# EQUIPMENT TIME-DELAY (ETD) MEASUREMENT TECHNOLOGY FOR CONTINUOUS WAVE TRANSPONDER

**Huang Chengfang**
**Southwest Institute of Electronics Technology, Chengdu, 610036, China**

**Hu Jianping**
**Southwest Institute of Electronics Technology, Chengdu, 610036, China**

## ABSTRACT

The Equipment Time-Delay (ETD) measurement technology for Continuous Wave (CW) transponder is discussed with emphasis on the principle of measuring the ETD of the intermediate frequency (IF) modulation transponder through measuring subcarrier modulation sideband tone phase. A general method for measuring ETD of different types of transponder (including IF-modulation transponder) is introduced. Finally the measurement method error is analyzed.

## KEYWORDS

Transponder, Equipment Time-Delay (ETD), IF-modulation transponder, range tone

## INTRODUCTION

In the Continuous Wave (CW) tracking measurement system, the signal will be delayed for a fixed time when it goes through the equipment because there are inertial elements in the equipment. The fixed time delay is called Equipment Time-Delay (ETD). The ETD measurement error and variation will introduce ranging error, which takes a large proportion in total error. How to accurately measure the ETD of the ground station and spaceborne transponder is an important research theme in the CW tracking measurement system. The traditional method for measuring ETD is comparison. A wideband frequency converter with small ETD is used as a reference because difference exists in uplink and downlink carrier frequencies. The ETD difference of the transponder and the frequency converter, $\tau_T - \tau_C$, can be get by the ETD Measurement System. The ETD sum of the ground station and the reference frequency converter $\tau_G + \tau_C$ can be get through the ground station calibration and be added with the result measured from the ETD measurement system, then the ETD of the tracking measurement system $\tau_G + \tau_T$ can be obtained. During the course of the spacecraft measurement, the flying reality range time-delay $\tau$ of spacecraft can be obtained by subtracting the system ETD from the measuring range data of the ground station, then the reality range of spacecraft, $R = C\tau/2$ ,can be calculated.

In the early 1980s, we successfully developed an ETD measurement system for transponder[1], which can directly measure the ETD of the measured unit (transponder or calibration frequency converter) without comparison. The operation principle is shown in Figure1. Under the measurement state, the switch is set to position 1, and the testing receiver is tuned onto downlink frequency so as to get the ETD $\tau_T + \tau_E$ of the measured transponder and the measurement system; under self-correction, the switch is set to Position 2, and the testing receiver is tuned onto uplink frequency so as to get the ETD $\tau_E$ of the measurement system itself. The ETD $\tau_T$ of the measured transponder will be calculated when making a subtraction $\tau_E$ from $\tau_T + \tau_E$. The measurement error induced by different carrier frequencies can be neglected because the wideband frequency mixer is used in testing receiver, and the range tone and modulation forms for uplink and downlink signals of tracking measurement system are same.

