A Calibration Method of Absolute Time Delay for Phased Array Antenna

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Abstract: Caused by the degradation of active amplifier, the absolute time delay drift of phased array antenna is produced. In order to meet the requirement of precise ranging for navigation system, absolute time delay of phased array antenna need to be calibrated. Using group delay theory, combining Mid-field calculation technology, a calibration method of absolute time delay for phased array antenna based on time delay self-calibration channel is proposed. Analysis results indicate that the same effect on self-calibration channel and phased array antenna by time delay drift of active RF component. The absolute time delay of phased array antenna can be calibrated by time delay of self-calibration channel. The calculation and the measured results show that the proposed method is feasible and efficient.

1. Introduction
The phased array antenna may cover the entire scanning range of the space with one beam, the flexibility of antenna beam scanning is fully utilized and the energy is distribute reasonably. Recently, phased array antenna technology is widely used in communication, navigation, electronic reconnaissance, phased array radar system and other tasks.

In a navigation system, in order to ensure that the positioning accuracy and the range accuracy of the system meet the requirements of users under a long-term work state, the phased array antenna is required to have an accurate transmit delay zero value. That is, the absolute delay of the phased array antenna must be stable. The absolute delay of phased array antenna is very sensitive to the change of its environment, and it is easy to drift due to the aging of active amplifying devices [1]. In order to ensure the time delay stability of phased array antenna, it is necessary to measure and correct the absolute time delay of phased array antenna quickly and accurately [2].

In this paper, a method of time delay calibration for phased array antenna is proposed. A self-calibration channel for time delay is arranged in the antenna. The analysis shows that if the active RF components have time delay drift, the time delay value of the time delay self-calibration channel and the absolute time delay value of the phased array antenna will have the same effect. Therefore, the absolute time delay value of the phased array antenna can be calibrated according to the change of the time delay value of the time delay self-calibration channel. The method has the advantages of simple equipment supporting, flexible testing environment and good test effect, and is suitable for delay calibration of phased array antennas with ranging requirements such as navigation, TT&C.

2. Time delay self-calibration system of phased array antenna
The phased array antenna studied in this paper is equipped with time delay self-calibration channel, which is composed of calibration module, calibration antenna and several high-frequency cables. In
Figure 1, the delay self-calibration system is compatible with transmit and receiving calibration.

![Block diagram of time delay self-calibration system](image1)

Figure 1 Block diagram of time delay self-calibration system

The calibration module is the core component of the time delay self-calibration channel. The main function of the calibration module is to establish the transceiver self-calibration radio frequency channel through internal channel switching. The calibration module is mainly composed of a radio frequency circuit part and a low frequency circuit part, wherein the radio frequency circuit part is a transmit calibration channel and a receiving calibration channel, and the main devices used are a SPDT and two SPST. The low frequency circuit mainly includes control signal driving circuit, which can provide enough current driving ability for microwave switch. The RF circuit of the calibration module only uses PIN switch and has no GaAs pHEMT amplifier, so the delay stability of the module is well.

The calibration antenna is mainly responsible for the transmitting and receiving of the calibration signal, and the 3dB beam width of the calibration antenna can cover the whole array antenna. The calibration antenna structure is shown in Figure 2. The calibration antenna consists of a rectangular circular waveguide conversion section, a circular polarizer and a radiation horn, wherein the rectangular circular waveguide conversion section realizes the conversion from a rectangular waveguide to a circular waveguide; the circular polarizer realizes the right-hand circular polarization wave; and the radiation horn is a wide-beam antenna.

![Structure of calibration antenna](image2)

Figure 2 Structure of calibration antenna

Using the phase array antenna time delay self-calibration system shown in Figure 1, the time delay self-calibration channel composed of coupler (including filter and 3dB coupler), active radio frequency channel (including feed network, T/R component, array antenna), calibration antenna, calibration module, high frequency cable, etc. is established, and the time delay value of the self-calibration channel is calibrated by VNA [3]. The absolute delay value of phased array antenna is calibrated by VNA in far-field environment. When the phased array antenna works, the time delay value of the self-calibration channel can be tested periodically through the transceiver or measurement equipment, and the absolute time delay value of the phased array antenna can be calibrated according to the test result.
3. Theoretical analysis

As shown in Figure 1, the phased array antenna transmit absolute time delay is $\gamma_t$, and the calculation formula is as follows:

$$\gamma_t = \gamma_{11} + \gamma_{21} + \gamma_3$$  \hspace{1cm} (1)

Among the components of $\gamma_t$, the time delay of transmit cable is $\gamma_{11}$, the through time delay of transmit coupler is $\gamma_{21}$, these components are all RF passive components, the time delay drift due to aging is avoided. Possible time delay drift is the active RF component transmit time delay $\gamma_3$ (More GaAs pHEMT amplifiers are used).

