VELOCITY ERROR ANALYSIS OF COHERENT AND NON-COHERENT TRANSPONDING TRACTORY MEASUREMENT SYSTEM

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ABSTRACT

This paper introduces two transponders combining coherent transponding and non-coherent transponding for multistatic trajectory measurement system and carrier Doppler frequency extraction principle, then derives each model of the velocity error for noise. The expressions of velocity error resulted by noise in coherent, IF-modulated and IF transform transponding configurations are also described. The conclusion is drawn: the system velocity error for noise is related to the transponder transponding configuration. And, the velocity error in coherent, IF-modulated and IF transform transponding configurations are compared in this paper.

KEYWORDS

Coherent and non-coherent transponding combined, IF-modulated transponding, IF-transform transponding, velocity error.

INTRODUCTION

The high-accuracy $3R\dot{R}$ multistatic system consists of three high-accuracy Doppler and range trackers which operates at CW and uses one transponder, with the advantages of high independence, convenient for deploying the stations and using for multistatic system co-operatively to achieve higher system measurement accuracy. However, the key to the high accuracy $3R\dot{R}$ measurement system is the implementation of transponder. As constraints were placed on the size, weight and power consumption of the transponder and the installation position of the antenna, the transponder configuration should be as simple as possible and easy to make. Up to now, the $3R\dot{R}$ transponder in practical application can be divided into two kinds: coherent transponding and non-coherent transponding. Using the coherent transponding transponder, the ground-station is simple, the transponder range error induced by Doppler frequency is small, and the single station is easy to achieve high-accuracy range and range rate data. However, the airborne subsystem needs to install three coherent transponders that are completely independent, so the size is large, power consumption is high, and antennas are difficult to be installed. On the contrary, using non-coherent transponder, as the non-coherent frequency beacon is introduced to the transponder, so its configuration can be significantly simplified, and the size, weight and power consumption can all be reduced. But the range error of the transponder is relatively higher, meanwhile, the ground station has to cancel the non-coherent beacon frequency in the retransmitted signals to extract carrier Doppler frequency for target velocity measurement, which has a certain influences on the velocity accuracy. Non-coherent transponding transponder is generally used in medium-accuracy multistatic system. Using the multistatic system combining coherent transponding with non-coherent transponding, one station is designed according to coherent configuration, so the system measurement accuracy is improved while the transponder configuration is relatively simple.

This paper describes two transponders combining coherent transponding with non-coherent transponding and the system extract carrier Doppler frequency principle. In the paper, the expressions for the velocity error resulted by the noise in coherent transponding, IF-modulated transponding and IF transform transponding configurations are described, and the velocity accuracy are also compared.

IF-MODULATED TRANSPONDING AND DOPPLER FREQUENCY EXTRACTION PRINCIPLE

The block diagram of coherent and IF-modulated transponding multistatic transponder and its uplink & downlink spectrum is shown in Fig.1. The three individual ground station uplink frequencies f_{R1}, f_{R2} and f_{R3} are respectively from ground stations A, B and C, the downlink signal is the united carrier signal phase modulated with f_{c1}, f_{c2} and f_e.

The transponder coherently retransmits the uplink frequency f_{R1} from the ground station A, i.e. the ratio of uplink carrier f_{R1} and the downlink f_T is a fixed constant, the ranging signal f_e modulated on f_{R1} is phase locked demodulated and re-modulated onto the downlink carrier f_T for transmitting.

