance of detection maximum range decrease because the receiver noise increases in accordance with wider bandwidth which provides high range resolution. Moreover, in the city and railway environment, it is necessary to measure the target range, velocity and angle simultaneously even in multiple target situations.

In the above mentioned technical background, we proposed Stepped multiple frequency complementary phase code (CPC)[4][5] which employs intra-pulse phase coded by CPC in order to divide range by range gates processed by CPC pulse compression. The CPC pulse compression by adding two complementary codes with compensation of Doppler shift using Pulse Doppler processing provides the superior range gate with extremely low range sidelobe. Between each range gates, the high range resolution is obtained by synthetic wideband processing which use of flourier transformation into the detected Doppler spectrum of each pulse compressed signal with the received stepped frequency signal. We have previously reported that the expected low range sidelobe and good range resolution is also obtained by means of experimental study using 24GHz off-line radar in anechoic chamber.

In this paper, it experimentally confirmed low range sidelobe after the CPC pulse compression is added and high range resolution even with narrowband receiver using millimeter wave radar in accordance with specified low power radio stations of the millimeter wave in anechoic chamber. In the first part of this paper, the principle of the Stepped multiple frequency CPC modulation is explained. Furthermore, the outline of the radar with the Stepped multiple frequency CPC modulation are described. In the Second section, experimental study from off-line signal processing in anechoic chamber by millimeter wave radar are presented. Finally, as an example of the application of millimeter wave radar, the measurement results which human detection in crossing and platform is shown. Furthermore, an the measurement results for the millimeter wave radar equipped with railway train is introduced.

2. Stepped multiple frequency CPC

The Stepped multiple frequency CPC modulation is characterized as follows.

① The transmission frequency sequence to which several transmit frequencies are switched by time division is used as shown Fig1.

② In each transmit frequency, the pulses whose phases are modulated with Code1 and Code2 by satisfied the complementary condition to each other are transmitted alternately by PRI(Pulse Repetition Intervals).

Next, we explain the concept of the signal processing for the Stepped multiple frequency CPC which is based on the CPC pulse compression and the synthetic bandwidth processing. Though synthetic bandwidth processing provides high range resolution by a narrow receiver bandwidth and the comparatively low speed AD, the observation time becomes long in general because the frequencies are switched by time division. Additionally the problems occur such as called range ambiguity. On the other hand, the transmit pulses modulate by the two complementary phase codes, and the pulse compression signal is used as a range gates to solve the range ambiguity problem.CPC can ideally achieve complete zero sidelobe. Nevertheless, under the influence of the Doppler shift, it is well known that the sidelobe level of the CPC pulse compression decreases and the range bias error in the synthetic bandwidth processing occurs respectively.

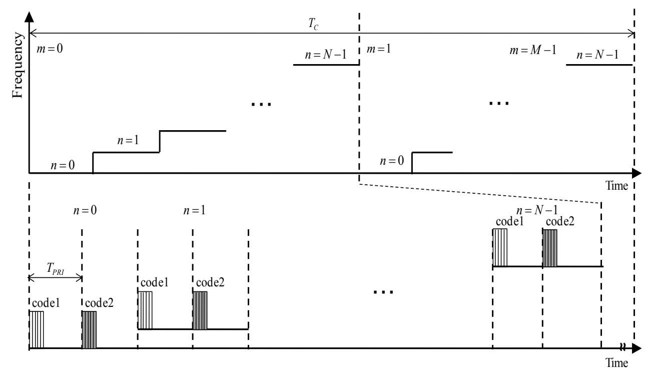


Fig.1 Transmission frequency sequence of Stepped multiple-frequency CPC.

As a consequence, the signal processing is performed in the following order, complementary code pulse compression, pulse Doppler filter, Doppler compensation, complementary code addition and synthetic wideband processing. One of the notable features is that eight frequency steps are able to use for millimeter wave automotive radar application which requires the some hundreds of meters in detection range, two hundred kilometer per hours in relative velocity and twenty Hz in data rate. Hence, receiver bandwidth and A/D performance are reduced to one eighth of the transmission frequency bandwidth which determines the final range resolution. The measurement signal and the signal processing about Stepped multiple frequency CPC will be described.