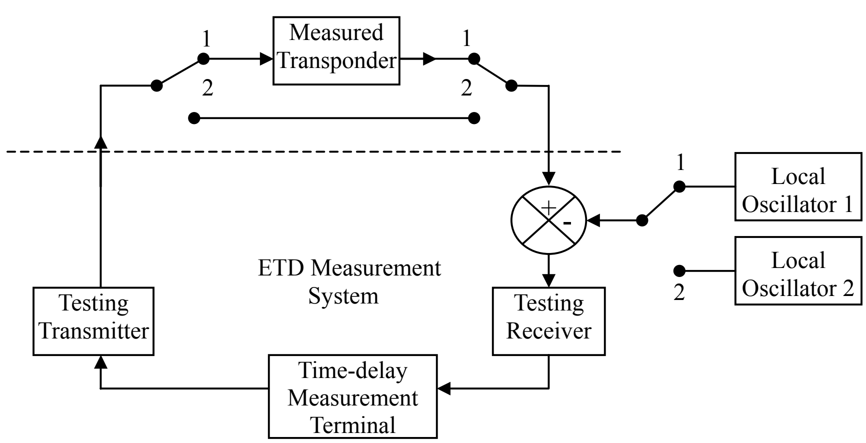


**Figure 1.** ETD Measurement System

The above method is only applicable to coherent transponding system or frequency transform transponding system, and not applicable to the IF-modulation transponding tracking system[2]. Its transponder can be illustrated in Figure 2. Due to the different modulation form of range tone between uplink and downlink signals in IF-modulation measurement system, the uplink tone is directly modulated onto the uplink carrier while the downlink tone is modulated onto IF-subcarrier and then the subcarrier is modulated onto downlink carrier, the transponder ETD can not be measured by above ETD measurement method. Therefore, the ground station calibration testing with the transponder is usually adopted to derive the whole system ETD $\tau_G + \tau_T$. The ETD calibration of the ground station takes the special calibration transponder with a smaller ETD as the reference, the ETD of the calibration transponder is obtained by test or estimation of its elements' parameters, so the induced range error may be larger.

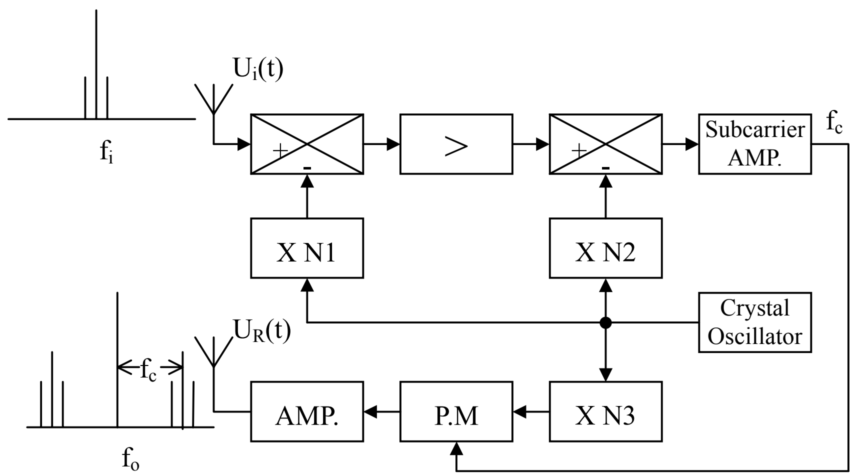


**Figure 2.** Schematic Diagram of IF-Modulation Transponder

This paper describes the CW transponder ETD measurement technology, with emphasis on operation principle of the IF-modulation transponder ETD measurement performed by measuring the range tone phase of the first order downlink subcarrier modulation sideband, introduces the common ETD measurement method for all kinds of CW transponder, including coherent transponder, frequency transform transponder, IF-modulation transponder as well as coherent and non-coherent combining transponder[3], and finally analyzes the measurement method errors.

## PRINCIPLE OF MEASURING ETD BY DEMODULATING TONE ON SIDEBAND

### 1.Format of Signal

The schematic diagram of IF modulation transponder and its uplink and downlink spectrum is shown in Figure 2. The uplink signal is phase-modulated by the range tone, that is to say, the uplink signal of system is represented as

$$U_i(t) = A_i Sin[\omega_i t + \Delta\Phi Cos(\Omega t + \Phi_0)] \qquad (2\text{-}1)$$

where $\omega_i$ = the carrier angular frequency of uplink signal,
$\Delta\Phi$ = the phase modulation index of range tone,
$\Omega$ = the angular frequency of range tone, and
$\Phi_0$ = the initial phase of range tone.

The system downlink signal is secondary phase modulation. The uplink signal received by transponder from the ground station becomes the IF (f $_c$) subcarrier signal after twice frequency conversion, then phase modulated onto the downlink carrier. So, the downlink signal transponded by transponder is represented as:

$$U_R(t) = A_c Sin\{\omega_0 t + \Delta\theta Sin[\omega_c t + \Delta\Phi Cos(\Omega t + \Phi_1)]\} \qquad (2\text{-}2)$$

where $\omega_0$ = the carrier angular frequency of downlink signal,
$\Delta\theta$ = the phase modulation index of subcarrier,
$\omega_c$ = the angular frequency of subcarrier,
$\Phi_1$ = the initial phase of transponded range tone.

