A FREQUENCY SCAN/FOLLOWING SCAN TWOWAY CARRIER ACQUISITION METHOD FOR USB SYSTEM

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ABSTRACT

This paper introduces a frequency scan/following scan twoway carrier acquisition method for USB and its following scan slope decision algorithm. Some measures are used to improve twoway acquisition speed such as selecting initiation direction and returning to zero in the shortest path, which can be implemented by software. Theoretic analysis, mathematical expression, design method and experiment results are provided. Practical engineering application shows the twoway acquisition using this new method has many advantages such as fast speed, low cost and programmability. The method has been used in Chinese USB system widely.

KEY WORDS

USB, twoway carrier acquisition, Allan variance, following scan decision

INTRODUCTION

For space TT&C system, fast and reliable target acquisition is a critical challenge. During system acquisition, the forward and return carrier acquisition and locking, so called twoway acquisition, is a key problem. In past TT&C system, it was decided that if twoway acquisition was achieved depending on the two locked indicators from carrier phase lock loops in uplink and downlink. In this case, the locked indicator from transponder onboard spacecraft was sent to ground station via telemetry channel, resulted in longer transmission time and lower reliability. A frequency scan acquisition operation mode on ground was used in Chinese united carrier TT&C system, wherein the corresponding twoway acquisition decision method, uplink/downlink frequency following scan decision, is used. By this method, after phase locked receiver is locked, its VCO following scan waveform is compared with transmitter frequency scan waveform to decide whether they are similar. This following scan waveform decision method takes longer time for decision and provides lower S/N for following scan decision signals, therefore has some effects on its acquisition probability and false alarm probability.

At present a new twoway acquisition method, i.e. following scan slope decision method, is proposed. By this approach, the modulator in uplink and carrier receiver in downlink are both digitalized at first, and then the calculated frequency code changing slope of Digital Control Oscillator (DCO) of digital carrier PLL is compared with the known setting value of uplink frequency scan slope in order to decide if the following scan is implemented, which can be performed by software after digitalized. Because of fast following scan slope calculation and appropriate algorithm selected to filter the desired signals to improve their S/N, fast twoway acquisition can be implemented with high acquisition probability. The functional block diagram for twoway acquisition is shown in Figure 1.