$$x(n,m) = exp\left[2\pi j\left(-\frac{2R}{c}(f+\Delta f\cdot n)+ f_d\cdot\left(2\cdot T_{PRI}\cdot n+2\cdot T_{PRI}\cdot N\cdot m+t_1'\right)\right)\right]\cdot exp[j\phi_1] \quad (1)$$

$$x(n,m) = exp\left[2\pi j\left(-\frac{2R}{c}(f+\Delta f\cdot n)+ f_d\cdot\left(2\cdot T_{PRI}\cdot n+T_{PRI}+2\cdot T_{PRI}\cdot N\cdot m+t_2'\right)\right)\right]\cdot exp[j\phi_2] \quad (2)$$

it is explained the signal processing of Stepped multiple frequency CPC as shown in Fig2.The baseband digitized signal after the analog to digital conversion in each m, n, and codes is set into the pulse compression processing. Next, in the pulse doppler filter, the pulse compressed signal with each n and codes is processed by discrete Fourier transform in the direction of m. Using each of the obtained Doppler frequency, the effect of Doppler shift for each code, to correct the phase difference caused by the delay time difference between each frequency step and each code. Bias error in the output pulse compression by a Doppler shift is very small in this case, the Doppler estimation and correction process is performed after pulse compression is possible. Phase correction processing on the signal after these, while reducing the amount of computation performed adding it to achieve a low range sidelobes. Obtain a range profile of high range resolution range gate signal by the addition result, the synthesized frequency step in the direction of it as input. Range Profiles obtained, the detection process is performed in the range direction. Detected value is the target range, the target relative velocity can be obtained from the corresponding frequency channel.

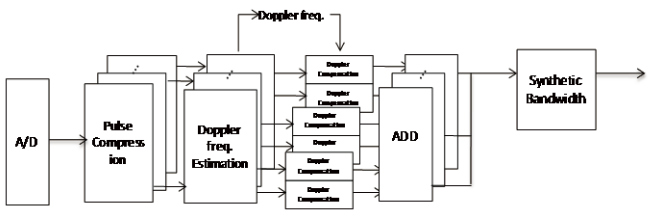


Fig.2 Schematic diagram of Stepped multiple frequency CPC.

3. Millimeter wave radar using stepped multiple frequency CPC

Millimeter wave radar based on the Stepped multiple frequency CPC is under development.The radar which employs the radar parameter in table.1 meets specified low-power radio station standard of the millimeter wave(transmit frequency 60.0-61.0GHz,withth of 500MHz,transmit power 10mW and Tx antenna gain 40dBi).

IF equipment includes Tx slot antenna and Rx 4-element array antenna. The stepped frequency signals from each eight PLL circuits are switched and mixed with CPC signals from D/A of Signal Processing equipment into the IF signal in the IF equipment. The IF signal are up-converted to millimeter wave and amplified in the RF equipment. Namely, the double-conversion architecture is adapted. On the other hand, The reflected millimeter wave signal received with each 4 Rx slot array antenna are amplified and down-converted to baseband signal

The signal processing unit consists of four compact PCI boards, such as the two of 4 A/D+2FPGA which perform signal processing, the 2D/A+FPGA which generates the CPC signals and control signals and the control unit I/ F board. In the signal processing unit, the baseband signals from 4 Rx antennas are converted into IQ-complex digital signals by 8 A/D converters at 160MHz, 16bit.4 IQ-complex digital signals at 160MHz, 16Bit from Rx antennas are set into Vertex-5 XC5VLX330 FPGAs and processed by the method mentioned in chap2 in real time. As shown in Fig.4,in the controller unit, the four signals processed by synthetic wideband processing are formed into five multi-beams, and applied to monopulse angle estimation method. Finally, the estimated relative velocity and high resolution range and angle of targets are indicated by GUI. Monopulse is performed on the detected target which is estimated velocity and range by signal processing of Stepped multiple frequency CPC in advance at Detection①. Under the condition that includes Rx 4-element array antenna, as compared with the case of processed directly from the raw data, the radar can be provides greater precision of monopulse.