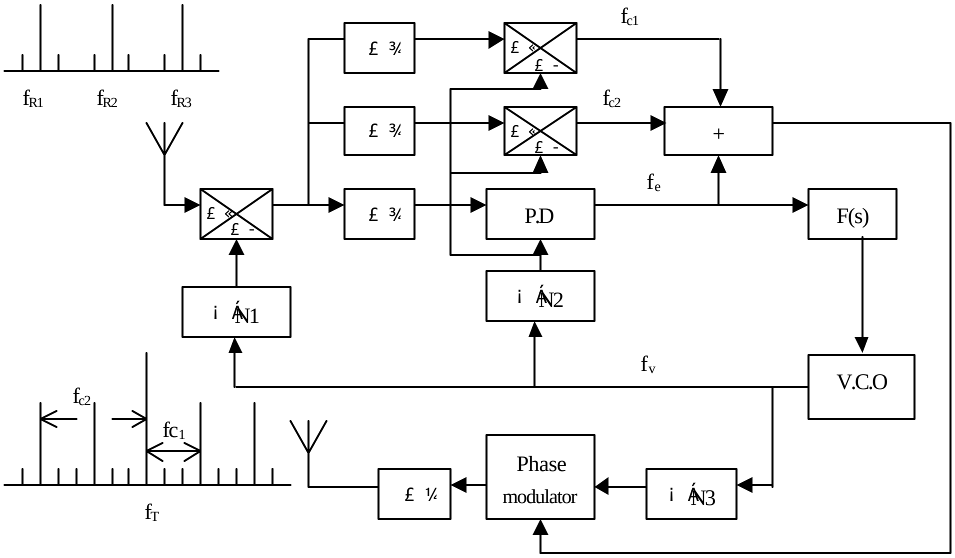

Fig.1 Block Diagram of the Coherent and IF-modulated Transponding Transponder

The transponder non-coherently retransmits the uplink frequencies f_{R2} and f_{R3} from ground stations B and C by means of IF modulation, i.e., sub-carriers f_{c1} and f_{c2} are obtained after the uplink signal being secondary down converted, and then modulated onto the downlink carrier f_T along with the raging signal f_e from the ground station A .

It can be known from Fig.1 that when the transponder loop is locked on the uplink frequency f_{R1} from the ground station A, its frequency relation is:

$$f_{R1} - Nf_v = N_2 f_V$$

$$f_T = N_3 f_v = \boldsymbol{r} f_{R1} \tag{1}$$

$$f_{c1} = f_{R2} - f_{R1} \tag{2}$$

$$f_{c2} = f_{R3} - f_{R1} \tag{3}$$

Where f_v is the frequency of the voltage-controlled oscillator (VCO), $\boldsymbol{r} = f_T \big/ f_{R1} = \dfrac{N_3}{N_1 + N_2}$ is the coherent ratio of the transponder.

It can be known from equation (1) that the carrier frequency f_T retransmitted by the transponder only contains the uplink from ground station A, so it is coherent with the uplink f_{R1} from ground station A, thus, the carrier Doppler can be extracted directly from it, but the retransmitted carrier f_T is non-coherent with f_{R2} and f_{R3} from ground stations B and C, so it can be seen as the frequency beacon of the transponder.

It can be known from equation (2) or (3) that the sub-carrier frequency retransmitted by the transponder contains two terms, the first, being a coherent component, is the carrier frequency of the ground station uplink at f_{R2} or f_{R3}, and the second, being a non-coherent component, is the frequency beacon of the transponder, thus, the carrier Doppler of the ground stations B or C can't be simply extracted from the sub-carrier frequency at f_{c1} and f_{c2}, and special processing method must be employed.

Doppler extraction principle of the IF-modulated non-coherently transponding is as the following:

Set the transmit signal carrier frequencies from ground stations A and B as f_1 and f_2, so the receive carrier frequencies of the transponder are $f_{R1} = k_1 f_1$, $f_{R2} = k_2 f_2$ due to the Doppler frequency induced by the relative movement of the target (k is the index, which is related to the radial velocity of target relative movement, k_1 isn't equal to k_2 as the locations of the ground station are different).

It is can be known from equations (1) and (2), the frequencies of the carrier and sub-carrier arriving the ground receiver are as the following respectively:

$$k' f_T = k' \boldsymbol{r} f_{R1} = k' k_1 \boldsymbol{r} f_1 \qquad (4)$$

$$k' f_{c1} = k' \left(f_{R2} - f_{R1} \right) = k' k_2 f_2 - k' k_1 f_1 \qquad (5)$$

Where the index k' is related to the radial velocity that the target moves relatively to the receive station.

