High-resolution imaging of a moving train by ground-based Ku-band radar with 4GHz signal bandwidth

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Abstract

This paper introduces our recently conducted high-resolution imaging experiment of a moving train by ground-based Ku-band radar with 4GHz bandwidth. The radar system design is briefly outlined, especially for the RF subsystem. The stepped-frequency chirp signal (SFCS) is used for realizing the 4GHz signal bandwidth. Synthetic aperture radar processing mode is used although the radar is stationary while the target is moving. The obtained radar images are presented and the electromagnetic scattering characteristics are analyzed. The radar images of 2GHz bandwidth are also presented for comparison with that of 4GHz bandwidth. In the obtained radar images, the scattering structures of windows, doors, ventilators of air-conditioner, and the compartment bodies are well shown.

1 Introduction

High-resolution radars have been widely applied to both military and civilian applications not only for reconnaissance but also for survey. High-resolution usually means large signal bandwidth needed. Nowadays even the digital technologies have experienced fast development, directly generating an ultra-wideband baseband radar signal, e.g. chirp signal as large as up to 2GHz, is still very difficult for a realistic radar system. A good choice is to divide the “big chirp” into a series of “small chirps” and each of them has just a small part of bandwidth. The stepped-frequency chirp signal or the stepped-chirp signal, or frequency jumped burst (FJB) just adopts this idea [1-4].

In recent three years, we have been focusing on developing RF subsystems for wide-band radar based on stepped-frequency chirp signal (SFCS) model or for interferometric radar and conducting imaging experiment for ground moving target by using the developed RF subsystems or the whole radar systems. Ground moving target experiment with ground-based radar is a very useful, necessary, and cost-effective work for development of radar system. By conducting this kind of experiment, we can test the key and important components or subcomponents with real data on one hand, and test and improve the signal processing algorithms on another hand.

We introduced our works on developing both Ka-band and Ku-band radar systems and presented experiment results in [5-13]. In the previous Ku-band and Ka-band systems, 2GHz bandwidth is realized. In this paper, we introduce a newly developed 4GHz bandwidth Ku-band RF subsystem and the imaging experiment with it. The imaged target is the same as before, i.e. a light-railway train. Fig. 1 shows the SFCS model, from which one can see that the SFCS is composed of a series of subchirps, each with a different but linearly increased carrier frequency. The mathematical model of SFCS can be expressed as follows,

\[ s_n(t) = \exp\left[ j(\omega_0 t + \alpha t^2) \right] 
- T_p / 2 \leq [t - n T_p] \leq T_p / 2 \]
\[ \omega_n = \omega_0 + 2\pi(n - 1)\Delta F, \quad n = 1 \sim N \]

where \( \alpha \) is the slope of subchirp, \( T_p \) is the time duration of subchirp, \( T_r \) is the pulse repetition interval between in a burst, \( T_b \) is the repetition interval between bursts, \( \omega_0 = 2\pi f_0 \) is the initial carrier frequency, \( \Delta F \) is the frequency step, which is usually selected in consideration of signal bandwidth of subchirp, \( B = [-\alpha T_p, \alpha T_p] / 2\pi \) is the bandwidth of a subchirp and the total synthetic bandwidth is \( B_F = (N - 1)\Delta F + B \), \( N \) is pulse number in a burst. Usually \( B \) is chosen a little bit larger than \( \Delta F \) better synthetic processing result.

![The SFCS model.](image)

Figure 1: The SFCS model.
In order to realize 4GHz signal bandwidth, 20 subchirps of 220MHz bandwidth are used in a burst with frequency step of 200MHz. Currently the developed digital chirp can only output a signal of 110MHz bandwidth, so a two-times multiplier is used to generate a IF chirp signal of 220MHz bandwidth. For showing the imaging effect as the signal bandwidth increased from 2GHz to 4GHz, both 2GHz image and 4GHz image are presented. The results indicate that as the range resolution improved, the azimuth resolution seems also “improved”. For example, the two-side doors in 4GHz image are much clear than that in 2GHz image.

