Design and Implementation of Signal Processor for High Altitude Pulse Compression Radar Altimeter

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Abstract. The paper describes the studies on design and implementation of signal processing algorithm for an intra-pulse LFM (linear frequency modulation) & inter-pulse PPM (pulse position modulation) compression High altitude radar altimeter. In order to enhance the performance of signal processing algorithm for compressed pulse, a correlation integration algorithm based on mismatched code is provided. The corresponding flight verification test, pulse compression test results and final processed output of signal processor in different terrain have been presented. Flight test shows that the signal processing algorithm of the high altitude pulse compression radar altimeter has very high processing gain and superior performance for weak echo signal detection.

Keywords: radar altimeter, pulse compression, pulse position modulation signal, LFM signal, signal processing

1. Introduction

In order to increase the operation altitude of a radar altimeter, the pulse compression technology is generally used without enhancing the power of transmitting pulse. LFM is a widely used pulse compression waveform for radar altimeter [1]. Such altimeter can get high operation altitude, high range resolution, and high altitude accuracy. Compared with the other pulse compression signals, its matched filter is insensitive to Doppler shift of the echo signal, so signals with different Doppler shift can be processed with only one matched filter [2]. Generally, long transmitting pulse period is chosen for pulse compression radar altimeter to avoid range ambiguity. But as a result, the duty cycle of the pulse is greatly reduced, and accordingly, the average power of transmitting pulse is also greatly reduced, making the advantage of pulse compression not fully used. If the pulse period is reduced, however, range ambiguity will appear. The method to resolve the problem is bringing additional modulation between pulses, such as inter-pulse binary phase code modulation [3], inter-pulse orthogonal code modulation [4], pulse position modulation (PPM) [7], etc. In [3], the signal processing of a Doppler radar altimeter is designed and simulated. This is an altimeter with intra-pulse LFM pulse compression and inter-pulse binary phase code. But the inter-pulse phase modulation and inter-pulse correlation processing after pulse compression increase complexity of the design; furthermore, because Doppler filtering is used, the signal processing of this kind altimeter has to be modified for different application accordingly, and that makes the design and application of the altimeter inconvenient. From the point of application, it is unnecessary

To use Doppler system for radar altimeter (except special application). To simplify the radar altimeter and signal processing system design, between the compressed pulses, PPM is brought in. With this method, only half of the pulses are transmitted in a code period （NTr, N is code length, Tr is pulse period）, making

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the average transmitting power reduced by 3dB, but because short pulse period can be used, the average transmitting power increase instead of decreasing. Furthermore, the gain of code correlation processing after pulse compression will greatly increase the sensitivity of the radar altimeter, thus the operation altitude of the altimeter will also increase obviously.

In this paper, the signal processing algorithm design and implementation of a pulse compression radar altimeter is presented, and this altimeter is based on intra-pulse LFM & inter-pulse PPM.

2. Waveform Description

The waveform of a radar altimeter based on intra-pulse LFM & inter-pulse PPM is shown in Figure1. Suppose the pulse width is τ, primary pulse period is T_r（or binary code width）, and binary code length $N = 2^m - 1$ （m sequence，m is the length of the register which generates the m sequence）, then the maximal unambiguous range of this waveform is $H_{max} = cNT_r/2$. When the inter-pulse modulation binary sequence is long, the duty cycle of the transmitting signal is：$D \approx \tau/(2T_r)$.
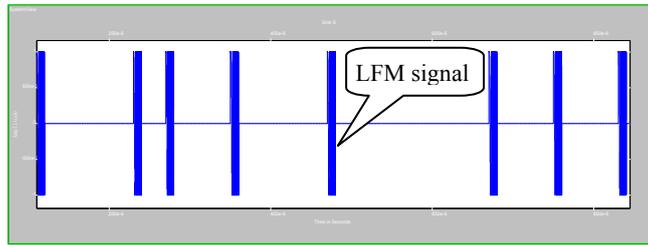

Fig. 1: Signal waveform of the intra-pulse LFM & inter-pulse PPM radar altimeter.