When bandwidth is not limited, the spectral characteristic of the downlink signal is:

$$\begin{aligned} U_R(t) &= I_m A_c e^{j\{\omega_0 t + \Delta\theta Sin[\omega_c t + \Delta\Phi Cos(\Omega t + \Phi_1)]\}} \\ &= I_m A_c e^{j\omega_0 t} e^{j\Delta\theta Sin[\omega_c t + \Delta\Phi Cos(\Omega t + \Phi_1)]} \\ &= A_c \sum_{n=-\infty}^{\infty} J_n(\Delta\theta) Sin\{\omega_0 t + n[\omega_c t + \Delta\Phi Cos(\Omega t + \Phi_1)]\} \end{aligned} \qquad (2\text{-}3)$$

Where we used the identity

$$e^{j\Delta\theta Sin(\omega_c t + \Phi)} = \sum_{n=-\infty}^{\infty} J_n(\Delta\theta) e^{jn(\omega_c t + \Phi)}$$

Equation(2-3) yields two types of sideband terms: the carrier $\omega_0$ and a set of sidebands $\omega_0 \pm n\omega_c$.

Because of the limitation of transmitting channel bandwidth of transponder and receiving bandwidth of ground stations, the signal arriving at ground station contains only the first order sideband and the phase and modulation index of tone signal of upper and lower sideband is varied, that is to say, the following equation exists:

$$
\begin{aligned}
U_R(t) = {} & A_c J_0(\Delta\theta) Sin\omega_0 t \\
& + A_c J_1(\Delta\theta) Sin\left[(\omega_0 + \omega_c)t + \Delta\Phi_1 Cos(\Omega t + \Phi_1)\right] \\
& - A_c J_1(\Delta\theta) Sin\left[(\omega_0 - \omega_c)t - \Delta\Phi_1^{'} Cos(\Omega t + \Phi_1^{'})\right]
\end{aligned} \tag{2-4}
$$

where the first item from right is the downlink carrier signal, the second item is the first order upper sideband signal and the third item is the first order lower sideband signal; $\Delta\Phi_1$ and $\Delta\Phi_1^{'}$ are the phase modulation index of the upper and lower sideband tone , respectively; and $\Phi_1$ and $\Phi_1^{'}$ represent respectively the tone phase of the upper and lower sideband.

From equation (2-1), (2-2) and (2-4) it can be seen that:

1) The secondary demodulation scheme must be adopted for the IF-modulation transponding ground station. In the first coherent demodulation, the subcarrier signal can be recovered to extract coherent carrier Doppler frequency for the velocity measurement of object. In the second demodulation, the range tone can be recovered to complete the ranging of object;

2) The ETD of IF modulation transponder can not be measured with traditional methods because the tone modulation forms of uplink and downlink signal are different;

3) The ETD information of transponder is included in the range tone of the upper and lower sideband of downlink. With testing receiver tuned onto the upper or lower sideband, the measurement system can demodulate its range tones respectively, thus, the tone phase $\Phi_1, \Phi_1^{'}$ and amplitude $\Delta\Phi_1$, $\Delta\Phi_1^{'}$ can be accurately measured, because the range tone and its modulation form of the first order sideband of the transponder is the same as that of the uplink signal so that the ETD test state is consistent with self-calibration state in order to accurately deduce the fixed time delay of ETD measurement system itself. If the accurately corresponding algorithm between the secondary demodulation range tone phase and the phase and amplitude of range tone of upper and lower sideband can be found, the measurement of ETD of various types of transponder can be realized.