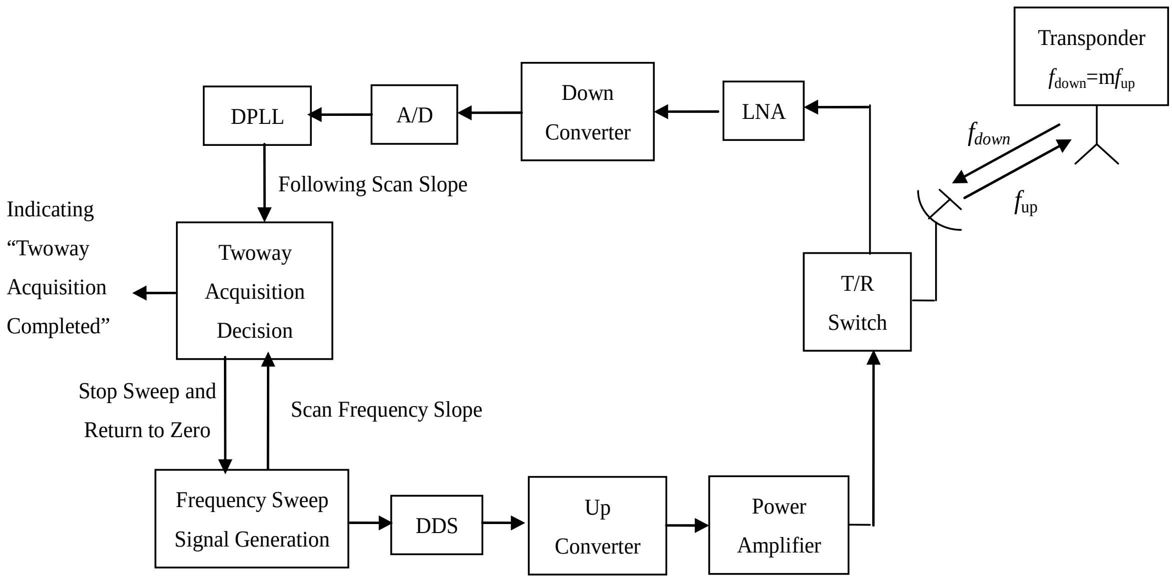

Figure 1 Frequency Scan/Following Scan Twoway Acquisition Block Diagram

TWOWAY ACQUISITION CRITERION

In this twoway acquisition mode, the twoway acquisition criterion is selected as: (1) For automatic twoway acquisition, either following scan decision or two-locked bi-decision is selected; (2) For manual twoway acquisition, tri-decision, i.e. following scan indicator light/ two-locked indicator light/following scan voltage indicator decision, is used to ensure reliable twoway acquisition.

After twoway acquisition is completed, the uplink and downlink frequency shall meet the following relationship:

$$f_d = mf_u \tag{1}$$

Where f_d is downlink frequency, f_u is uplink frequency, and m is coherent turnaround ratio, all of which are known.

When the third order digital carrier loop is used in ground receiver, for linear scan frequency $\dot{f}_u$, DCO scans following with downlink frequency without steady-state error, then

$$\dot{f}_{DCO} = \dot{f}_D = m\dot{f}_u \tag{2}$$

The item on the right of the above equation is a known constant, when the calculated $\dot{f}_{DCO}$ meets the above equation, the following scan is decided. But in practice, interference n(t) is presented in $\dot{f}_{DCO}$:

$$\dot{f}_{DCO} = m\dot{f}_u + n(t) \tag{3}$$

Where n(t) includes: (1) interference caused by signal phase noise, $n_T(t)$; (2) interference caused by receiver thermal noise, $n_R(t)$; (3) digital quantized noise, $n_D(t)$; and (4) effect from objective Doppler frequency changing rate, $n_d(t)$.

In twoway acquisition decision, the signal-to-interference ratio(S/N) is decided by the first item(signal) and the second item(interference) on the right of the Eq.(3), where S is slope of frequency scan signals, N is frequency fluctuation noise. The higher S/N, the larger acquisition probability and the smaller false alarm probability. S/N is relevant to frequency scan slope $\dot{f}_u$ and algorithm of $\dot{f}_{DCO}$. The faster frequency scan speed, the higher S/N.

FOLLOWING SCAN SLOPE ALGORITHM

For linear frequency scan signals, as shown in Figure 2, *f(t)* is a triangular wave frequency scan signal, its scan speed is $\dot{f}$. The frequency scan oscillator is digitalized; so its linear accuracy and reliability can be very high. C(t) is a sampling signal, which samples continuously without interval and its sampling time is $T_1 = T_2 = T_3 \cdots = T$. It is measured as followings:

(1) During each sampling period T, the mean measured frequencies are $\bar{f}_1, \bar{f}_2, \bar{f}_3, \cdots \bar{f}_{n-1}, \bar{f}_n$

(2) Because of linear scan, its frequency scan slope is

$$\dot{f} = a = \frac{\bar{f}_2 - \bar{f}_1}{T} = \frac{\bar{f}_3 - \bar{f}}{T} = \cdots = \frac{\bar{f}_n - \bar{f}_{n-1}}{T} \tag{4}$$

