Enhancement of Range Resolution using Two Receivers in Continuous Time Frequency Modulation Technique

Kapil Dev Tyagi

Abstract*: The resolution in range in continuous time frequency modulation (CTFM) is directly proportional to the pulse width of the compressed signal. The two receiver technique for continuous transmission frequency modulation processing was proposed as a technique to make resolution independent of the pulse width. In two receiver technique the output is without any discontinuity in time. Practically, it has been observed that the resolution in range is also limited by the pulse width of the probe signal bandwidth in the two receiver CTFM technique. The actual performance and limitation of the two receiver technique has been given in this paper.

Keywords: Two receiver, Range-resolution, unperceptive-time.

I. INTRODUCTION

There are several applications of sonar processing where the range resolution plays a very important role in extracting the information [1-5]. According to Gough et al [6], "by using two receivers in continuous transmission frequency modulation system the received signal can be made smoothly continuous, due to which there is a complete elimination of the phase discrepancy and unperceptive-time and one can get desired resolution in range". We found that the improvement in resolution offered by two receiver technique is not as significant as expected. In practice, the improvement is only about 5% to 15% depending on the unperceptive-time width over a regular CTFM method. The resolution in range of CTFM technique is given as *CW/2*, where *C is* the sound speed in the medium and *W is* the pulse-width of the test signal [7]. The issue in two receivers' technique is the discontinuities in phase in the output waveform that occurred due to phase inconsistency at the edges of the stitched waveform segments of the two receivers in the beat frequency signal in each transmission. The phase discrepancy issue causes the statements of Gough et al [1] to be false. Their claim states that "we have removed the unperceptive-time from the output waveforms of the two receivers, thus producing the waveform continuous". This problem was not realized earlier, so actual improvement obtained using two receivers is explained in this paper.

The next section discusses the two receiver technique. Section III describes the hurdle in obtaining better resolution in range using two receiver method. Section IV describes the discrepancy of the claim of two receiver technique. Finally, conclusion part of this paper is presented.

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II. TWO RECEIVER CTFM BASICS

The perceptive-time also known as blind time actually limits the observation duration that results in limitation of range resolution in CTFM [6]. Gough et al [6] claimed to remove the unperceptive-time in two receiver processing also known as dual demodulator CTFM (DDCTFM) that results in increase in the perceptive-time. Larger observation time gives better estimation of frequency and therefore resolution in range improves. As demonstrated in Figure 1, the output waveform of two receivers must contain in phase sinusoids, whose instantaneous frequencies are directly proportional to the range of the reflected signal. To make the combined output of two receivers continuous, a signal generator in the second channel as depicted in Figure 1 is used. This extends the duration of transmitted signal by an amount equal to the maximum unperceptive-time. The signal generator at the receiver generates a linear frequency modulated (LFM) waveform that is in time consistency with the transmitted signal and also the rate of change of the probe signal frequency is same. The increase in frequency is from f_2 to f_3 of the signal generator. So, in the two receivers' method has two different channels, with both channel technique is same as

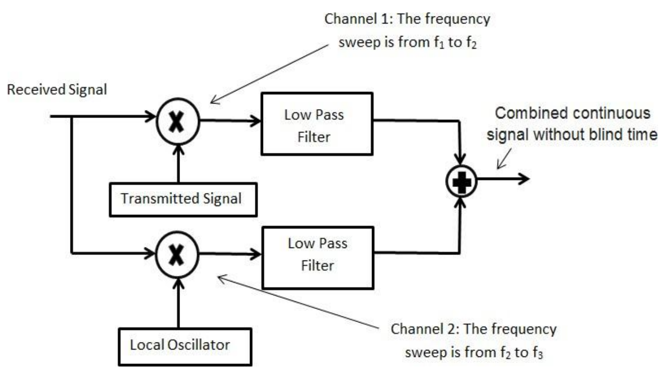

Fig. 1: Receiver processing of two receiver CTFM technique.

CTFM technique [8]. The received signal and the transmitted signal are multiplied with each other in channel 1 and after that low pass filtering will remove sum frequency components. In the second channel, the signal received is multiplied with the signal from the output of local signal generator and after that it is low pass filtered. This removes the sum frequencies.

Then, the output from each channels are added to get a continuous time waveform without any discontinuity in time. Now, these added filtered signals from the two channels will result in an improved range-resolution as the observation time is extendable to any required duration.