Solving above simultaneous equations, the carrier Doppler of ground station B or C can be obtained, i.e. the ground station B or C is able to extract the transponder beacon frequency from the received carrier frequency, and cancel the beacon frequency in the sub-carrier, thus, the coherent carrier Doppler frequency of this station is obtained as shown in Fig.2. where $\sigma_{\phi I}$ is the carrier phase jitter induced by the receiver noise, $\sigma_{\phi 2}$ is the phase jitter of the sub-carrier.

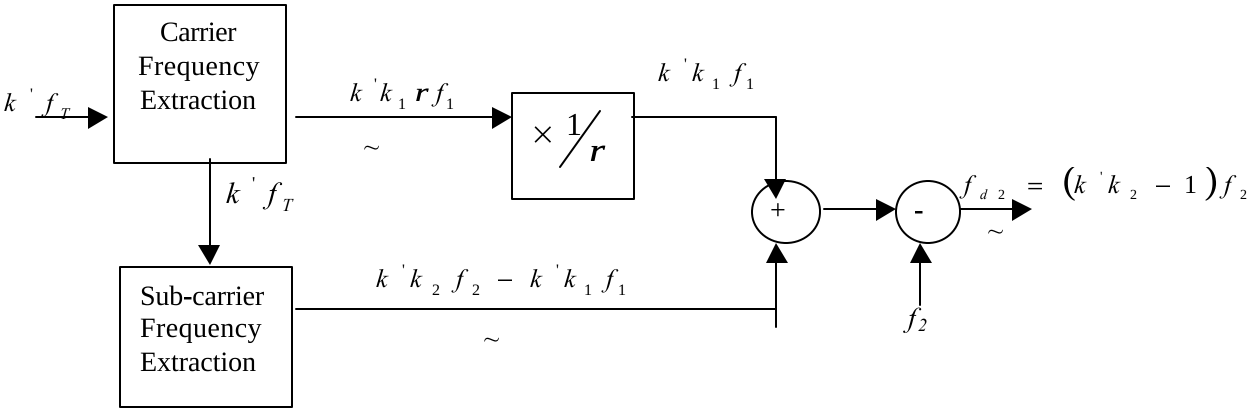

Fig. 2 Doppler Extraction Block Diagram of IF-modulated Transponding

IF TRANSFORM FROM TRANSPONDING AND DOPPLER EXTRACTION PRINCIPLE

The block diagram and uplink/downlink spectrum of the IF transform transponder is shown as Fig. 4, the phase lock loop of the transponder locks the VCO frequencies onto f_{R1}, the uplink signals f_{R1}, f_{R2} and f_{R3} from the three ground station A, B and C are directly retransmitted to its ground station after secondary frequency conversion and amplification, so, it is known as IF transform transponder. As the three LO signals are obtained by phase locked dividing and multiplying of the signals from ground station A at f_{R1}, so the carrier frequency f_{T1} are coherent with f_{R1}, but the downlink frequencies f_{T2} or f_{T3} containing frequency f_{R1} are non-coherent with uplink f_{R2} or f_{R3}.