$$(\bar{f}_n - \bar{f}_{n-1})^2 = a^2T^2 \qquad (5)$$

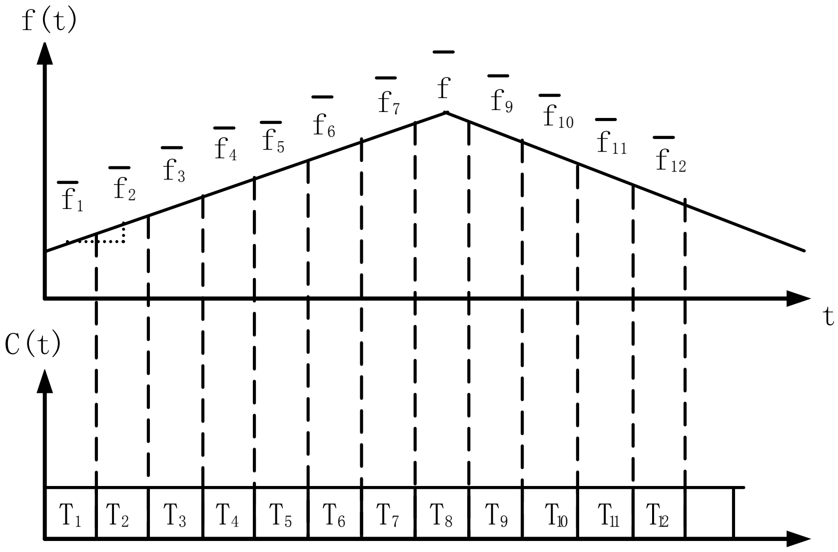

Figure 2 Allan Variance Calculations for Linear Frequency Scan

For linear frequency scan, $\left\langle(\bar{f}_n - \bar{f}_{n-1})^2\right\rangle = (\bar{f}_n - \bar{f}_{n-1})^2 = a^2T^2$

Where, $\langle\cdots\rangle$ is a mean value, because Allen variance is given by

$$\sigma_{ys}^2(T) = \frac{1}{2}\left\langle\left(\frac{\bar{f}_n}{f_0} - \frac{\bar{f}_{n-1}}{f_0}\right)^2\right\rangle = \frac{1}{2f_0^2}\left\langle(\bar{f}_n - \bar{f}_{n-1})^2\right\rangle \qquad (6)$$

So $\left\langle(\bar{f}_n - \bar{f}_{n-1})^2\right\rangle = 2f_0^2\sigma_\gamma^2(T)$, substituting Eq.(5) into it to give

$$a = \frac{\sqrt{2}}{T} f_0 \sigma_{ys}(T) \qquad (7)$$

Eq.(7) shows a meaningful result that the frequency scan slope of linear frequency scan signal equal to the product of Allan variance multiplied by $\left(\frac{\sqrt{2}}{T} f_0\right)$. So if the Allan variance $\sigma_{ys}^2(T)$ is measured, the scan rate a is measured, where the T and f_0 are known. Following advantages are provided by this method:

(1) Remove the effect of Doppler frequency shift. When the object moves at uniform speed, assuming Doppler frequency shift is f_d, then it can obtained from Eq.(6) that

$$\sigma_{ys}^2(T) = \frac{1}{2f_0^2}\left\langle\left[(\bar{f}_n - f_d) - (\bar{f}_{n-1} - f_d)\right]^2\right\rangle = \frac{1}{2f_0^2}\left\langle(\bar{f}_n - \bar{f}_{n-1})^2\right\rangle$$

It can be seen that the value of Allan variance is not changed. In addition, for slow frequency component, adjacent sampling values are subtracted, so most of its effect is eliminated.

(2) Among all variances, the measure time of Allan variance is the shortest. So the above calculation can be completed in short time, significantly reduced twoway acquisition time.

(3) For the effect caused by signal phase noise $n_T(t)$, this method relate the short term stability with S/N of following scan decision convenient for engineering design and measurement. Their relationship is derived as follows: the beacon signals transmitted by spacecraft are locked by carrier PLL in ground receiver before twoway acquisition process beginning. Its short term stability $\sigma_{ynT}(T)$ is one of main reasons resulting in false alarm, and is used to design decision threshold. When the twoway acquisition process initiated, the scan frequency signal is transmitted from ground station to make transponder and ground receiver scanning follow it. The following scan signal is $\sigma_{ys}^2(T)$, then

$$S/N = \frac{\sigma^2{}_{ys}(T)}{\sigma^2{}_{ynT}(T)} = \frac{a^2 T^2}{2 f_0^2 \sigma_{ynT}^2(T)} \quad (8)$$

(4) For receiver noise $n_{R(T)}$, the method realize filtering of $H(\omega) = [\sin^2(\omega T/2)]/(\omega T/2)$ to improve S/N of following scan decision signals. The characteristics of $H(\omega)$ is shown in Figure 3.

