High Resolution Moving Train Imaging Experiments with Stepped-Frequency Radar System

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Abstract

In this paper, the experiment system for high resolution moving train imaging is introduced. For the experiments, there are three objectives: realizing moving targets imaging as an inverse synthetic aperture radar; verifying the effects of range profile resolution improvement by stepped-frequency; comparing the dechirp and matched filtering methods. During experiments, moving train imaging results have been attained via two imaging methods. The differences of imaging results by two methods are shown respectively. The objective for verifying improvement on range resolution by stepped chirp is realized.

1 Introduction

Since the limitations on producing large bandwidth chirp signal and sampling rate, stepped-frequency approach has been an alternative to avoid these obstacles in high resolution range profile imaging. In this paper, radar experiment system is established based on stepped frequency. In the experiment system, synthesized bandwidth is up to 2GHz with 20 steps and because each step is limited to 120MHz, the sampling rate can be reduced to 200Msps even for matched filtering method. Such way does provide an economically realizable manner to upgrade a conventional system to get higher performance.

As stated in [1][2], a stepped-frequency system possesses wide bandwidth by sending a train of narrow-bandwidth subpulses carried on stepped frequency, which are then received and combined coherently to achieve higher resolution. In our Ka-band experiment system, maximum bandwidth reaches to 2GHz through combining 20 subpulses with 120MHz bandwidth, which are modulated on 20 carrier frequencies stepped with 100MHz. Pulse-to-pulse spectrum overlap is set to 20MHz.

In our experiment system, two pulse compression methods have been verified. For easier sampling of received IF signal, dechirp approach is adopted; for wider range of observation, matched filtering method is used. When dechirp method is selected, the sample rate reduces to 50Msps, which can be even lower. This is far smaller than the requirement for matched filtering method.

In the former parts of this paper, system architecture and basic principle of the experimental radar system are described. Then, some experimental results are demonstrated.

2 System components and parameters

The system architecture and practical components of the experimental radar system are shown in Figure 1. Due to short time duration of echo, two antennas are used in the experimental system to carry out transmitting and receiving separately.

Several key components are described as follows:

2.1 Frequency synthesizer and DDS

Frequency synthesizer with the direct digital synthesizer (DDS) generates stepped-frequency pulses by high-speed and wideband frequency switching. Up-
converter and preamplifier are also included in this unit. All frequencies produced by frequency synthesizer are coherent with high stability 100MHz DRO. To assure the switching speed of 20 hops, the 20 carrier frequencies are produced ready through 20 independent units, the hopping is realized by high speed switching.

DDS in this system is a kind of direct digital waveform synthesizer. Chirp waveform is pre-calculated and stored in ROM. When parameters are set, waveform data is transferred to RAM. According to the control signal, waveform data is send to D/A sequentially, which converts the digital data into analog chirp baseband signal. The chirp bandwidth is 120MHz.

2.2 Receiver

Receivers of two configurations for dechirp and matched filtering have been constructed. The received signals are converted into I/Q components by quadrature demodulator, which is the key component in receiver. In demodulating process, when dechirp method is adopted, the received signals are mixed with the counterparts of transmitted signals; when matched filtering method is chosen, the received signals are mixed with the three stages converting signal. As previously stated, receiver for dechirp mode can be drawn as Figure 2.

Figure 2 Receiver for dechirp

In dechirp mode, there is only a single stage down-converter. The mixing signal coming from frequency synthesizer is same as transmitted signal. Due to the short duration for echo and special observing target in our experiment, there is no delay and no time extension for the mixing signal. All this will lead to some range information loss. Under our experimental condition, because of the short distance between radar and target, the loss can be neglected.

Figure 3 Receiver for matched filtering

Receiver for matched filtering mode is shown in Figure 3. In this mode, three-stage downconverter architecture is chosen. The frequency of first stage local oscillator is controlled to hop from 28.1GHz to 30.1GHz, which is synchronous with transmitted hopping signals. The frequencies of second and third stage local oscillator are fixed 3.8GHz and 1.1GHz respectively.

2.3 Time sequence controller

All the timing signal comes from time sequence controller. It also produces trigger for sampling. The main control signals are drawn in Figure 4.

In our DDS, to reduce jitter between subpulses, when DDS trigger arrives, DDS produces 20 subpulses continuously with PRI 8us and time width 6us.

Figure 4 Time sequence

2.4 A/D and data storage

The demodulated I/Q analog IF signals are fed into signal sampler (A/D& Data Storage unit) as shown in Figure 1. The A/D& Data Storage unit performs the analog to digital transform (A/D) to convert analog signal into digital data, eventually stores the raw data into solid state storage. Figure 5 gives the architecture of the A/D card whose interface is CPCI. It is a general purpose card which is developed for radar data sampling. It has 8 channels to convert analog signal to digital data with up to 400Msps at 14 bit precision. The high speed raw data is sent to storage system through link interface of DSP(TS201). The data rate can be up to 300MBps.