III. ISSUES IN TWO RECEIVER METHOD

It is observed by the analysis of the two receiver output that there is an issue of time mismatch discrepancy in the waveform due to phase mismatch. The output of two receivers must contain a waveform that is sinusoidal in nature and have no discrepancy in phase coming from both channels at the edges. In reality, there is a discrepancy in phase in the added and concatenated filtered sinusoids waveforms as indicated in Figure 2.

The plot of time and frequency of transmitted waveform and waveforms after mixing with local oscillator are depicted in Figure 2. The very first waveform of Figure shows the plot of time-frequency of the transmitted waveform and the received waveform signals in case of only a single received echo. The 2nd waveform of Fig. 2 shows the wrong jump frequency waveforms that does not contain the range information. The 3rd waveform is the correct beat frequency waveform. The frequency of beat waveform gives the required information about the delay of the received waveform. The waveform at jump are incorrect as it contains artifacts about the delay of the received waveform. As shown in Figure 2, the required beat frequency waveform is achieved from a segment of the total duration of transmitted waveform cycle only from first channel. For the remaining part of each transmission after the frequency changes of the transmitted signal, the beat frequency signal becomes unperceptive in first channel. The waveform duration for which, one gets the unwanted beat frequency signal is unperceptive -time and it is range dependent. The unperceptive -time limits the total useful period of the desired frequency waveform. Thus, the resolution of received frequency and hence resolution in range also limited. To make unperceptive–time useful one more channel with a local signal generator was proposed in [6]. The desired added waveform from the two different receivers is depicted by the 5th waveform, which does not contain any phase discrepancy. However, in reality the actual concatenated sinusoid waveforms shown by the 6th waveform contains the phase discontinuity, that limits the perceptive -time duration and the hence the resolution in range. The actual improvement in the observation time and range resolution is only maximum up-to 50% of obtained in CTFM.

IV. MATHEMATICAL EXPLANATION OF PHASE MISMATCH IN THE ADDED WAVEFORM

Let transmitted waveform $x(t)$ be a linear frequency modulated signal (up-chirp) represented as:

$$x(t) = \cos\left(2\pi\left(f_1 t + \frac{\mu t^2}{2}\right)\right) \text{ ………… (1)}$$

here f_1 is the starting frequency of the transmitted signal and μ is the rate of change of sweep. Let the instantaneous phase $\varphi_x(t)$ of the transmitted waveform be given as:

$$\varphi_x(t) = 2\pi\left(f_1 t + \frac{\mu t^2}{2}\right) \text{………… (2)}$$

Let signal received waveform $y(t)$ be a delayed version of the transmitted probe waveform and is given as:

$$y(t) = \cos\left(2\pi\left(f_1(t-\tau) + \frac{\mu(t-\tau)^2}{2}\right)\right) \text{……….. (3)}$$

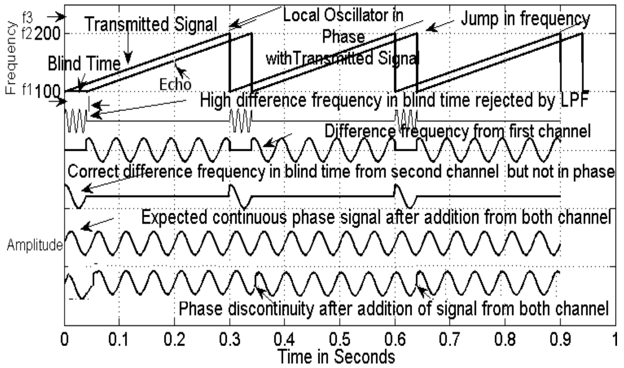

Figure 2: Time-frequency plot and two receiver processing: difference between desired waveform (2nd from bottom) and actual waveform (bottom).

where τ is the delay in the waveform received from target. The phase at receiving time of $y(t)$ be given as:

$$\varphi_y(t) = 2\pi\left(f_1(t-\tau) + \frac{\mu(t-\tau)^2}{2}\right) \text{………. (4)}$$

here $\varphi_y(t)$ is the phase of $y(t)$ at any given time t.