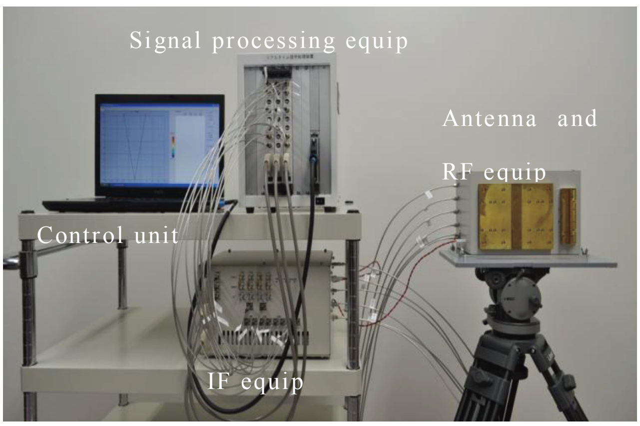


Fig.3 Outline view of the radar.

Table 1 Radar parameter

Transmit frequency	60.25-60.75GHz
Pulse bandwidth	80MHz
Pulse width	0.2μsec(30m)
Code length	16
PRI	3.5μsec
Pulse number: M	512
Frequency step width	60MHz
Frequency step number:N	8
Transmission bandwidth	500MHz
Observation time	29msec
A/D sampling frequency	160MHz

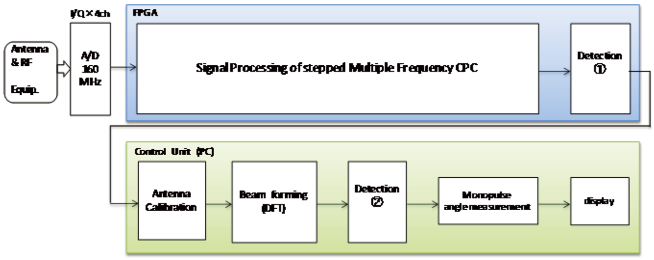
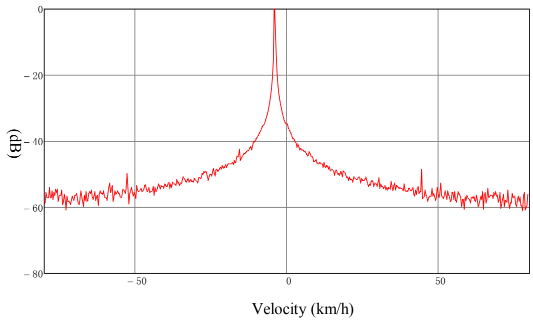


Fig.4 Schematic diagram of Signal processing equip and Control unit.

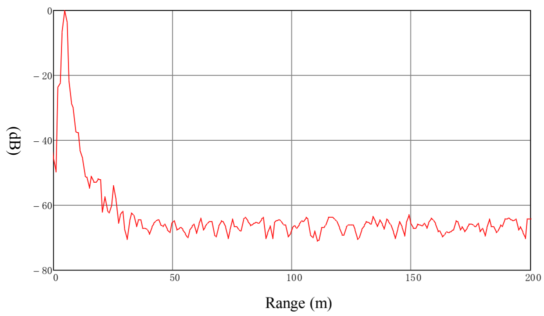
4. Experimental study in anechoic chamber

The experimental study evaluates low range sidelobe after the CPC pulse compression is added and the range resolution which Stepped multiple frequency CPC obtain. The radar parameter was designed, as shown in the table 1. An experimental measurement in anechoic chamber was carried out radiating the radar signal to the moving target.

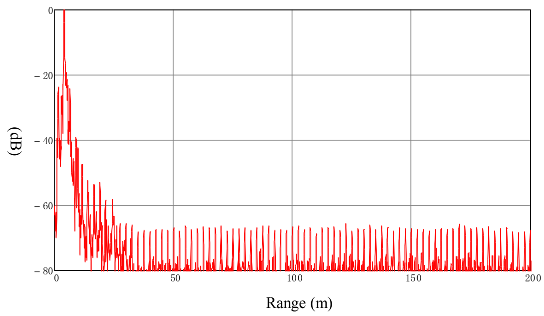
Fig.5 show the experimental result (target range 3.9-5.5m,velocity-4km/h). In Fig.5(a),it is shown that an obtained target relative velocity is -4km/h. In Fig.5(b),the range sidelobe after CPC addition using comparatively short code length of 16 achieves ultra-low level at -60 dB in average between the range from 20 to 200m.The pulse width (in other word, the range gate) after CPC addition is 2.3m. As a consequence, it is confirmed that the range resolution of the expected 0.3m which by the synthetic wideband processing was obtained with 160MHz 16bit A/D. Stepped multiple frequency CPC can achieve up to 110dB isolation against the target range, different target velocity can be expected.