Figure 5 Block diagram of A/D card

### TABLE I Experimental radar system parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>33–35GHz</td>
</tr>
<tr>
<td>Frequency Step</td>
<td>100MHz</td>
</tr>
<tr>
<td>Subpulse Bandwidth</td>
<td>120MHz</td>
</tr>
<tr>
<td>Subpulse Width</td>
<td>6us</td>
</tr>
<tr>
<td>Subpulse Numbers</td>
<td>20</td>
</tr>
<tr>
<td>Subpulse PRI</td>
<td>8us</td>
</tr>
<tr>
<td>PRF</td>
<td>1600Hz</td>
</tr>
<tr>
<td>A/D sampling rate</td>
<td>50Msps(Dechirp)</td>
</tr>
<tr>
<td></td>
<td>200Msps(Matched filtering)</td>
</tr>
<tr>
<td>A/D precision</td>
<td>14bit</td>
</tr>
</tbody>
</table>
3 Observing target and experimental methods

Figure 6 Experiment setup

Figure 6(a) shows the picture of the train which is taken as observation target. The train has 6 compartments, and its total length including connections between compartments is about 118m. The velocity of train is about 70kmh. Figure 6(b) is the experimental site and system. Figure 6(c) sketches the geometry of side-looking mode of the experimental radar system. The direct distance between radar and the train is about 50m. The radar is on the position higher than train about 9m. Then the grazing angle can be calculated about 10°.

Dechirp is a kind of signal processing method pointing at the problem of imaging with chirp signal. Its main procedure in hardware is that mixing the received echo signal with reference signal, which has same FM slope with transmitted signal rather than point-frequency LO signal. Different with matched filtering method, the range profile produced by dechirp method is in frequency domain. In this way, the range information is converted to frequency, that is to say, different frequency represents different range.

With dechirped data, the imaging operation is described as follows:

Step 1. Get subpulses from each burst.
Step 2. For each subpulse, perform time shift in time domain. The shift quantity is

$$nLeod - nLF \frac{\Delta f}{k}$$

where n denotes steps, t_L represents subpulse’s PRI, Δf is step frequency and k is FM slope.
Step 3. Connected all subpulses to synthesize a whole pulse.
Step 4. Perform FFT of combined signal and then range profile is achieved.
Step 5. Perform pulse compression operation in azimuthal direction which is same as Range-Doppler algorithm, then final imaging result is obtained.

Compared to dechirp method, matched filtering method is a bit more complicated. There will be 2 more operations relative to FFT. The following steps are performed to combine all subpulses in spatial domain with matched filtering method:

Step 1. Extract the subpulses from each burst. Then, each subpulse’s echo is converted into spectral domain by FFT respectively.
Step 2. Perform matched filtering in spectral domain, that is to say, multiply echo’s result of FFT by conjugate of reference function’s FFT. Different from single pulse compression, IFFT is not performed now.
Step 3. Because each subpulse is sampled at base band, to synthesize the whole spectrum, each subpulse’s frequency has to shift in terms of its number of hops and step frequency.
Step 4. Concatenate all spectrums together with the overlap of 20MHz cut away.
Step 5. Taking IFFT of the combined spectrum yields the impulse response of stepped chirp.
Step 6. Same as step 5 of dechirp method.
Adopting the experiment system as well as methods described above, we conduct the imaging experiment. The primary results are illustrated in next section.

4 Experimental Results

To verify the performance of stepped frequency, we find a target’s impulse response in imaging result of each method to manifest the effect of resolution improvement.

Figure 7 and Figure 8 compare resolution improving trend between the dechirp result and matched filtering result. It can be seen that two methods get similar results.

Figure 7 shows the point target response of a practical target with N (N=1, 2, 4, 8, 16, 20) stepped frequency. When N = 1, the 3dB resolution is about 1.2m and when N=2, the resolution is about 0.6m. As N becomes bigger, the resolution is improved which complies with the relationship between signal bandwidth and resolution. The target is away from the ra-
dar about 107m. We use this target to compare the effect of resolution improvement of N steps. Because the observing environment is complicated, it is difficult to find such a target which is same as the ideal point target. What we can do is to keep this target away from influence coming from adjacent targets.

And then, in Figure 8, the point target response curves are obtained through matched filtering method. The target’s location in range is about 131m. When N=1, same with dechirp method, due to only 120MHz bandwidth, the resolution is quite poor for observing cross section of train in range direction is only about 1m width. After 20 stepped frequency SAR imaging, the resolution in range is less than 0.1m. Under such condition, more details of the train can be found, such as connections, ventilators, and so on.

Figure 7 Range profile with different steps of dechirp method
Figure 8 Range profile with different steps of matched filtering method

Figure 9 and Figure 10 demonstrate the observed results which have also been processed in azimuthal direction. From Figure 9 and Figure 10, first of all, six compartments can be distinguished clearly. The most obvious feature in the imaging result is the connections between compartments which are marked in Figure 6(a). Same color with the background means that signals are hardly reflected at this position. According to this feature, the length of each compartment in the image can be figured out. It is in good agreement with practical measurement. Contrast to the weak echo characteristics of connections, the scattering characteristics of air-conditioners’ ventilators, which are on the top of both ends of each compartment, manifest almost the strongest amplitude because of its corner reflectors configuration. The point-like imaging result of ventilators is clear in Figure 9 and Figure 10. They locate at right side of the “straight line”, which shows combined effect of compartments’ bodies, doors, and windows.

Figure 9 Train imaging result with dechirp method
Figure 10 Train imaging result with matched filtering method

5 Conclusion

With experimental radar system described in the previous sections, imaging results show that by using stepped-chirp signals, high range resolution up to 0.1m can be obtained. By comparing pulse compression techniques of dechirp and matched filtering, it can be found that, in such an observation case, data rate can be reduced greatly with dechirp method, while the resolution and image quality is basically equal to matched filtering method. Then high speed ADC and great data amount can be avoided. The functions of the experimental radar system are verified by experiments well.

References