**2.Algorithm of ETD by Sideband Measurement**

The secondary demodulation principle of ground station is shown in Figure 3. The received signal transponded by transponder multiplies the coherent local carrier $Cos\omega_0 t$ to complete the first coherent demodulation. Then it multiplies the coherent local subcarrier $Cos\omega_c t$ to complete the second coherent demodulation. The secondary demodulation output signal $U_0(t)$ is represented as:

$$U_0(t) = U_R(t) \cdot Cos\omega_0 t \cdot Cos\omega_c t$$

$$= \frac{1}{4} A_c J_1(\Delta\theta)\left\{Sin\left[\Delta\Phi_1 Cos(\Omega t + \Phi_1)\right] - Sin\left[-\Delta\Phi_1^{'} Cos\left(\Omega t + \Phi_1^{'}\right)\right]\right\}$$

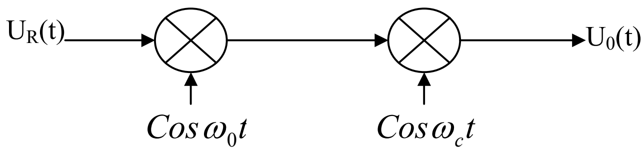


**Figure 3.** Secondary Coherent Demodulation

Under the condition of small angle modulation and linear demodulation, $Sin\theta \approx \theta$, then

$$\begin{aligned} U_0(t) &= \frac{1}{2} A_c J_1(\Delta\theta)\left[\Delta\Phi_1 Cos(\Omega t + \Phi_1) + \Delta\Phi_1^{'} Cos\left(\Omega t + \Phi_1^{'}\right)\right] \\ &= \frac{1}{2} A_c J_1(\Delta\theta)|\Delta\Phi| Cos\left(\Omega t + \Phi_1 + \overline{\Phi}\right) \end{aligned} \tag{2-5}$$

where $|\Delta\Phi| = \sqrt{\Delta\Phi_1^{\,2} + \Delta\Phi_1^{'2} + 2\Delta\Phi_1 \Delta\Phi_1^{'} Cos\left(\Phi_1^{'} - \Phi_1\right)}$

$$\overline{\Phi} = tg^{-1}\left[\frac{\Delta\Phi_1^{'} Sin\left(\Phi_1^{'} - \Phi_1\right)}{\Delta\Phi_1 + \Delta\Phi_1^{'} Cos\left(\Phi_1^{'} - \Phi_1\right)}\right] \tag{2-6}$$

The ETD of transponder is:

$$\tau_T = \frac{\lambda}{4\pi C} \cdot \left(\Phi_1 + \overline{\Phi} - \Phi_0\right) \tag{2-7}$$

where $\lambda$ = the wavelength of range tone,
C = velocity of light, and
$\left(\Phi_1 + \overline{\Phi} - \Phi_0\right)$ =the tone phase induced by time delay of transponder.

Thus it can be seen that the ETD of transponder can be calculated with equation (2-6) and (2-7) if the amplitude and phase of the upper and lower sideband tone are measured respectively.

In case of $\Delta\Phi_1 = \Delta\Phi_1^{'}$, $\overline{\Phi} = \left(\Phi_1^{'} - \Phi_1\right)/2$ can be obtained from equation (2-6). Then, the ETD of transponder is simplified as:

$$\tau_T = \frac{\lambda}{8\pi C}\left(\Phi_1 - \Phi_0 + \Phi_1^{'} - \Phi_0\right) \tag{2-8}$$

where $\Phi_1 - \Phi_0$ = the upper sideband tone phase shift induced by time delay of transponder

$\Phi_1^{'} - \Phi_0$ = the lower sideband tone phase shift induced by time delay of transponder.