As shown in Figure 1, the self-calibration channel transmit absolute delay is $\gamma_s$, and the calculation formula is as follows:

$$\gamma_s = \gamma_{11} + \gamma_{12} + \gamma_{13} + \gamma_{14} + \gamma_{21} + \gamma_3 + \gamma_4 + \gamma_5 + \gamma_6 + \gamma_{22}$$  \hspace{1cm} (2)

Among the components of $\gamma_s$, the time delay of receiving cable is $\gamma_{12}$, the time delay of cable between calibration antenna and calibration module is $\gamma_{13}$, the time delay of cable between calibration module and receiving coupler cable is $\gamma_{14}$, the time delay of calibration antenna is $\gamma_5$, the time delay of calibration module transmit channel is $\gamma_6$, the coupling time delay of receiving coupler is $\gamma_{22}$, these components are all RF passive components, the time delay drift due to aging is avoided. The time delay of array antenna to calibration antenna is $\gamma_4$, the stability of $\gamma_4$ needs to be proved.

In this paper, the calibration antenna is located on the side of the array antenna. The position relation between the array antenna and the calibration antenna is shown in Figure 3. The calibration antenna points to the center of the array antenna, which needs to be located below the phased array antenna scanning range. The number of phased array antenna elements is 320 (16×20), the elements spacing is 0.5$\lambda$, the two-dimensional array of triangular grids is used to distribute the array [4]. The layout of array antenna elements is shown in Figure 4. The direction of X is row direction (m) and Y direction is column direction (n).

![Figure 3 Layout of array antenna and calibration antenna](image1)

![Figure 4 Layout of array antenna elements](image2)

During the transmit channel calibration, the array antenna is the transmit antenna and the calibration antenna is the receiving antenna. The calibration antenna and the array antenna elements are all in the other's midfield [5, 6]. The midfield formula can be used to calculate the power of the calibration antenna receiving signal, the formula is as follows:

$$P_t = A_t \Phi^8 = \sum_{m=1}^{16} \sum_{n=1}^{20} \frac{G_2(G_1 \cos(\theta_{m,n} \phi_{m,n}) \rho_{m,n} \lambda \sin(-j \beta_{m,n} \phi_{m,n}) \exp(-j \beta_{m,n} \phi_{m,n}))}{4\pi r_{m,n}^2}$$  \hspace{1cm} (3)

The signal power received by calibration antenna is $P_t$, the amplitude of transmit signal is $A_t$, and the phase of transmit signal is $\Phi$. The gain of array antenna element is $G(\theta_{m,n} \phi_{m,n})$, the angles to calibration antenna in the array element’s coordinate system are $(\theta_{m,n} \phi_{m,n})$. The gain of calibration antenna is $G_c(\theta_{c,m,n} \phi_{c,m,n})$, the angles to the array elements in calibration antenna’s coordinate system are $(\theta_{c,m,n} \phi_{c,m,n})$. The distance between array elements and calibration antenna is $r_{m,n}$. The output power of the array antenna elements are $P_{0(m,n)}$. The phase-shift value of the array antenna elements are
\( \delta_{m,n} \), which can synthesize the array antenna beam point to calibration antenna. The total number of rows is \( M \), and the total number of columns is \( N \).

The formula of \( \gamma_4 \) is as follows, which is the first derivative of phase to frequency[7,8].

\[
\tau_4 = -\frac{d\phi}{d\omega} = -\frac{1}{2\pi} \frac{d\phi}{df}
\]

(4)

In order to prove the stability of the time delay value \( \gamma_4 \), \( \pm 1 \)dB random amplitude error and \( \pm 5^\circ \) random phase error has been set to all of the array antenna elements. The time delay value \( \gamma_4 \) is calculated by formula (3) and (4), the number of samples is 20, and the calculation results are shown in Figure 5. It can be seen from the calculation results that the fluctuations of \( \gamma_4 \) are within the range of \( \pm 0.015 \)ns, such fluctuation are very small.

![Figure 5 Stability analysis of transmit time delay \( \gamma_4 \)](image)

According to the above analysis, in the component part of \( \gamma_4 \), only the active RF component transmit time delay \( \gamma_3 \) can cause time delay drift, which is consistent with the array antenna transmit absolute time delay \( \gamma_6 \). Therefore, \( \gamma_6 \) can be calibrated by the measured results of the time delay \( \gamma_4 \). As shown in Figure 1, the phased array antenna receiving absolute time delay is \( \gamma_j \), and its calculation formula is as follows:

\[
\gamma_j = \gamma_{12} + \gamma_{21} + \gamma_3
\]

(5)

Among the components of \( \gamma_j \), the time delay of receiving cable is \( \gamma_{12} \), the through time delay of receiving coupler is \( \gamma_{21} \), these components are all RF passive components, the time delay drift due to aging is avoided. Possible time delay drift is the active RF component receiving time delay \( \gamma_3 \) (More GaAs pHEMT amplifiers are used).

As shown in Figure 1, the self-calibration channel receiving absolute delay is \( \gamma_r \), and the calculation formula is as follows:

\[
\gamma_r = \gamma_{11} + \gamma_{12} + \gamma_{13} + \gamma_{15} + \gamma_{22} + \gamma_{3} + \gamma_{4} + \gamma_{6} + \gamma_{21}
\]

(6)

Among the components of \( \gamma_r \), the time delay of cable between calibration module and transmit coupler is \( \gamma_{15} \), the coupling time delay of transmit coupler is \( \gamma_{22} \), the time delay of calibration module receiving channel is \( \gamma_6 \), these components are all RF passive components, the time delay drift due to aging is avoided. The time delay of array antenna to calibration antenna is \( \gamma_4 \), the stability of \( \gamma_4 \) needs to be proved.