(a)Velocity estimation result.



(b)Range gate output.



(c)Range estimation result.

Fig.5 Offline signal processing resluts of target.

5. Measurement results

5.1. Measurement results for typical situation

As shown in Fig.6,the target specification was set to be the range of the target 63.8-65.4m and velocity ±4 km/h In this case, the target was set to corner reflector(CR). Fig.7 shows the real-time signal processing result in the situation of Fig.6. In the figures the horizontal axis corresponds to time and the vertical axis corresponds to range[m], relative velocity [km/h], angle [deg], and amplitude [dB] in order from the top. Estimating the range corresponding to the relative velocity that was estimated by Doppler frequency estimation as shown in Fig2. Using the above, Fig7. was exclude from stationary objects to detected targets. It experimentally confirmed to be able to separate the maneuvering target and the stationary objects from this according to the velocity, and to presume the target correctly.

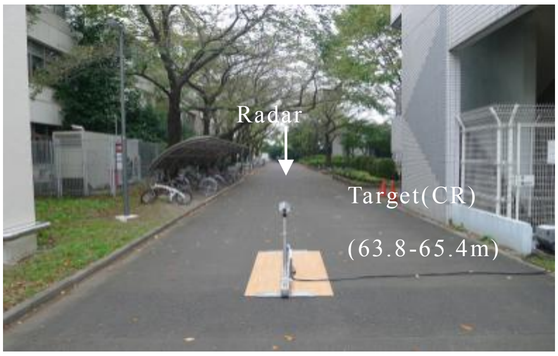


Fig.6 Experimental set up.

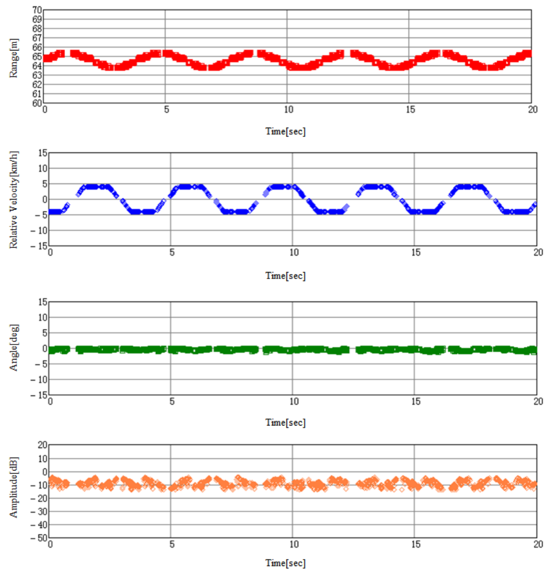


Fig.7 Measurement result.

As shown in Fig.8, two people approaching from the position of about 24m from the radar in the same environment as in Fig.6.

Fig.8 Detection of CR and multiple human experiment.

Fig.9 shows the real-time signal processing result in the situation of Fig.8. Stationary objects have been excluded from the display as well as Fig.9. In Fig.8, it can be seen that, unlike corner reflector, there have been variations in the speed of movement of the limb in humans. Moreover, the targets were separated by the range though the velocity of the corner reflector and humans were almost the same between 22.5~23.5sec. Additionally, mluti targets were separated by range and angle between 30~31sec. It is shown to measure the target range, azimuth angle and relative velocity even in multiple target situations

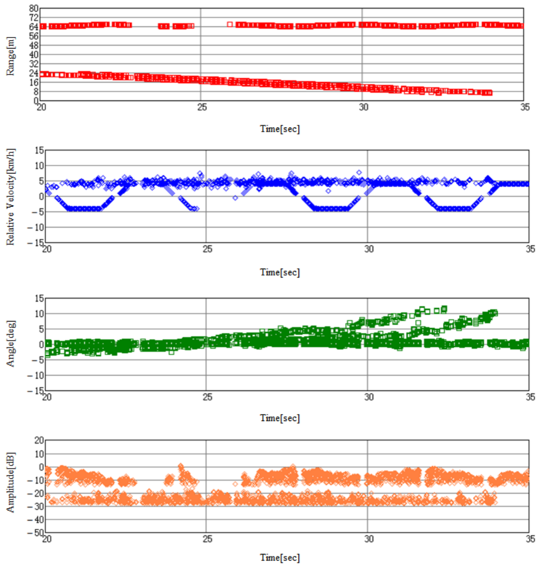


Fig.9 Measurement result.