## HOW TO MEASURE THE ETD BY SIDEBANDS

### 1. Principle of Sideband Coherent Demodulation

The sideband coherent demodulation is shown in Figure 4. Tune respectively the testing receivers on the sideband carrier frequency and multiply the coherent local signal $Cos(\omega_0 + \omega_c)t$ or $Cos(\omega_0 - \omega_c)t$, the range tone can be demodulated from sideband. Equation (2-4) multiplying $Cos(\omega_0 + \omega_c)t$ can get the range tone demodulated from the upper sideband, which is:

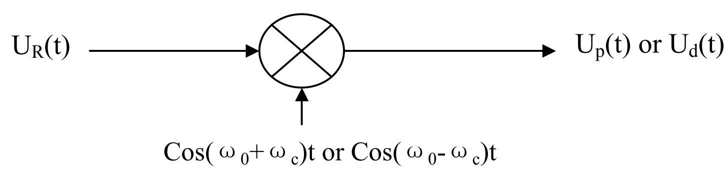


**Figure 4.** Sideband Coherent Demodulation

$$
\begin{aligned}
U_p(t) &= U_R(t) \cdot Cos(\omega_0 + \omega_c)t \\
&= \frac{1}{2} A_c J_1(\Delta\theta) Sin[\Delta\Phi_1 Cos(\Omega t + \Phi_1)] \\
&\approx \frac{1}{2} A_c J_1(\Delta\theta) \Delta\Phi_1 Cos(\Omega t + \Phi_1)
\end{aligned}
$$

Thus the amplitude $\Delta\Phi_1$ and phase $\Phi_1$ of upper sideband tone can be obtained.

Similarly, the lower sideband tone can be obtained which is:

$$
U_d(t) \approx \frac{1}{2} A_c J_1(\Delta\theta) \Delta\Phi_1^{'} Cos(\Omega t + \Phi_1^{'})
$$

So, the phase shifts of upper and lower sideband tones can be measured respectively using sideband coherent demodulation, then the ETD of IF modulation transponder can be calculated by equations (2-6) and (2-7).

## 2. How to Measure the ETD by Sidebands

Shown in figure 5 is how to measure the ETD of IF modulation transponder with the aid of sideband demodulation. The measuring process is as follows:

1) Set the switch on position 2, tune the testing receiver frequency onto the uplink signal. The measurement system performs self-calibrating. Then measure the tone phase difference $\Phi_E$ of measurement system itself;

2) Set the switch on position 1, tune the testing receiver frequency onto the upper sideband transponded by transponder. Measure the phase $\Phi_2$ of the upper sideband range tone. Then, tune the testing receiver frequency onto the lower sideband transponded by transponder, measure the lower sideband range tone phase $\Phi_2^{'}$, then the upper and lower sideband range tone phase shift induced by the time delay of transponder is:

$$\Phi_1 - \Phi_0 = \Phi_2 - \Phi_E \quad \text{and} \quad \Phi_1^{'} - \Phi_0 = \Phi_2^{'} - \Phi_E$$

3) Substituting above data into equation (2-8) can get the ETD of IF modulation transponder.

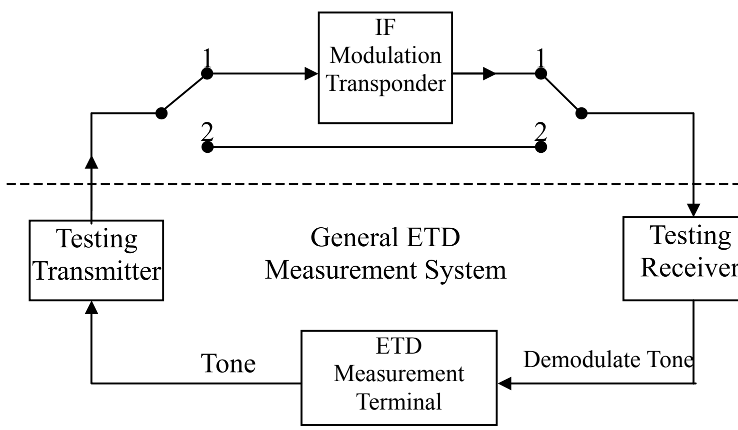


**Figure 5.** Sideband Measurement

## 3.General Method for ETD of CW Transponders

From above analysis it can be seen that the ETD of IF modulation transponder can be obtained by measuring the range tone phase shift of the first order sideband transponded by transponder. The ETD testing principle shown in figure 1 can be used as the general measurement method for ETD of three kinds of transponders. For coherent or frequency transform transponders, the tone phase shift of downlink carrier signal is measured to obtain the ETD of transponder; for IF modulation transponder, the tone phase shift of the upper and lower first order sideband transponded by transponder is respectively measured and then the ETD of transponder is calculated with equation (2-8).