The transmitted waveform and received waveforms are mixed. The resultant signal is filtered to get only low frequency signal in first channel as demostrated by the Figure 1. We obatin the ideally required signal from a range cell during the unperceptive–time, a frequency generator at receiver is deployed. According to Gough et al [6] if the LFM frequency generator is used and is in time continuation with the transmitted waveform of the other channel with the same rate of change of frequency with time, we will get a smooth sinusoidal waveform in time after the addition of the two waveforms from two different receivers. Let the local signal generator waveform which is in time continuation with the transmitted waveform be given as:

$$z(t) = \cos\left(2\pi\left(f_2 t + \frac{\mu t^2}{2}\right)\right) + \varphi_I \text{………… (5)}$$

where starting frequency of local signal generator is f_2, that must be equal to the final frequency of the transmitted chirp waveform. Initially the phase φ_I of the local oscillator is same as the final phase of the transmitted waveform. The start phase φ_I is calculated using (2) as:

$$\varphi_I(t) = 2\pi\left(f_1 T + \frac{\mu T^2}{2}\right) \text{……………… (6)}$$

Let phase value of signal $z(t)$ be given by $\varphi_l(t)$:

$$\varphi_l(t) = 2\pi\left(f_2 t + \frac{\mu t^2}{2}\right) + \varphi_I \text{………… (7)}$$

The filtered waveform at the output of first channel has a phase calculated as:

$$\varphi_{f1}(t) = \varphi_x(t) - \varphi_y(t) \text{………. (8)}$$

The filtered waveform at the output of the second channel has the phase given as:

$$\varphi_{f2}(t) = \varphi_l(t) -$$

$\varphi_y(t)$............ (9)

The start frequency f_1, the end frequency f_2 and the chirp waveform duration T be taken as 0.1 kHz,0.2 kHz and 300 ms corresponding. The delay in the received waveform τ be 93 ms. The amount of μ is 333.3 Hz/sec. The amount of phase of the probe waveform at t = 300 ms given by (2) is $(90\pi)_{mod2\pi}$ = 0 radians. The amount of phase of the echo waveform at this instant of time calculated as given in (4) is $(55.68)_{mod2\pi}$ = 1.68π radians. Thus, the instant phase of the filtered waveform calculated by (8) at t = 300 ms from first channel is $(34.32\pi)_{mod2\pi}$ = 0.32π radians. The probe waveform will be back to its start frequency of 100 Hz at t = 300 ms, for the next clock. After this instant the required waveform during the unperceptive–time is provided by second receiver. Equations (4) and (7) give the phase of the echo waveform φ_y and signal generator waveform φ_l at t = 300 ms are $(55.68)_{mod2\pi}$ = 1.68π and $(90\pi)_{mod2\pi}$ = 0 radians respectively. Now, by (9) the start phase of the filtered waveform from second channel is $(34.32\pi)_{mod2\pi}$ = 0.32π radians. Therefore, the waveforms from the two channels is continuous without any discrepancy at t = 300 ms.

The desired waveform at t = 393 ms, is obtained from second channel. The local signal generator phase φ_l and the echo waveform φ_y at t = 393 ms using (7) and (2), are $(130.08\pi)_{mod2\pi}$ = 0.08π and $(90\pi)_{mod2\pi}$ = 0 radians. Thus, the filtered waveform from second channel at the end of the first cycle has phase $(40.08\pi)_{mod2\pi}$ = 0.08π radians calculated by (9). The required waveform after t = 393 ms is obtained from first channel. The phase of the transmitted waveform φ_x and the received waveform φ_y given by (2) and (4), are $(21.48\pi)_{mod2\pi}$ = 1.48π and $(90\pi)_{mod2\pi}$ = 0 radians. The start phase of first receiver using (8) is $(68.52\pi)_{mod2\pi}$ = 0.52π radians. The phase value is quite different from the phase of $(40.08\pi)_{mod2\pi}$ = 0.08π. Therefore, the added filtered waveform from the two receivers has a strong phase mismatch after t = 393 ms. The useful perceptive–time of the sinusoidal waveform corresponding to a received signal is increased by a time period equal to unperceptive–time, which is only a fraction of total LFM duration. Hence, one cannot increase the perceptive–time to any required value as given in [1]. The phase expressions for the waveforms of the two receivers at various time instants with an example are given in table I to illustrate the time discontinuity issue.

Simulation study of phase mismatch in the added signal: For the simulation the chirp parameters are taken to be 0.1 kHz, 0.2 kHz and 0.3second corresponding to the start frequency f_1, stop frequency f_2 and period T. The chirp waveform parameters generated by local LFM signal generator are as follows: 0.2 kHz, 0.24 kHz and .12 seconds corresponding to the start frequency f_2, stop frequency f_3 and period T. The total transmission duration is 12. Thus, received waveform time is 3.6 seconds. The perceptive–time is fixed and it is 0.12 seconds. The initial phase of the probe waveform is set to 0. The start phase of probe waveform generated from the local signal generator is set to the same value as that of the final phase of probe signal waveform at 0.3 seconds. The echoes waveforms are delayed and decayed in strength versions of the probe signal. The received waveform delay is 0.96 seconds. Thus, the processed waveform frequency of two receiver CTFM technique for this simulation must be 32 Hz. However, it is calculated to be 31.01 Hz as shown in Figure 3. Due to phase mismatch in every cycle of the transmitted chirp, the observation time is limited to same value as in case of CTFM technique and therefore there will be an ambiguity in the estimation of the correct frequency.