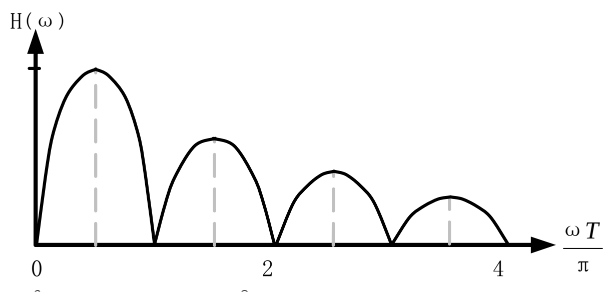

Figure 3 Frequency Domain Characteristics of Allan Variance

The phase noise spectrum density caused by receiver noise, which is assumed Additive Gauss White Noise, is $S_\varphi(\omega) = N_0 / P_s$, where P_s/N_0 is ratio of signal noise to power spectrum density of received signals, the Allan variance of frequency fluctuation noise is

$$\sigma_{ynR}^{2}(T)=\frac{1}{2\pi\ \omega_0^2}\int_{-\omega_L}^{+\omega_L}S_{\phi}(\omega)\omega^2\ |H(\omega)|^2 d\omega$$

$$=\frac{N_o}{\pi\omega_0^2 p_s}\int_0^{\omega_L}\frac{\omega^2 Sin^4(\omega\ T/2)}{(\omega\ T/2)^2}d\omega$$

$$=\frac{2N_o}{\pi\omega_0^2 T^3 p_s}[\frac{3\omega_L T}{4}-\frac{3}{4}Sin\omega_L T - Sin^3\frac{\omega_L T}{2}Cos\frac{\omega_L T}{2}] \quad (9)$$

Where, ω_L is the PLL bandwidth. Then S/N of following scan decision signal is obtained by:

$$S/N=\frac{\sigma_{ys}^2(T)}{\sigma_{ynR}^2(T)}=\frac{a^2T^2}{2f_0^2\sigma_{ynR}^2(T)}=a^2\pi^3T^5P_S\Big/N_o[\frac{3\omega_L T}{4}-\frac{3}{4}Sin\omega_L T-Sin^3\frac{\omega_L T}{2}Cos\frac{\omega_L T}{2}] \quad (10)$$

The total noise power is $(\sigma_{ynT}^2+\sigma_{ynR}^2)$. In practice, the $\sigma_{ynR}>>\sigma_{ynT}$, the digital quantized noise $n_D(T)$ can be ignored. Eq.(10) can be calculated by computer and is illustrated by Figure 2. In engineering application, the above algorithm can be simplified to further simplify design and shorten calculation time. Because positive and negative frequency scan rates existed, $\langle|\overline{f}_n-\overline{f}_{n-1}|\rangle$ is taken for calculation. Because of *n(t)*, two thresholds, $H_o^{'}$ and $H_o^{''}$, are designed to reduce false alarm, as shown in Figure 4. When $H_0^{''}>\langle|a|\rangle>H_0^{'}$, following scan is decided. Narrower intervals between two thresholds, smaller error acquisition probability, but smaller the acquisition probability also. To ensure reliable twoway acquisition, error acquisition probability shall be reduced as possible. The effect of *n(t)* should be accounted for interval between two thresholds. For the objects with high acceleration, the main effect comes from n_d, i.e. $H_0^{''}\approx a+n_d$, $H_0^{'}\approx a-n_d$, where $a=m\dot{f}_u$ is a known value. For the objects with low acceleration, the effect of $n_R(t)$ shall be considered. The rectangular pulse in Figure 3 is the signal by which the following scan is decided. After returned to zero, the twoway acquisition is kept by the other circuit. Both the above calculation and decision can be implemented by software, therefore the hard decision device can be omitted to obtain economic benefit.