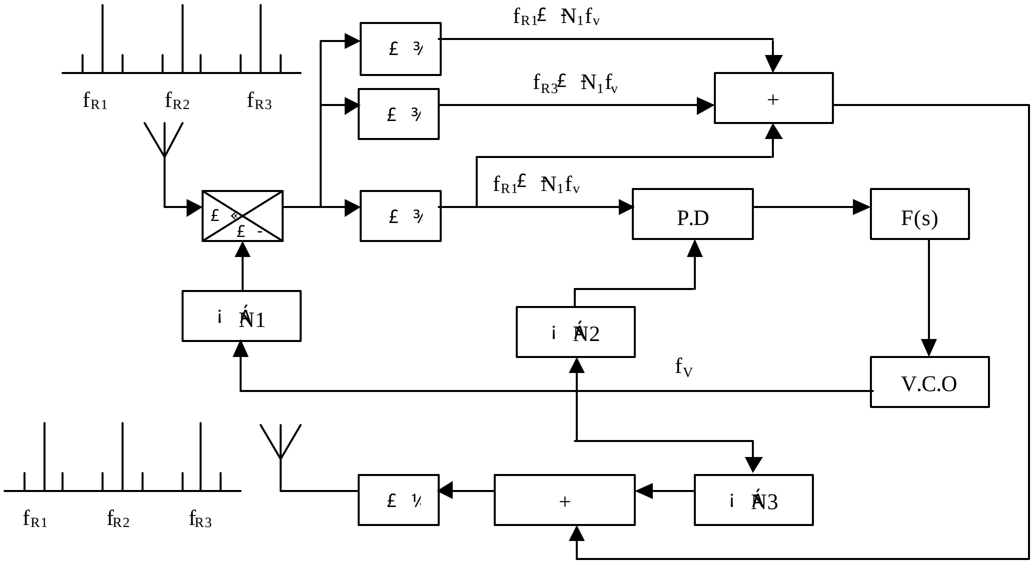

Fig.3 Block Diagram of Coherent and IF Transform Transponding

It can be known from Fig.3 that the frequency of the transponder is as the following:

$$f_{T1} = N_3 f_v + \left(f_{R1} - N_1 f_v\right) = r f_{R1} \tag{6}$$

$$f_{T2} = f_{R2} - (1 - r) f_{R1} \tag{7}$$

$$f_{T3} = f_{R3} - (1 - r) f_{R1} \tag{8}$$

Where $f_v = \dfrac{1}{N_1 + N_2} f_{R1}$

$r = \dfrac{f_{T1}}{f_{R1}} = \dfrac{N_2 + N_3}{N_1 + N_2}$ is the coherent ratio of the transponder,

$1 - r = \dfrac{N_1 - N_3}{N_1 + N_2}$ is the relative frequency difference between uplink and downlink.

IF transform transponding Doppler extraction block diagram is shown as Fig.6, $\sigma_{\phi 1}$ is the phase jitter induced by the receiver noise on the beacon carrier frequency f_{T1}, $\sigma_{\phi 2}$ is the phase jitter of f_{T2}.

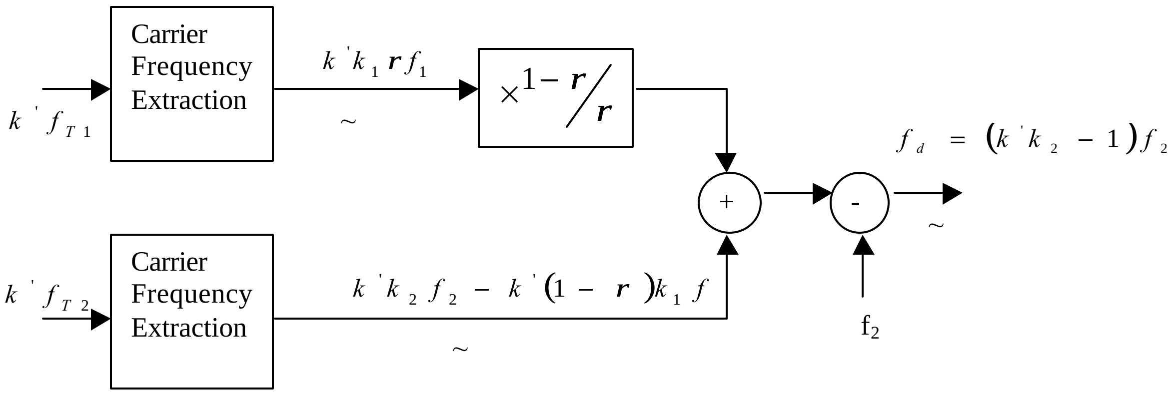

Fig.4 Doppler Extraction Block Diagram of the IF Transform Transponding

VELOCITY MEASUREMENT ACCURACY ANALYSIS

The velocity measurement error are mainly produced by the frequency jitter of the transmitter source, receiver noise, phase jitter of the DCO in the digital PLL and the quantization error of the frequency, in which, the velocity error generated by the receiver noise is related to the transponding configuration of the transponder. The velocity error induced by the receiver noise will be analyzed and compared under the three transponding configurations in this section.