5.2. Measurement results for railway situation

The radar was set up in parallel to ground at the position of 0.8m in height under the platform as shown in Fig.10. It walked from both ends of the platform (20m in length width, the width 10m, and 1 m in height) in groups of two on the edge of the other side. At this time, the only target is to tumble from the center of the platform, was stopped at fall position.

Fig.10 Experiment to detect the fall from the platform.

Fig.11 shows the real-time signal processing result in the situation of Fig.10. Incidentally, stationary objects have been excluded from the display. Without detecting the pedestrians on the platform, it was detected only the target. At this time, about 5m at the fall position and speed due to fall from the platform was able to be obtained. We confirmed that from the above results, in situations where more than one person is walking on the platform, and a fall is detected only from the platform.

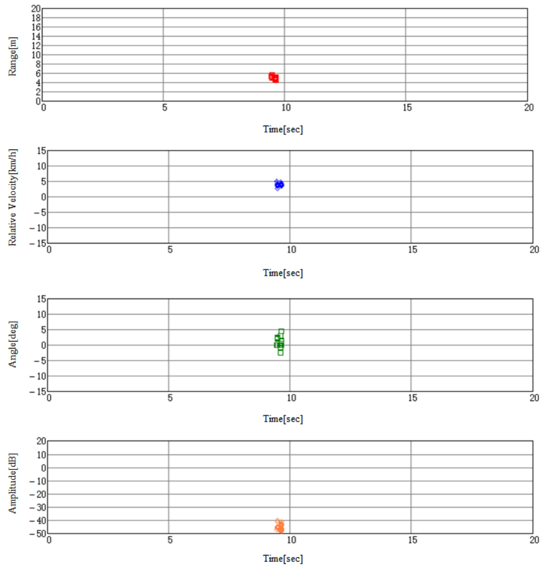


Fig.11 Measurement reslut.

The radar was set up next to the crossing gate as shown in Fig.12. By the time difference, two people moved in the direction that went away from radar, and other two people approached radar respectively.

Fig.12 Detection of multiple human experiment in crossing.

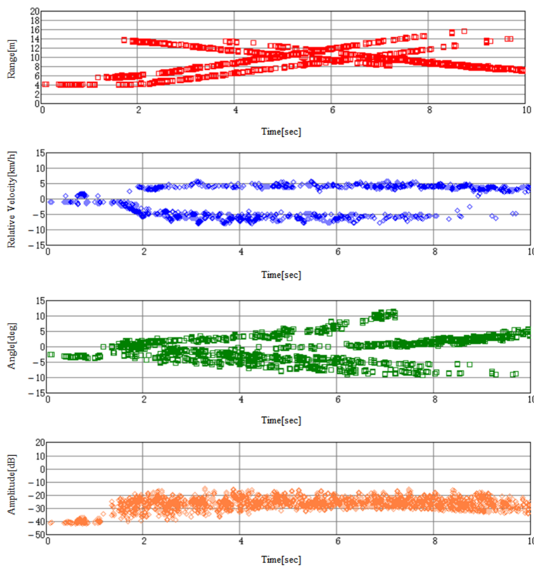


Fig.13 Measurement reslut.

Fig.13 shows the real-time signal processing result in the situation of Fig.12. Stationary objects have been excluded from the display. It is seen that the target with different velocity was separated from velocity since 2sec. Moreover,it confirmed that it was able to separate in the situation in which two or more targets were adjacent as shown in Fig.13 between 5~7sec.

Fig.14 Experiment in railway.

The antenna & RF equip of the radar was equipped in the front of the train that is traveling at about 10km/h as shown in Fig.14. On the other hand, the target was set up by 30-degree angle against the rail, and was reciprocated by 4 km/h. At this time, a straight line range of a railway track is about 120m.