For the traditional pulse radar altimeter, to ensure that the measure of altitude is unambiguous and the suppress of the ambiguous altitude is 20dB～30dB, then the pulse period is selected according to the formula $T_{rp} = (5\sim10)H_{max}/2C$；But for the inter-pulse PPM signal, the pulse period is selected according to the formula $T_r = T_{rp}/N$. Therefore, the inter-pulse PPM makes the average transmitting power reduced by 3dB, but because the pulse period decreases, the average transmitting power increase by 10lgN dB. As a result, the final average transmitting power increases $(10\lg N - 3)$ dB.

3. Signal Processing Algorithm of the Altimeter and Its Implementation

Because pseudo-random PPM is applied, there is no need to use complete coherent system for the altimeter. Instead, after detection, incoherent correlation integration processing between the compressed pulses is used. Correlation processing can greatly increase the gain of signal processing and the sensitivity of the pulse compression radar altimeter. Its basic algorithm model is shown in Figure 2.
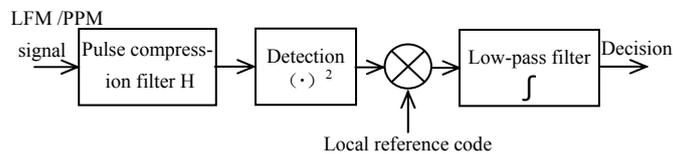

Fig. 2: Processing algorithm model of the intra-pulse LFM& inter-pulse PPM signal.

In the algorithm, LFM+PPM IF pulses with bandwidth 10MHz are sampled with 60MHz frequency, and then digital down conversion is performed to convert the signals to base-band. After reducing the signal rate (decimating) and low pass filtering, time domain pulse compression and detection are performed on base-band. The compressed pulses after amplitude detecting perform the incoherent correlation integration and smooth filtering with the local reference codes according to the range bins. Then threshold decision is performed to finish the detection and processing of the altimeter echo. Figure 3 is the implementation block diagram.
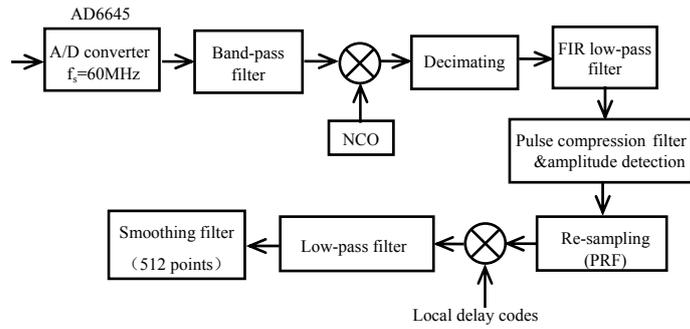
Fig. 3: Block diagram of the pulse compression radar altimeter's signal processing algorithm implementation.

3.1. Pulse compression processing based on distributed algorithm

Time domain compression is used for the pulse compression processing. In order to save the hardware resources of the FPGA, considering the symmetry of LFM compressed signals, a 200 order FIR filter based on DA algorithm (Distributed Arithmetic, DA for short) is used to compress the LFM pulses. Because the DA algorithm uses the lookup table (LUT) method to implement a large amount of multiply operations with constant inside the FPGA, the whole algorithm has only shift and add operations and complex multiply arrays are unnecessary. As a result, a lot of memory spaces are saved, making the speed of the circuit increase. The time clock of the compress filter is above 200MHz, so the real time pulse compression in whole range is realized. Figure 4 shows the basic structure of the pulse compression FIR filter based on the DA algorithm.
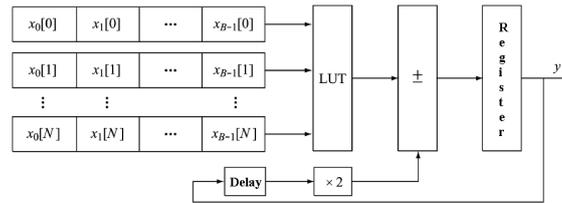

Fig. 4: Basic structure of the pulse compression FIR filter based on the DA algorithm.