(1) Coherent Transponding

Coherent transponding velocity error model is shown as Fig.5, the received velocity message is included in the downlink carrier frequency, and the extracted Doppler frequency f_d is the Doppler of the uplink carrier frequency f_1.

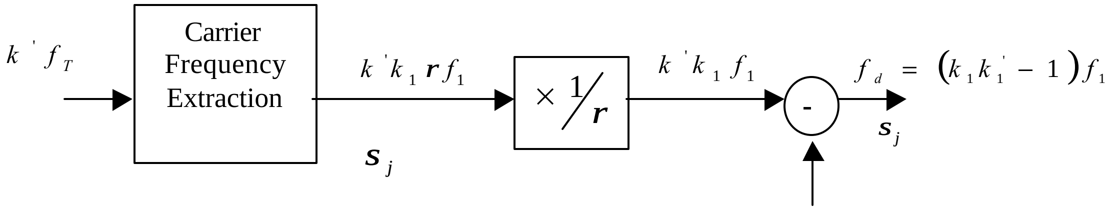

Fig.5 The Velocity Error Model of Coherent Transponding

The downlink carrier frequency is extracted using the phase locked loop, the phase error induced by the receiver noise is s_{j1}[1], the phase noise s_j from the f_d extractor is:

$$s_j = \frac{1}{r} s_{j1} = \frac{1}{r}\left[2(SNR)_{BL1}\right]^{-\frac{1}{2}} = \frac{\sqrt{B_{L1}}}{r\sqrt{(S/\Phi)_C}} \tag{9}$$

Where $(SNR)_{BL1}$ is the signal-to-noise ratio of the carrier phase lock loop□ B_{L1} is the noise bandwidth of the carrier phase lock loop, $(S/\Phi)_C$ is the ratio of its signal power and noise power spectral density(dB·Hz). The velocity error generated by phase error of the phase lock loop is [2]:

$$s_v = \frac{l_1}{4p}\cdot\frac{s_j}{T} \tag{10}$$

Where ë$_1$ is the wavelength of the uplink carrier signal, T is the sampling interval of the velocity extractor. Substituting equation (9)into equation (10),the velocity error of the coherent transponding resulted by receiver noise is:

$$s_{v1} = \frac{l_1}{4pr}\cdot\frac{1}{T}\cdot\frac{\sqrt{B_L}}{\sqrt{(S/\Phi)_C}} \tag{11}$$

(2) IF-modulated Transponding

Fig.2 is the velocity error model of IF-modulated transponding. The downlink carrier frequency is $k'f_T$, the sub-carrier frequency k'fc is demodulated by carrier loop. The Doppler f_{d2} is the Doppler of uplink carrier f_{R2} or f_{R3}.

It is known from Fig.2 that the phase error resulted by the Doppler extractor is:

$$s_j = \left[\left(\frac{1}{r}s_{j1}\right)^2 + s_{j2}^2\right]^{\frac{1}{2}} = \frac{1}{r}\frac{\sqrt{B_{L1}}}{\sqrt{(S/\Phi)_C}}\left[1 + r^2\frac{B_{L2}}{B_{L1}}\frac{(S/\Phi)_C}{(S/\Phi)_{SC}}\right]^{\frac{1}{2}}$$

Where B_{L1} is the noise bandwidth of the carrier phase lock loop, B_{L2} is the noise bandwidth of the sub-carrier phase lock loop, generally, $B_{L1}=B_{L2}$, $(S/\Phi)_C$ is the ratio of the carrier signal power and noise power spectral density(dB·Hz), $(S/\Phi)_{SC}$ is the ratio of sub-carrier signal power and noise power spectral density(dB·Hz). The velocity error resulted by receiver noise is:

$$s_v = s_{v1}\cdot\left[1 + r^2\cdot\frac{(S/\Phi)_C}{(S/\Phi)_{SC}}\right]^{\frac{1}{2}} \tag{12}$$