## ERROR OF ETD ALGORITHM FOR SIDEBAND MEASUREMENT

Because of complexity of equation (2-6) and small difference between upper and lower sideband tone modulation index, equation (2-8) is usually used to calculate the ETD of transponder in engineering application. When $\Delta\Phi_1 \neq \Delta\Phi_1^{'}$, algorithm error will appear. From equation (2-6) the tone phase error between the algorithm and actual phase is:

$$\Delta = tg^{-1}\left[\frac{Sin\left(\Phi_1^{'} - \Phi_1\right)}{\frac{\Delta\Phi_1}{\Delta\Phi_1^{'}} + Cos\left(\Phi_1^{'} - \Phi_1\right)}\right] - \frac{1}{2}\left(\Phi_1^{'} - \Phi_1\right) \tag{4-1}$$

The phase error $\Delta$ vs. $\left(\Phi_1^{'} - \Phi_1\right)$ with $\Delta\Phi_1 / \Delta\Phi_1^{'}$ as a parameter is shown in figure 6.

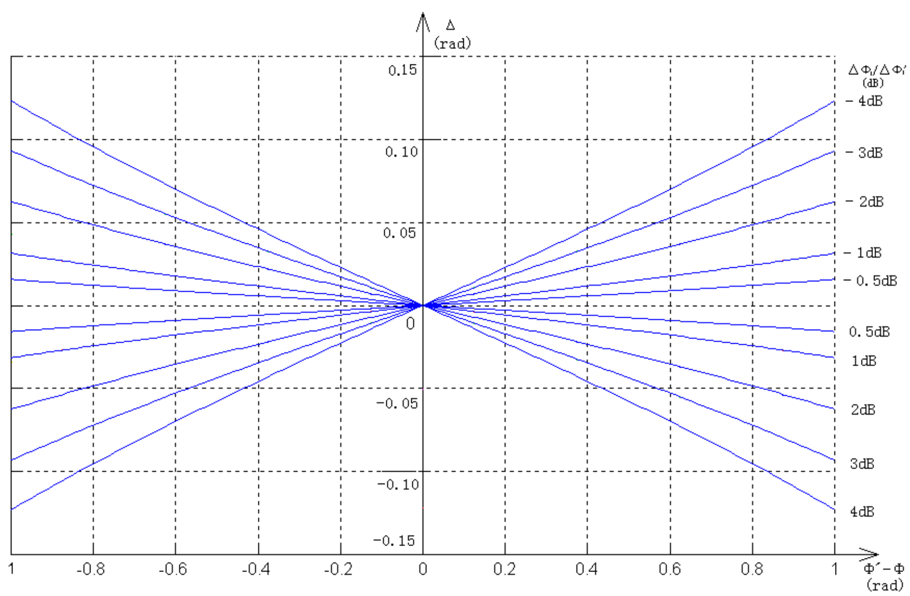


**Figure 6.** Approximately Algorithm Error

According to the principle of IF modulation transponder and actual test results, it can be known that the relative difference of modulation index between upper and lower sideband tone is usually less than 0.5dB, and the tone phase difference $\left|\Phi_1^{'} - \Phi_1\right| \le 0.2$ rad. Based on figure 6, it can be seen that the induced phase error $\Delta \le 0.0029$ rad, so the algorithm error can be neglected. If upper tone phase is equal to that of the lower, $\Phi_1^{'} = \Phi_1$, then the ETD of transponder can be obtained by only measuring the tone phase of one sideband.

## CONCLUSION

Above measurement principle has been verified in the general ETD measurement equipment of CW transponders. Adopting all-digitized signal processing terminals and with software reconfiguration technology the ETD of coherent transponder, frequency transform transponder and also IF modulation transponder can be respectively measured, providing useful data for improving tracking system range accuracy.

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