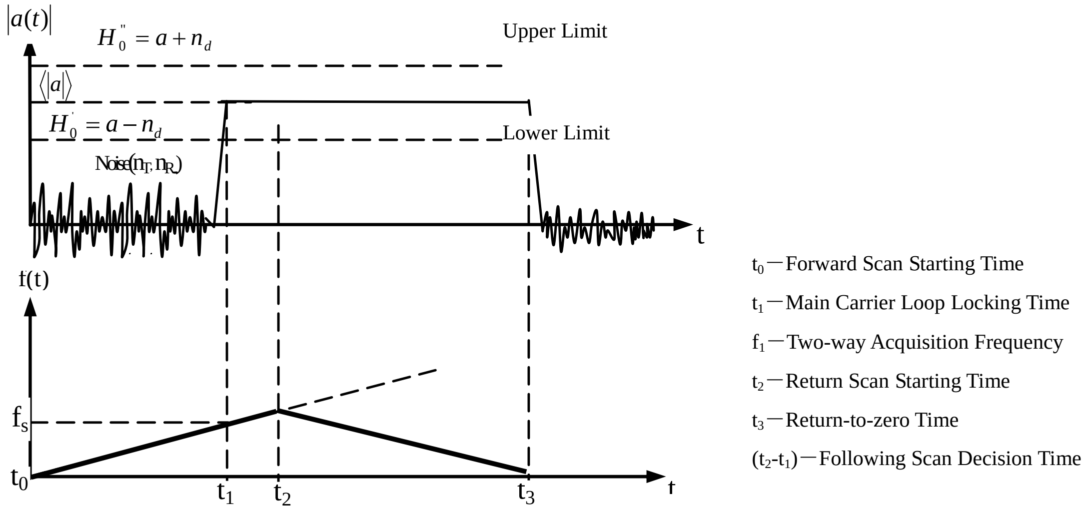

Figure 4 Two Thresholds Decision Waveform Diagram

TWOWAY ACQUISITION PROCESS

Without considering the time delay for space transmission, the twoway acquisition process is shown in Figure 5.

In the figure, $t_{angle\ guide}$ is the time when the object is aimed at after angle guided; $t_{beacon\ acquisition}$ is the time when the beacon from transponder is acquired by ground carrier loop after the ground antenna aimed at object; T_F is the time for FFT guiding and PLL capturing; $t_{angle\ acquisition}$ is the time when the tracked object is acquired by angle tracking system, T_A is the time for angle acquisition; t_0 is the time scan starting, the corresponding frequency is center transmit frequency f_0 of ground station; t_1 is the time when the signal is acquired by ground carrier loop, T_f is the time when the scan frequency is acquired,

$$T_f = t_1 - t_0 = \frac{(f_s - f_0)}{\dot{f}} + T_F$$

where f_s is center receive frequency of transponder PLL, which includes frequency instability and inaccuracy of transponder VCXO and object’s Doppler frequency f_d; $\dot{f}$ is frequency scan rate; t_2 is the time when the following scan is completed and frequency scan is stopped. $T_D=t_2-t_1$ is following scan decision time; t_3 is the starting time of return-to-zero scan frequency, and $T_S=t_3-t_2$ is the time when the frequency scan is paused to avoid all PLLs losing lock caused by frequency change rate stepping when the direction of return-to-zero scan frequency changed from positive to negative; t_4 is the time when return-to-zero is completed; $T_W=t_4-t_3$ is the return-to-zero time. To ensure PLL tracking normally, original frequency scan rate, which could be in reverse direction, shall return to zero at a uniform speed during T_W period. No frequency skip shall be allowed at return-to-zero point; otherwise the frequency lock shall be lost instantaneously. From the figure, one can obtained that $T_W=(t_2-t_1)+(t_1-t_0)=T_D+$

T_f, twoway acquisition time T_{DD} is（t_4-t_0）, $T_{DD}=2T_f+2T_D+T_S+T_{delay}+T_{propagation}$, where T_{delay} is the circuit delay, $T_{propagation}$ is radio wave propagation time.