Where $s_{v1} = \frac{l_2}{4pr}\cdot\frac{1}{T}\cdot\frac{\sqrt{B_{L1}}}{\sqrt{(S/\Phi)_C}}$

$$s_v = s_{v1}\left[1 + r^2\right]^{\frac{1}{2}} \tag{13}$$

for $(S/\Phi)_C = (S/\Phi)_{SC}$

Where $\left(1 + r^2\right)^{\frac{1}{2}}$ is the velocity error weighting factor of IF-modulated transponding, because ñ>0, the velocity error resulted by the IF-modulated transponding is higher than that by coherent transponding.

(3) IF Transform Transponding

Fig.4 is the velocity error model of IF transform transponding, the received carrier are the $k'f_{T1}$ and $k'f_{T2}$ respectively, the extracted Doppler is in the uplink carrier Doppler frequency at f_2 or f_3.

It is known from Fig.4 that total phase noise resulted by the Doppler extractor is:

$$s_j = \left[\left(\frac{1-r}{r}\right)^2 s_{j1}^2 + s_{j2}^2\right]^{\frac{1}{2}} = \frac{1}{r}\frac{\sqrt{B_{L1}}}{\sqrt{(S/\Phi)_{C1}}}\left[(1-r)^2 + r^2\frac{B_{L2}}{B_{L1}}\frac{(S/\Phi)_{C1}}{(S/\Phi)_{C2}}\right]^{\frac{1}{2}}$$

Where $(S/\Phi)_{C1}$ is the ratio of signal power and noise power spectral density for the carrier at f_{T1}, B_{L1} is its loop noise bandwidth, $(S/\Phi)_{C2}$ is the ratio of signal power and noise power spectral density for the carrier at f_{T2} or f_{T3} , B_{L2} is its loop noise bandwidth, in general,

$B_{L1}=B_{L2}$.

The velocity error resulted by IF transform transponding is:

$$\boldsymbol{s}_v \text{£½} \boldsymbol{s}_{v1} \cdot \left[(1-\boldsymbol{r})^2 + \boldsymbol{r}^2 \frac{(S/\Phi)_{C1}}{(S/\Phi)_{C2}} \right]^{\frac{1}{2}} \qquad (14)$$

$$\boldsymbol{s}_v = \boldsymbol{s}_{v1}\left[(1-\boldsymbol{r})^2 + \boldsymbol{r}^2\right]^{\frac{1}{2}} = \boldsymbol{s}_{v1}\left[1-2\boldsymbol{r}(1-\boldsymbol{r})\right]^{\frac{1}{2}} \qquad (15)$$

for $(S/\Phi)_{C1} =| (S/\Phi)_{C2}$

Where $\left[(1-\boldsymbol{r})^2 + \boldsymbol{r}^2\right]^{\frac{1}{2}}$ is the weighting factor of the velocity error resulted by IF transform. When ñ<1, i.e. while the system downlink frequency is lower than uplink frequency, the velocity error resulted by noise of the IF transform transponding is lower than that of coherent transponding, in the contrary, it is higher than that of coherent transponding.

CONCLUSION

It can be known from above analysis that the receiver velocity error by noise is related to the transponding configuration of the transponder and the system coherent ratio. The equations (11),(12) and (14)give respectively the expressions of the velocity error resulted by the noise of coherent transponding, IF-modulated transponding and IF transform transponding.

When the value of (S/Φ) and B_L of the coherent branch are respectively equal to that of non-coherent branch, the error induced by IF-modulated transponding is higher than that of the other two configurations;the noise error induced by IF transform transponding is minimum whenñ<1, and the noise error induced by coherent transponding is minimum when ñ>1.

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