Phase Compensation Method for Active Phased Array Antennas in Operating Environment based on Electromechanical Coupling Model

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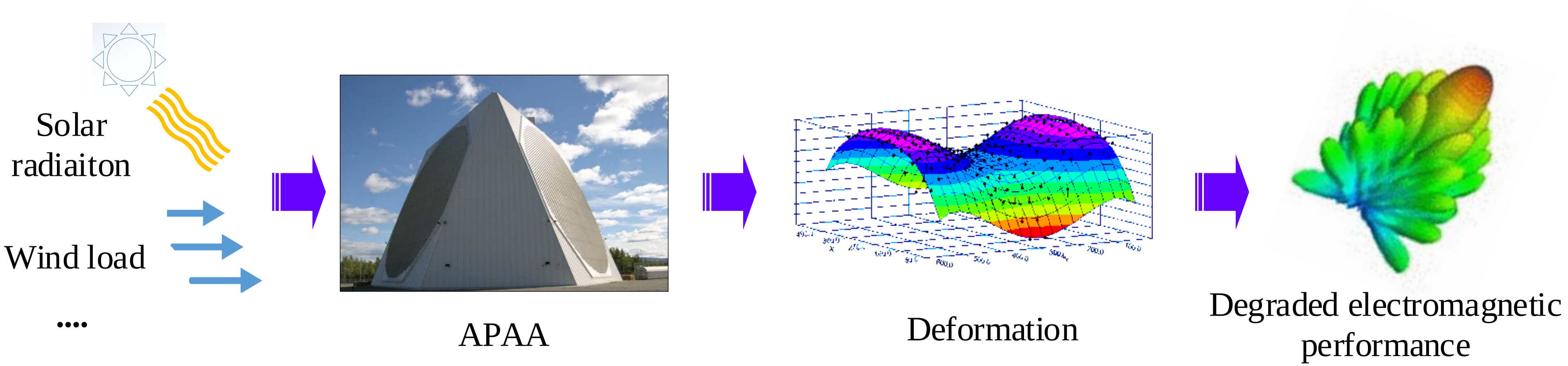
Background

Research Problems

For Active Phased Array Antenna (APAA), any disturbance on antenna could entail a deformation on radiating surface due to complex environmental loads, including wind load, solar radiation, high thermal power consumption, random vibration and thermal environment. The deformation eventually provoke an uncontrollable beam squint and soaring sidelobes, and even a decrease of main lobe gain, which has been proven as a barrier to improve the capability of APAA.

Moreover, array antennas tend to high performance, high frequency and high integration, the structural parameters and electromagnetic performance are more closely coupled, which can finally seriously restrict the realization of high-performance APAA.



Background

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Research Status

Compensation method

- structural compensation
- electronic compensation

- **Actuator or adjustment mechanism is used to control the structural accuracy of the antenna array, but the structural complexity and weight will increase.**

T. Jeffrey, "Phased-array radar design: application of radar fundamentals," The Institution of Engineering and Technology, 2009.

- **By controlling the parameters of the active device, such as the length of cable of phase shifter, to adjust the antenna performance, but it is not feasible in service stage.**

S. H. Son, J. S. Yun, U. H. Park, et al., "Theoretical analysis for beam pointing accuracy of stair-planar phased array antenna with tracking beam," IEEE Antennas and Propagation Society International Symposium, Columbus, OH, 2003, vol. 4, pp. 204-207.

- **Monitored the phase difference between elements by installing an analog integrated circuit for each element, to compensate the phase difference among elements**

H. Schippers, J. H. van Tongeren, P. Knott, T. et al., "Vibrating antennas and compensation techniques Research in NATO/RTO/SET 087/RTG 50," 2007 IEEE Aerospace Conference, Big Sky, MT, 2007, pp. 1-13.