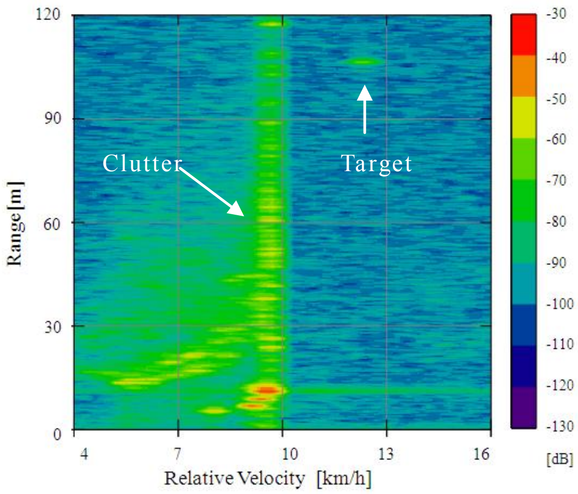


Fig.15 Offline Signal processing resluts.

Fig.15 shows the results of off-line signal processing that is performed the signal is converted from analog to digital between Coherent Pulse Interval. In the figures the horizontal axis corresponds to the relative velocity and the vertical axis corresponds to the range. At this time, velocity resolution is 0.3 km/h, and range resolution is 0.3m. The output that had the spread in the direction of range at the relative velocity about 10 km/h which it corresponded at the velocity of the train was obtained. Its spread represents the stationary object (called clutter), such as a utility pole ground, rail.

Next, Fig.16 shows the result of the real-time signal processing. First, the speed of the train has estimated using detected data. Next, detected data in the vicinity of the estimated speed regarded as a stationary object and exclude it from the display. Since the target is present on the rail, the detected data that exist on the rail were displayed by using the angle. In the railway environment where a lot of object made from metal existed, we confirmed to be able to detect the corner reflector from 120m though it was a disadvantageous design parameter to the long range target detection. The parameters possess wide beam, wideband (transmission bandwidth 500MHz), transmit frequency 60GHz (oxygen absorption attenuation 15dB/km) and power 10mW. Therefore it is expected to improve maximum detectable range by parameter selection, such as antenna gain, transmission frequency and, frequency bandwidth from the above results. Future issue is applied for the tracking filter and clutter suppression processing to improve the detection performance.

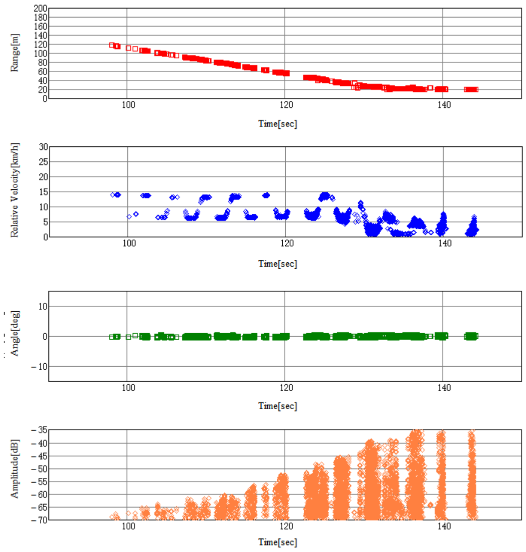


Fig.16 Measurement reslut.

6. Conclusion

In this paper, it experimentally confirmed low range sidelobe after the CPC pulse compression is added and high range resolution even with narrowband receiver using millimeter wave radar in anechoic chamber. As an example of the application of millimeter-wave radar, the measurement results which human detection in crossing and platform is shown. Furthermore, an measurement results for the Millimeter wave Radar equipped in front of railway train is introduced.

This study was supported by the Program for Promoting Fundamental Transport Technology Research (No.2009.02) from the Japan Railway Construction, Transport and Technology Agency (JRTT)

References

[1] Takayuki Inaba, Tetsuo Kirimoto,"Automotive Millimeter Wave Radars", Vehicle Technology 64-2, Feb.2010.

[2] The Ministry of internal affairs and communications, "ARIB STD-T48 ver2.1", I The Ministry of internal affairs and communications, 2006.

[3] Donald R. Wehner," High resolution radar 2nd edition", Artech House, 1994

[4] Takayuki Inaba, "Multiple Target Detection for Stepped Multiple Frequency Interrupted CW Radar", IEICE Trans.Commun., vol.J89-B No.3, pp.373-383, Mar.2006.

[5] Masato Watanabe, Takayuki Inaba, Hikaru Tsubota, Takahiro Yano," Development of Millimeter wave Radar using Stepped Multiple Frequency Complementary Phase Code modulation,ICSANE2011,SANE2011-81