The rest of the paper is organized as follows. Section 2 depicts the radar system briefly especially on the transmitter and receiver; Section 3 presents the imaging experiment as well as discusses signal processing issues and analyzes the results; Section 4 finally concludes the paper.

2 The radar system

The radar system is composed of standard-gain horn antennas with 25dB gain, frequency synthesizer included with frequency up-convertor, receiver, central control electronics realized by FPGA, 4-channel data recording device with maximum sampling rate of 400MHz, and power supplier. There may have two choices for implementing SFCS in hardware, one is based on matched filtering approach (MFA), and the other one is based on dechirping approach (DA). The advantage of MFA is that the observation swath is not restricted and the signal processing is stable, but the disadvantage is the total data rate is very high. One the contrary, the DA has the disadvantage of limited observation swath and the signal processing is not so stable due to the influence of target tracking accuracy, but it has the outstanding advantage of very low data rate resulted. Right now the RF subsystem based on MFA has been developed and the RF subsystem based on DA will be completed in the near future.

The RF subsystem is composed of frequency synthesizer (FS) unit, frequency up-convertor unit (FUC, included in FS unit) and receiver unit. The FS uses a 100MHz high-stable crystal oscillator, frequency multipliers and dividers, phase-lock dielectric oscillators and switches to generate the stepped frequencies changing from 11.0GHz to 14.8GHz at 200MHz step (used for the second local frequencies for transmitter and the first local frequencies for receiver) and other fixed frequencies. The FUC is composed of a mixer and a switch pair, which uses a “1 to 5” switch and a “5 to 1” switch to divide the up-converted frequency band of 12.68GHz – 14.68GHz into five subbands and filter them by five different bandpass filters. The receiver adopts a two-stage down-conversion structure with the first LO frequencies stepped along with the transmitted signal and the second LO frequency fixed at 1100MHz, so the final baseband I/Q can be limited to the same -110MHz to +110MHz range for each subchirp. It is to say, the reception of all of the 20 subpulses share the same IF and I/Q demodulator components. By this way the system design can be simplified remarkably.

3 Imaging experiment

A light-railway train is chosen as the experiment target. The radar is positioned about 56m away from the train and with the antenna boresight perpendicular to the railway. Due to the short distance reason, two antennas must be used, one for transmitting and one for receiving. The antenna beams can just cover part of the train also due to the short distance, so we must use SAR model not ISAR model for imaging processing, although the radar is stationary while the target is moving. One may take it for granted to think the ISAR processing model should be used, however ISAR model is not applicable in this case. We know that the basic idea of ISAR imaging is based on the rotational model, which assumes that the targets should be totally exposed to the radar beam during the imaging time. We also know that the common condition...
should be met for both ISAR and SAR imaging is that there must have relative motion between the target and the radar. We must point out that even we adopt the SAR imaging model, there are some differences, i.e., the influence of the clutter in real SAR case is usually unavoidable, but in our case, it plays almost no influence because their Doppler spectra are almost around zero frequency, which can be easily directly removed in Range - Doppler domain.

The data processing mainly includes the following steps:
1. Data preliminary processing, i.e. raw data format conversion from ASCII to float numbers.
2. The correction of amplitude and phase imbalances for each subchirp and the amplitude imbalance between subchirps according to calibration data [14].

(1) Correction of amplitude imbalance between subchirps
The first step is to record the received signals directly from the attenuated transmitted subchirp signals. Fig. 4(a) and Fig. 4(b) show the received 20 subchirp signal, form which one can see that the transmitted and received signals for each subchirp are different in amplitude. Accord to the recorded average signal amplitude of each subchirp, the imbalance between subchirps can be corrected by normalizing the echo signal of each subchirp with the average amplitude of the calibration waveform.

Fig. 4(c) shows the corrected spectrum of the whole 20 subchirps.