◈ **It is necessary to study how to quickly determine the excitation phase adjustment to compensate the electromagnetic performance of deformed antenna without affecting the weight and complexity of the antenna.**

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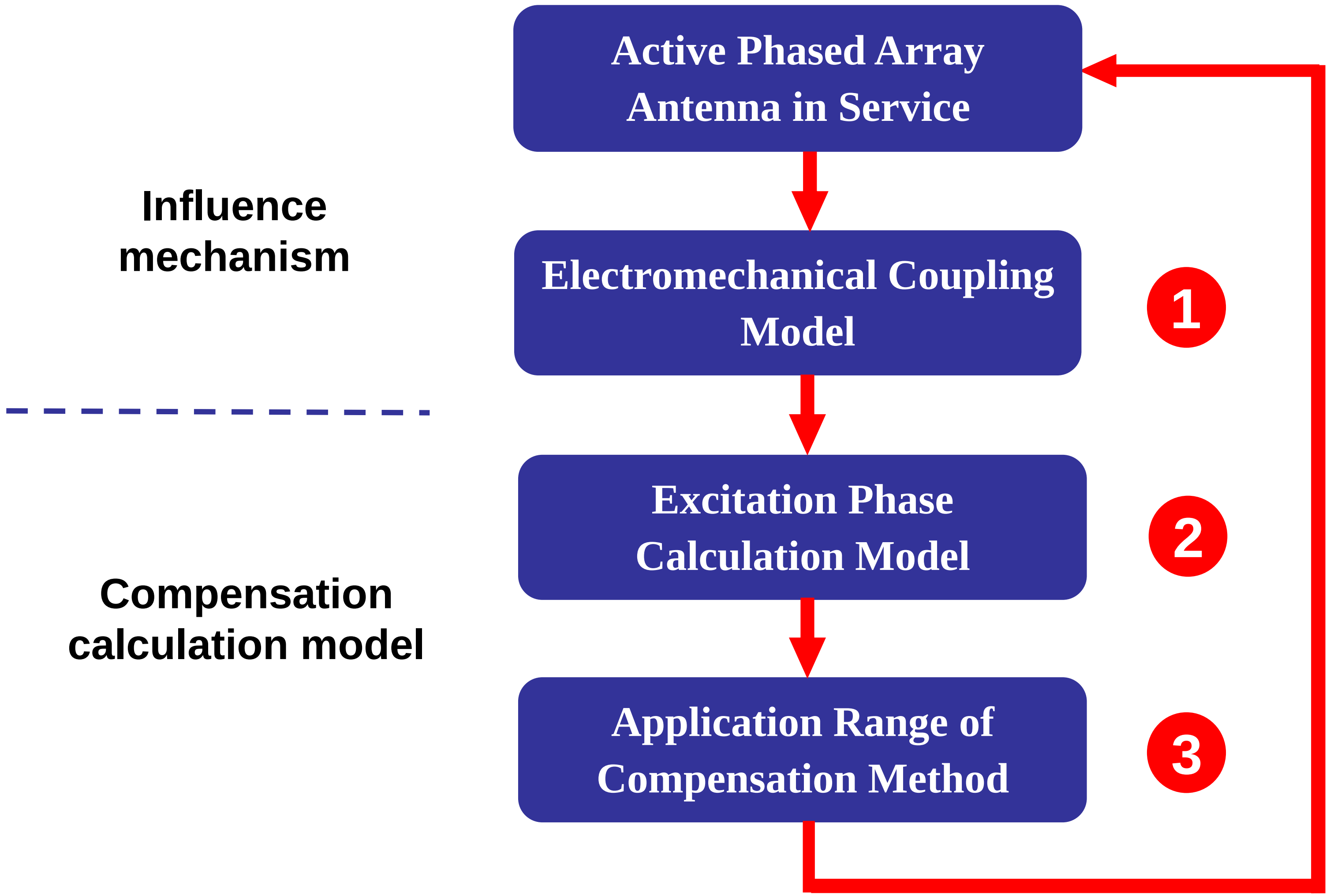
Phase Compensation