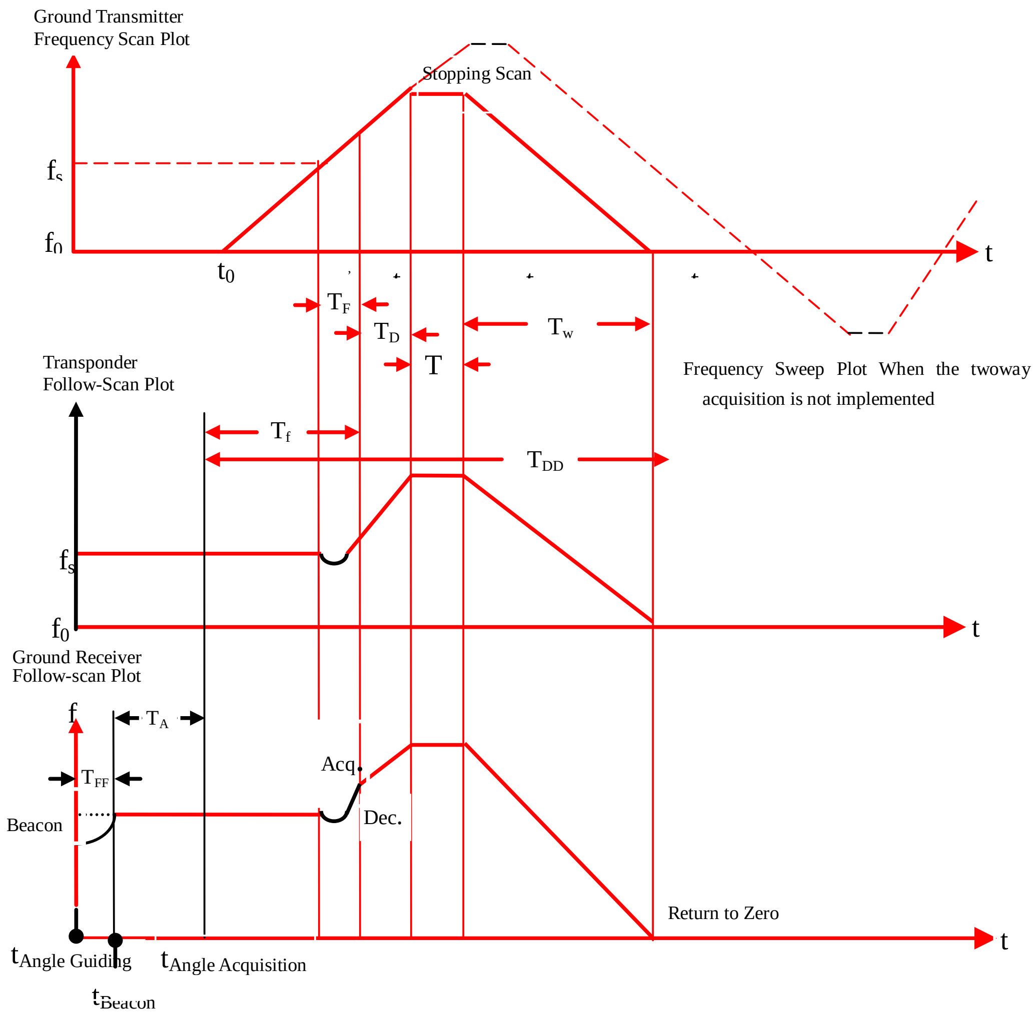

Figure 5 Twoway Acquisition Process Chart

In above twoway acquisition frequency scan figures, to fasten the twoway acquisition speed, following measures are taken:

(1) Direction selection when scan initiated: when the scan is initiated, the frequency scan direction is selected to moving to f_s value. If moving to reverse direction, more T/2 time shall be taken.

(2) Return-to-zero at uniform speed in a shortest path: in order to save time, the return-to-zero direction shall move to f_0, this is the shortest path for return-to-zero at original speed.

In this design, DDS device is used to implement frequency scan. It is programmable, and can implement following functions by software:

(1)When the scan is initiated, the scan direction shall be selected according to preset Doppler frequency;

(2) During return-to-zero, the direction shall be selected basing on the positive or negative of

the difference between frequency at scan stopping time and center frequency f_0;

(3) The scan shall be paused for 100ms during scan stopping and then the return-to-zero frequency scan is performed;

(4)Because of its high short term and long term stabilities, DDS can act as a part of frequency source. So return-to-zero can be implemented by making the DDS frequency uniformly returning to center frequency. In addition, if the frequency is swept by DDS, it shall provide high linearity and highly accurate slope for scan frequency, and can be programmed to control accurately scan frequency initiated point, stopping point, speed and range. This is in favor of following scan slope calculation and fast twoway acquisition. It can be seen that the frequency scan using DDS and digital carrier loop are the base of this method.

CONCLUSION

The method proposed in this paper has been applied in Chinese USB system successfully. Its following scan decision time is 200ms. Compared with traditional methods, automatic twoway acquisition time is as short as their 1/4, system acquisition time is 1/2.5. By using software, some benefits can be obtained such as simplified hardware, improved reliability and reduced cost.

Both theoretical analysis and engineering application show that this method is a new twoway acquisition method with fast speed, high reliability and low cost.

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