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  \text{specturm}_{c}(\text{echoes}) = \frac{\text{specturm}(\text{echoes}) \cdot \text{specturm(idea chirp)}}{\text{specturm(calibration)}}
\]

(2) Correction of amplitude and phase imbalances for subchirps.
The first step to correct the amplitude and phase imbalances for each is to obtain the spectrum correction function (SCF), which can be obtained by dividing the spectrum of an idea chirp (with same parameters as that of subchirp) with the corresponding spectrum of the calibration waveforms. The second step is to multiply the spectrum of the echo with the SCF. After the above steps, the echoes can by compressed by matched filtering using an idea chirp as the matched function.

Fig. 5 shows the original I component of the echo of a subchirp from a point target (a) and that with amplitude and phase errors corrected (b). Fig. 5 (b) clearly indicates that the amplitude imbalance of the subchirp signal has been very well corrected (or compensated).
Let’s express the echoes as follows,

\[ s_m(t) = \int_{r_1}^{r_2} g_o(r) \exp \left[ j \left( \omega_o t - \frac{2r}{c} + \frac{1}{2} \alpha (t - \frac{2r}{c})^2 \right) \right] dr \]  

where \( g_o(r) \) is scattering coefficients of observing target, \( r \in [r_1,r_2] \) is the range of target.

After performing simple variable substitution \( \tau = \frac{2r}{c} \), (3) turns into

\[ s_m(t) = \int_{2}^{2} g_o(\tau) \exp \left[ j \omega_o (t - \tau) + \frac{1}{2} \alpha (t - \tau)^2 \right] d\tau \]  

With \( b_r(t) = \exp \left[ j \omega_o t + \frac{1}{2} \alpha t^2 \right] \), (4) can be transformed into convolution version.

\[ s_m(t) = g_o(t) * b_r(t) \]  

For matched filtering type receiver, echoes are converted to baseband. This operation can be described as:

\[ s_{\text{ms}}(t) = s_m(t) \cdot \exp (-j\omega_o t) = [g_o(t) * b_r(t)] \cdot \exp (-j\omega_o t) \]  

In fact, all the formulations above describe the operations of hardware. After the baseband signals have been sampled, the rest of operations are conducted on computer.

Perform FFT of (6), the formulation in spectrum domain is

\[ S_{\text{ms}}(\omega) = G_s(\omega - \omega_o) \cdot B_o(\omega - \omega_o) \]  

For normal range processing without stepped frequency, to get the scattering coefficients of observing target \( g_o(r) \), the pulse compression is via matched filtering, that is

\[ G_s(\omega - \omega_o) = S_{\text{ms}}(\omega) \cdot B_o^*(\omega - \omega_o) \]  

\[ (8) \]

Where \( B_o^*(\omega - \omega_o) \) is complex conjugate of \( B_o(\omega - \omega_o) \).

As the description of (8) in spectrum domain, before coherently synthesizing all subpulses, the frequency shift must be done:

\[ G_s^*(\omega) = G_s(\omega - \omega_o + n\Delta\omega) = S_{\text{ms}}(\omega + n\Delta\omega) \cdot B_o^*(\omega - \omega_o + n\Delta\omega) \]  

\[ (9) \]

All subpulses are processed in this way and then they are coherently synthesized. The whole spectrum with broadened bandwidth can be expressed as

\[ G(\omega) = \sum_{n=0}^{19} G_s(\omega - \omega_o + n\Delta\omega) = \sum_{n=0}^{19} S_{\text{ms}}(\omega - \omega_o + n\Delta\omega) \cdot B_o^*(\omega - \omega_o + n\Delta\omega) \]  

\[ (10) \]

Then, range profile of resolution improved can be obtained through IFFT operation.

\[ g(r) = \text{IFFT}(G(\omega)) \]  

\[ (11) \]

4. Azimuth compression by treating the azimuthal signal as a chirp signal. Due to the train speed is unknown, so it must be estimated from the echo data [11, 13].