During the receiving channel calibration, the calibration antenna is the transmit antenna and the array antenna is the receiving antenna. The midfield formula can be used to calculate the power of the array antenna receiving signal, the formula is as follows:

\[
P_r = A_r e^{j\phi_r} = \left( \sum_{i \in R} \frac{G_{\theta_r \phi_r} G_{\phi_r \phi_r} G_{\theta_r \phi_r} G_{\phi_r \phi_r} \lambda (e^{-jN_{\phi_r}} e^{j\phi_r})}{MN_{\phi_r}} \right)^2
\]

(7)

The signal power received by array antenna is \( P_r \), the amplitude of receiving signal is \( A_r \), and the phase of receiving signal is \( \phi_r \). The output power of the calibration antenna is \( P_1 \), the gain of array antenna elements receiving channel is \( G_{\theta_r \phi_r} \).

The formula of \( \gamma_4 \) is as follows, which is the first derivative of phase to frequency.
\[ \tau_{r4} = \frac{d\phi}{d\omega} = \frac{1}{2\pi} \frac{d\phi}{df} \quad (8) \]

In order to prove the stability of the time delay value \( \gamma_{r4} \), ±1dB random amplitude error of and ±5° random phase error has been set to all of the array antenna elements. The time delay value \( \gamma_{r4} \) is calculated by formula (7) and (8), the number of samples is 20, and the calculation results are shown in Figure 6. It can be seen from the calculation results that the fluctuations of \( \gamma_{r4} \) are within the range of ±0.015ns, such fluctuation are very small.

![Figure 6 Stability analysis of receiving time delay \( \gamma_{r4} \)](image)

According to the above analysis, in the component part of \( \gamma_r \), only the active RF component receiving time delay \( \gamma_{r4} \) can cause time delay drift, which is consistent with the array antenna receiving absolute time delay \( \gamma_{rj} \). Therefore, \( \gamma_{rj} \) can be calibrated by the measured results of the time delay \( \gamma_r \).

### 4. Experimental verification results

Since the phased array antenna studied in this paper works in narrow band, the time delay analysis and test results of the single frequency are given in this paper.

| Item | Transmission time delay (ns) | Receiving time delay (ns) |
|------|-------------------------------|--------------------------|
| \( \gamma_{11} \) | 2.58 | \( \gamma_{11} \) | 2.58 |
| \( \gamma_{12} \) | 2.57 | \( \gamma_{12} \) | 2.57 |
| \( \gamma_{13} \) | 3.02 | \( \gamma_{13} \) | 3.02 |
| \( \gamma_{14} \) | 3.03 | \( \gamma_{15} \) | 3.06 |
| \( \gamma_{21} \) | 1.92 | \( \gamma_{22} \) | 1.92 |
| \( \gamma_{3} \) | 3.1 | \( \gamma_{3} \) | 3.4 |
| \( \gamma_{4} \) | 0.72 (calculation) | \( \gamma_{4} \) | 0.72 (calculation) |
| \( \gamma_{5} \) | 0.96 | \( \gamma_{5} \) | 0.96 |
| \( \gamma_{6} \) | 1.11 | \( \gamma_{6} \) | 1.17 |
| \( \gamma_{22} \) | 1.93 | \( \gamma_{21} \) | 1.95 |
| Total | 20.94 | Total | 21.35 |

VNA is used to measure the components time delay values (except \( \gamma_{r4}, \gamma_{r4} \)) of phase array antenna time delay self-calibration system, the transmit time delay \( \gamma_{r4} \) is calculated according to formula (3) and (4), the receiving time delay \( \gamma_{r4} \) is calculated according to the formula (7) and (8). The measurement and calculation results are shown in Table 1.

Using the time delay self-calibration system shown in Figure 1, the measured value of transmit time delay \( \gamma_t \) is 20.99ns by VNA, the calculation result of transmit time delay \( \gamma_t \) is 20.94ns, the calculation result agree well with the measured value. The measured value of receiving time delay \( \gamma_r \) is 21.44ns by VNA, the calculation result of receiving time delay \( \gamma_r \) is 21.35ns, the calculation result agree well with the measured value. Based on the above analysis, the correctness of the phased array antenna time delay calibration method is proved.

### 5. Conclusion

In this paper, a calibration method of absolute time delay for phased array antenna is proposed, which
can be modified according to the time delay value of self-calibration channel. Illustrated by the example of one kind of phased array antenna, such method is used to calculate the self-calibration time delay value of the antenna. The deviation between calculation result and measured value is less than 0.1ns, the calculation result agree well with the measured value, which is proves the validity and the correctness of the proposed method.

This method is of high measurement accuracy, simple equipment and easy operation, which is suitable for phased array antenna with requirement of precision ranging.

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