Research Idea

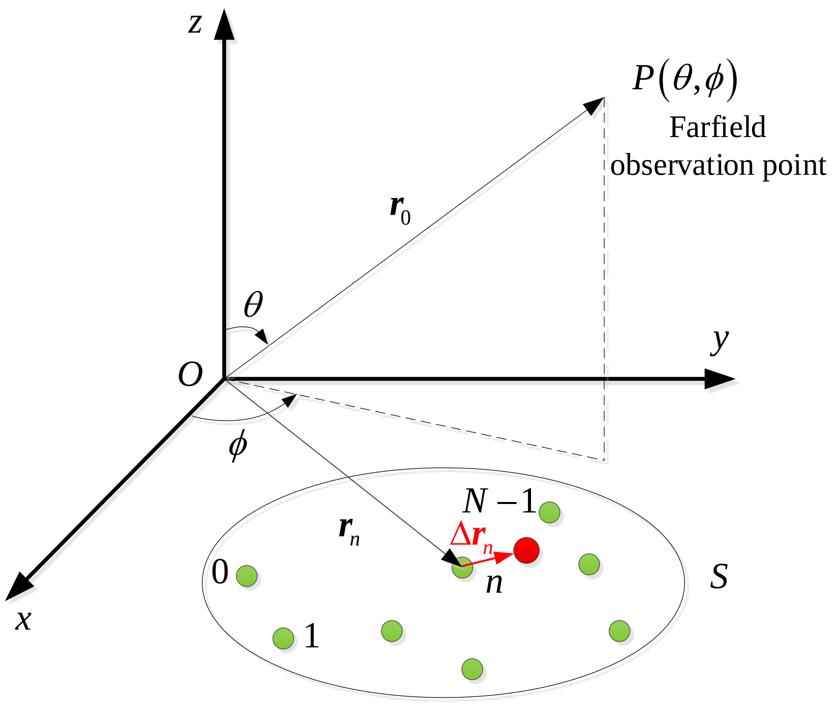
Based on electromechanical coupling model of APAA, the compensation method is presented.



Phase Compensation

1 Based Electromechanical Coupling Model [1]

The electromechanical coupling model of active phased array antenna is introduced.



Suppose the position error of the *nth* element is $\Delta\boldsymbol{r}_n(\boldsymbol{\delta})$, the performance of deformed array antenna is as below, which is the coupled structural-electromagnetic model.

$$\boldsymbol{E}_s(\theta,\phi)=\sum_{n=1}^{N} f_n(\theta,\phi)\boldsymbol{I}_n \exp\left\{jk\left[\boldsymbol{r}_n+\Delta\boldsymbol{r}_n(\boldsymbol{\delta})\right]\cdot\boldsymbol{r}_0\right\}$$

Excitation current ($\boldsymbol{I}_n$)

Space phase difference ($\Delta\boldsymbol{r}_n(\boldsymbol{\delta})$)

[1] Congsi Wang, Baoyan Duan, et al. Coupled structural-electromagnetic-thermal modelling and analysis of active phased array antennas. IET Microwaves, Antennas & Propagation, 2010, 4(2): 247-257.

Phase Compensation

2 Excitation Phase Calculation Model

To compensate the effect of distortion, supposed the phase is $\varphi_c = \varphi_n + \Delta\varphi_n$, the compensated performance is

$$E_c(\theta,\phi) = \sum_{n=0}^{N-1} f_n(\theta,\phi) I_n \exp(j\varphi_c) \exp\left\{ jk\left[\boldsymbol{r}_n + \Delta\boldsymbol{r}_n(\boldsymbol{\delta}) \right] \cdot \boldsymbol{r}_0 \right\}$$

It is necessary to minimum the difference between the compensated and the ideal performance $\boldsymbol{E}_0(\theta,\phi)$, that is

$$\min \left| E_c(\theta,\phi) - E_0(\theta,\phi) \right|$$

Finally, the excitation phase adjustment are deduced

$$\Delta\varphi_n = -k\Delta\boldsymbol{r}_n(\boldsymbol{\delta}) \cdot \boldsymbol{r}_{0s}$$

Phase adjustment

where $\boldsymbol{r}_{0s} = \sin\theta_s \cos\phi_s \boldsymbol{i} + \sin\theta_s \sin\phi_s \boldsymbol{j} + \cos\theta_s \boldsymbol{k}$ is the unit vector toward the specified direction (θ_s, ϕ_s) .