Because we do not use any instrument to accurately measure the train speed and the view angle of radar boresight, they must be estimated through data processing. Indeed, the train speed \( V \) and the radar viewing angle \( \theta_b \) are related through the following equations:

\[ V = \sqrt{\left( \frac{\lambda f_{ao}}{2} \right)^2 - K_o R / 2}. \]  

\[ (12) \]

\[ \theta_b = \arcsin \left( \frac{\lambda f_{ao}}{2V} \right). \]  

\[ (13) \]

In the above two equations, only \( R \) is measured (which is the shortest distance between radar and the train), so we have to find a way to estimate the other parameters. In fact we have a simple way to do so: we adjust the boresight of antennas to let \( f_{ao} = 0 \) (which can be obtained from the Doppler spectrum through FFT in azimuthal direction), i.e. \( \theta_b = 0 \), then only \( V \) needs to be estimated. As we know, the Doppler rate \( Ka \) in (11) has much impact on the final radar image. On one hand, if it is far from the true value, the resulted radar image will be defocused, and on the other hand, if it is just slightly smaller or larger than the true value, then the azimuthal dimension...
gotten from the radar image would be slightly larger or smaller than the truth. The true length of the train can be obtained from a website, and it is found to be about 116-118 m in total. So we can judge whether the estimation of $V$ is accurate or not by comparing the retrieved azimuthal dimension in radar image with the length of 116-118m.

Even if we do not adjust the antennas to let $f_{DC} = 0$, we still can estimate both $V$ and $\theta_t$ through a joint estimation (searching) scheme according to the calculated $f_{DC}$ in consideration of possible Doppler ambiguity number. The judgement of the estimation accuracy is also based on the retrieved train length compared with the truth. In case with no target dimension available, we still can get an approximated estimation of Ka through an iterative process.

Fig. 6 presents the imaging result with 4GHz bandwidth (20 subchirps used). Fig. 7 presents the imaging result with 2GHz (10 subchirps used), Fig. 8 presents the imaging result with previously developed 2GHz system (20 subchirps used, the frequency step is 100MHz). For better understanding the radar images, the optical photo of the train is also presented in Fig. 9, from which one can see that the train is composed of 6 compartments, each with 3 same-size windows, 4 same-size doors, and 2 same-sized ventilators of air-conditioners. The train length from radar image is about 122m which is about 4 meters shorter than the truth. The main reason is because the train moves at a changing speed, or at accelerating or at decelerating, but the image is generated based on an average speed. Another reason is due to the electromagnetic scattering of the two locomotives, which results in the equivalent scattering centres apart from the physical ends.

Fig. 6 - Fig. 9 all clearly show the structure of the train as introduced above, i.e. the compartments (there are six), the windows (there are three in each compartment), the doors (there are four in each compartment), and the ventilators (the areas marked by dashed ellipse in Fig. 6) are well identified. After comparing Fig. 6 and Fig. 7 one can see that the two-sided doors and the ventilators in Fig. 6 are much clearer than that in Fig. 7. By comparing Fig. 8 and Fig. 9, one can find that although the signal bandwidths are the same, but radar images look different. The reason is due to the depressing angles are different for Fig. 7 and Fig. 8. One may find an interesting phenomenon that in the middle compartments of Fig. 6, Fig. 7, and Fig. 8, the information about doors and windows seem not as clear as that in the left and the right compartments. The reason is because there are much more people in the middle compartments than that in tow side compartments, and the multi-scattering effect between the people and the train body in the middle compartments is much stronger.

We should point out that the vertical axes of Fig. 6, Fig. 7, and Fig. 8 are about 12.5 times larger than the horizontal axes for clearly showing the structure of the train along range direction.

4 Conclusion

The Ku-band radar with 4GHz bandwidth is introduced as well as the radar imaging experiment for a moving train with this radar system. The 4GHz bandwidth is achieved by synthesizing 20 subpulses with a frequency step of 200MHz, each subpulse has a bandwidth of 220MHz. The RF subsystem design for implementing the SFCS model is presented. The obtained high-resolution radar images clearly show the doors, the windows, and the ventilators. Both 4GHz radar image and 2GHz radar images are presented for comparison. The reason why

References