Table- I: Expressions and values of the receiver phases at various time instants

Parameter	Expression	Example
Start frequency	f_1	100 Hz
Stop frequency of $x(t)$	f_2	200 Hz
Sweep duration	T	300 ms
Delay in $y(t)$	τ	93 ms
Sweep rate	$(f_2 - f_1)/T$	333.3 Hz/sec.
Phase of $x(t)$ at $t = T$	$\varphi_x(t)$ as given in (2)	90π
Phase of $y(t)$ at $t = T$	$\varphi_y(t)$ as given in (4)	55.68π
Phase of $z(t)$ at $t = T$	$\varphi_l(t) = \varphi_i$	90π
Phase of $x(t)$ at $t = T + \tau$	$\varphi_x(t)$ at $t = T + \tau$	40.08π
Phase of $y(t)$ at $t = T + \tau$	$\Phi_{y(t)}$ at $t = T + \tau$	90π
Phase of $z(t)$ at $t = T + \tau$	$\varphi_l(t)$ at $t = T + \tau$	130.08π
Phase of channel 1 at $t = T$	$\varphi_{f2}(t) = \varphi_x(t) - \varphi_y(t)$	34.32π
Phase of channel 2 at $t = T$	$\varphi_{f2}(t) = \varphi_l(t) - \varphi_y(t)$	34.32π
Phase of channel 1 at $t = T + \tau$	$\varphi_{f2}(t) = \varphi_x(t) - \varphi_y(t)$	-49.92π
Phase of channel 2 at $t = T + \tau$	$\varphi_{f2}(t) = \varphi_l(t) - \varphi_y(t)$	40.08π

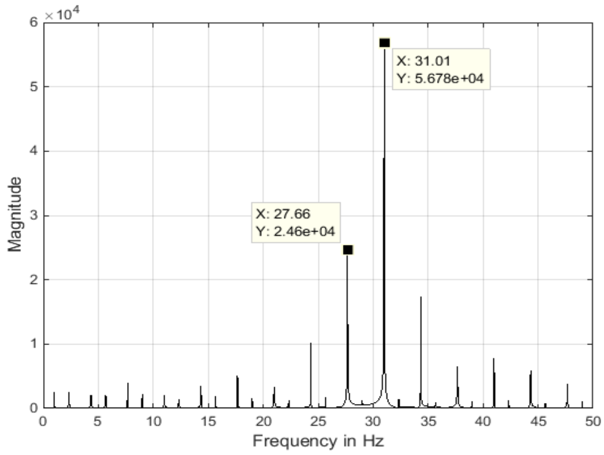

Fig. 3: Phase discrepancy issue illustration by using DFT plot obtained from processed waveform of two receiver CTFM processing.

V. RESULTS AND OBSERVATIONS

Table 1. Results obtained by the proposed method and comparison with the previous claims

Maximum improvement in range-resolution using proposed two receiver method over CTFM	Factor of 1.5
Maximum improvement in range-resolution claimed in literature CTFM	Infinite (Claim proved to be wrong in Section IV)

Therefore, gain in the range resolution in two receiver CTFM technique is very limited. Actual improvement factor over conventional CTFM technique depends on the utilization duration of unperceptive–time. The maximum gain in resolution up to 50% in is negligible compared to the amount claimed in [6].

Side-lobe artifact issue: There is a problem of side-lobe artifacts in the received signal waveform. The location of artifacts is at multiples of 1/T Hz from the frequency of the waveform and it appears in the form of peaks at several frequencies in FFT of the output of two receiver technique. For the example taken in section IV, the artifacts are demonstrated in Figure 3. These artifacts cause the detection of the weaker echoes very difficult.

VI. CONCLUSION

It is observed that the improvement using two receiver CTFM method is 1.5 times the maximum range-resolution obtained in CTFM. The issues in two receiver CTFM technique proposed in [6] are presented. The analysis using equations and simulations illustrated that the two receiver CTFM technique which claims that "we have removed the unperceptive–time of CTFM sonar to obtain any desired range resolution" [6].

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