3 Application Range of the Compensation Method

Once the position error of antenna element is $\boldsymbol{\delta} = [\delta_{z1}, \delta_{z2}, \cdots, \delta_{zN}]^{\mathrm{T}}$, when the electromagnetic performance error can be specified as $E_{R_m} \le \zeta$, the structural deformation that can be compensated is

$$\boldsymbol{\delta} \le (\mathbf{E}_o^T \mathbf{E}_o)^{-1} \mathbf{E}_o^T \left[\frac{\zeta - f_a(\theta,\phi)}{jk(\cos\theta - \cos\theta_0)} \right]$$

Maximum structure deformation

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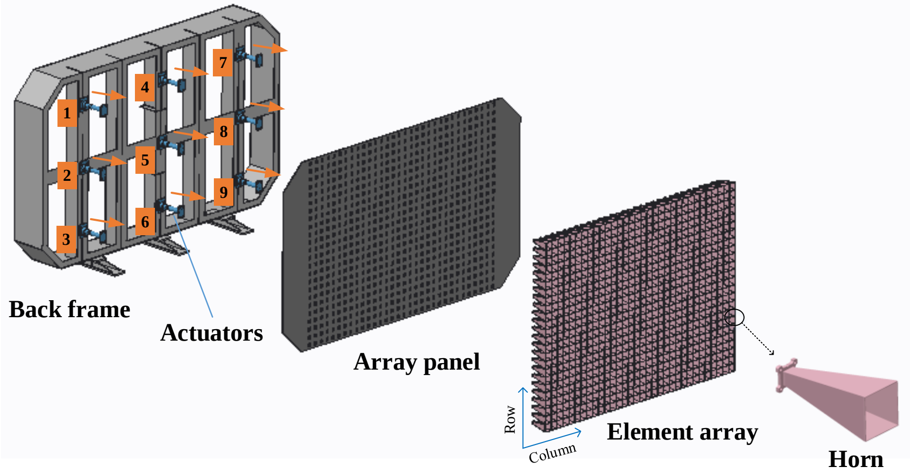
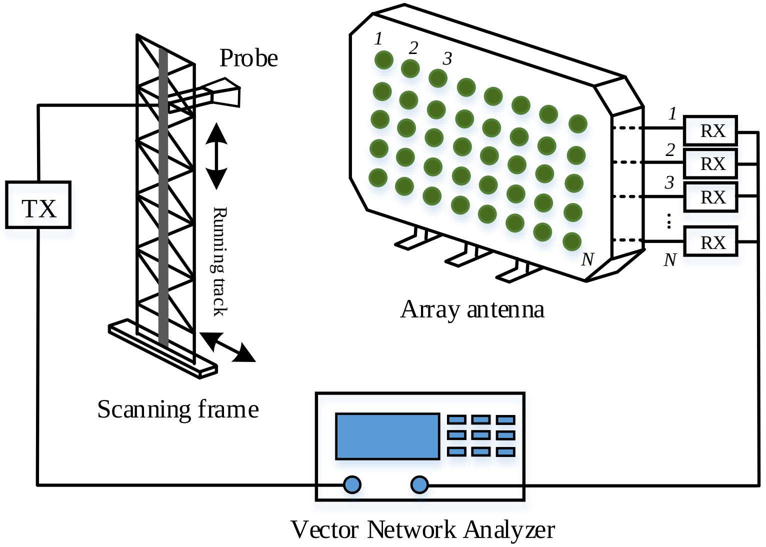
Experimental Verification

Architecture of experimental platform

An X-band APAA with 24×32 elements is illustrated, which mainly includes the back frame, actuators, array panel and element array. The operating frequency is 9.375 GHz, and the initial excitation current is Taylor's weighted distribution in amplitude and equal in phase. The array panel is connected with the back frame by nine actuators, which are controlled independently and used to simulate the structural deformations in operating environment.