3.2. PPM correlation mismatch processing

The time ambiguity function of pseudo-random PPM signal has high level range side lobes [6], making the ratio of altitude correlation peak level to correlation noise floor level very low(less than 6dB by simulation). The high correlation noise level sometimes makes the target detection give the false decision, so we have to consider it carefully when we make the signal processing design.

One feasible method is performing correlation mismatch processing to the compressed pseudo-random PPM signal with bipolar delay codes. That means the delay code pulses are not single-polarity pulses but bipolar pulses. This is different from the transmitting random PPM signals, which are single-polarity pulses. The bipolar delay code pulses then correlate with the echo signals. The simulation results indicate: with this method, the ratio of altitude correlation peak level to the correlation noise floor is above 10dB. For the implementation, considering the limitation of the FPGA capacity, before the PPM correlation mismatch processing, limit the amplitude of the detection pulse (1bit quantization), and that greatly reduces the requirement of the hardware for incoherent correlation integration processing after amplitude detection of compressed pulses. The detection processing performance of the signal processor to weak signal is also improved at the same time.
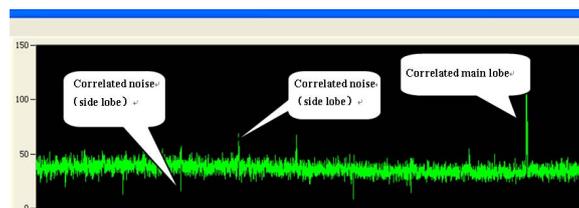

Fig. 5: Mismatch processing output of the pseudo-random PPM signal.

Figure5 shows the correlation peak output of the altimeter's signal processor with mismatch processing at the fix altitude of 20000 meters (laboratory test). Because the width of bipolar mismatch pulse is inappropriate, the ambiguity range noise peaks appear above the noise floor, but the level of the noise floor has decreased greatly.

3.3. Smoothing filtering after correlation integration

When the SNR is low, the amplitude of the output signal after pulse compression and incoherent correlation integration procession will fluctuate, and decision jitter will appear if fix threshold decision is used. To solve the problem, a 512 order data smoothing filter is cascaded after the correlation filter. A sliding-window of 512 points is used for the smoothing filter to improve the data fluctuation.
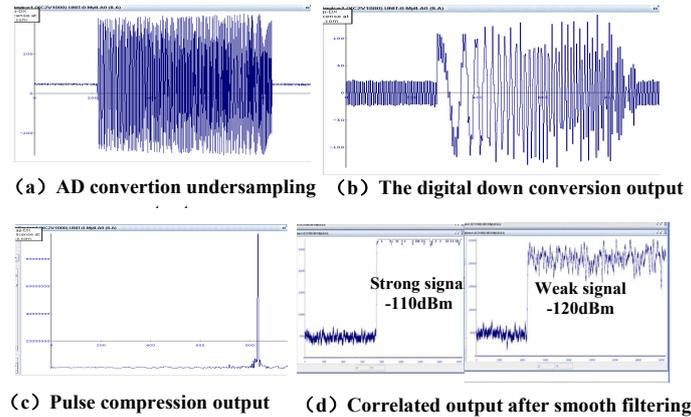

（a）AD convertion undersampling   （b）The digital down conversion output

（c）Pulse compression output   （d）Correlated output after smooth filtering

Fig. 6: Test results of altimeter's signal processor.

3.4. Implement of signal processing algorithm

The signal processing algorithm of the high altitude pulse compression radar altimeter is implemented by two chips XC2V1000 FPGA. One FPGA is used to implement the digital receiver front-end and pulse compression algorithm, the other is used to implement the incoherent correlation filtering of the pseudo-random PPM signal, the correlation smoothing filter and the timing control of the altimeter. AD6645 of the AD company is used as a convertor. The IF echo signal is converted to differential signal by the wide band transformer ADT4-1WT and then comes into the input port of AD6645. The output of AD6645 comes into the FPGA directly to be processed. Limited by the capacity and speed of the FPGA, the signal rate and word length are optimized to improve the signal processing performance. Figure 6 shows the test results of the signal processor in laboratory.

4. Flight Experiment of the High Altitude Pulse Compression Radar Altimeter

To verify the waveform design of the high altitude pulse compression radar altimeter, especially the adaptability of the waveform and its signal processing algorithm to different topographies, flight experiment of the altimeter was performed with a helicopter to different topographies. Figure 7 shows the test results of the altimeter signal processor's incoherent correlation integration and compressed pulse output to four different topographies and different signal strength at the fix height 3000 meters. To verify the altitude measuring ability of the altimeter, in the experiment, power of the transmitting signal was attenuated to different topographies. All the test results in Figure7 were obtained for the weak echo signals.

The results indicate that: different topographies have little effect on the performance of altimeter's pulse compression. Because the pulse width and FM bandwidth are selected appropriately, the influence of ground de-correlation time on the performance of pulse compression in [8] does not appear. Besides, the results show that the echo signal strength (SNR) of the altimeter for the forest topography decrease at least 10dB than for the hill topography.

The characteristic of the altimeter's waveform, especially great gain of signal processing algorithm make the test sensitivity of the altimeter better than -125dBm when the pulse compression ratio is 100, and code length is 63 bits. The flight test results also show that this altimeter has the ability to measure altitude higher than 100 kilometers.
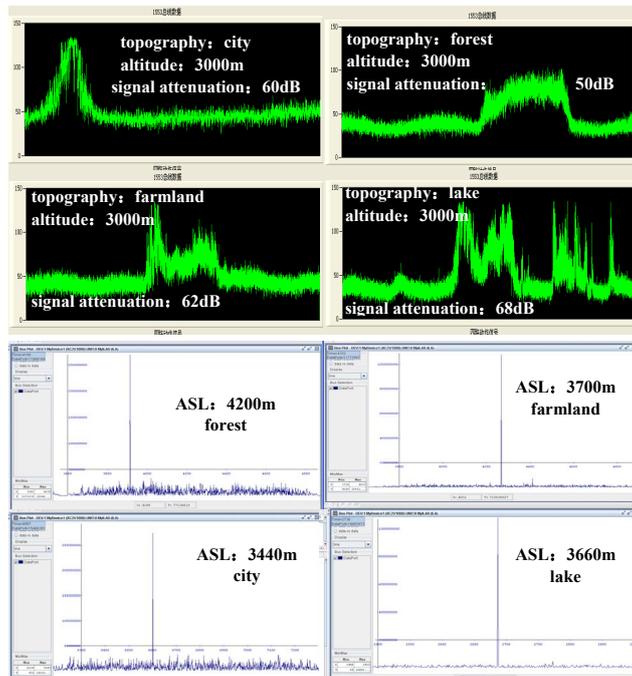
Fig. 7: Test results of altimeter's pulse compression and incoherent correlation integration output (four different topographies).

5. Conclusion

In this paper, on the basis of traditional LFM pulse compression radar altimeter, a radar altimeter's waveform based on intra-pulse LFM & inter-pulse PPM is proposed. The signal processing algorithm of the altimeter and its implementation are provided. For the correlation processing after pulse compression, the design of inter-pulse code correlation mismatch is used to lower down the correlation noise. The feasibility and adaptability to different topographies of the waveform and its signal processing algorithm are validated by the flight test. At present, the waveform and its signal processing algorithm have been applied to engineering projects.

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