(a) Composition diagram of APAA



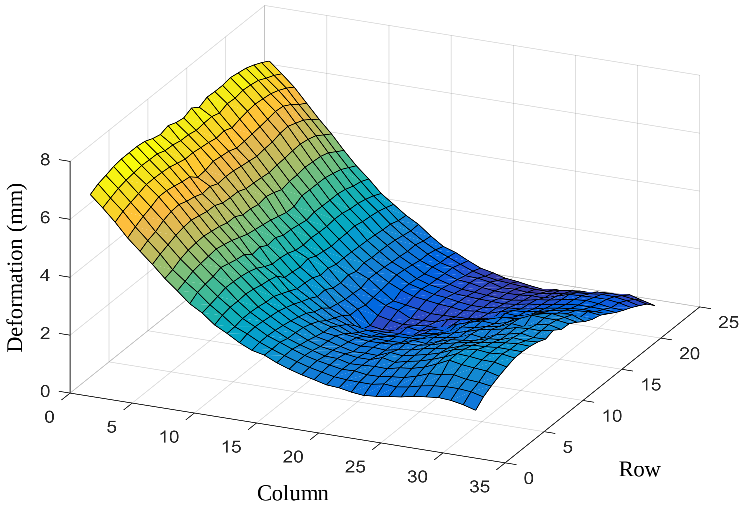
(b) Electromagnetic measurement system

Architecture of experimental platform and electromagnetic test system

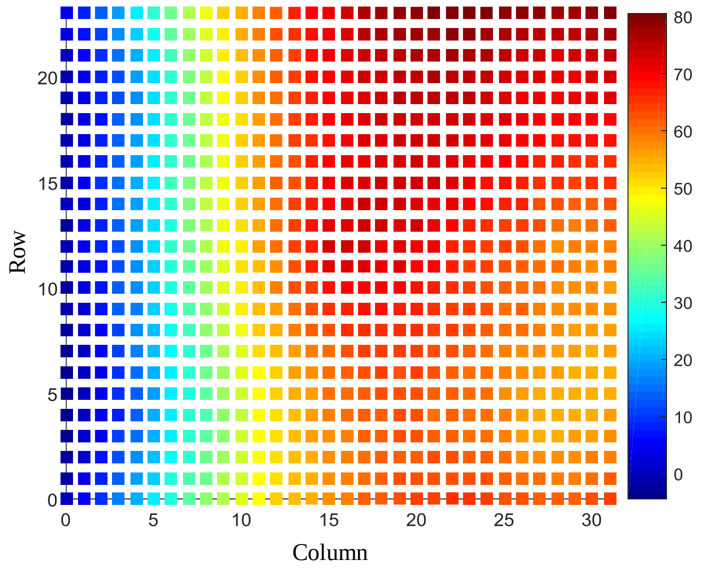
Experimental Verification

Excitation phase adjustment from the compensation model

Comprehensive considering the effect of operating environment, a typical structural deformation is taken to verify the compensation method. With the main beam pointing as the angle $(0°,0°)$, the corresponding phase adjustment is calculated according to the presented excitation phase calculation model, with the result as shown below.



Deformation shape of the phased array antenna

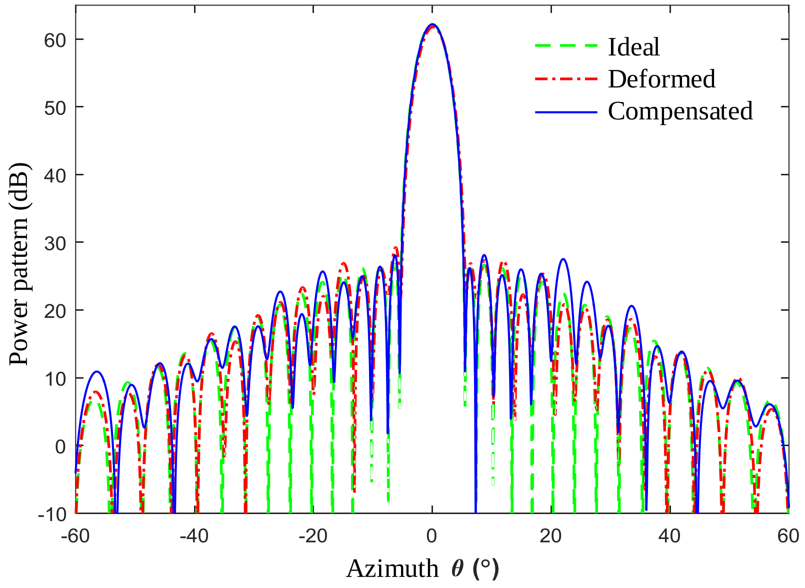


Excitation phase adjustment of antenna elements

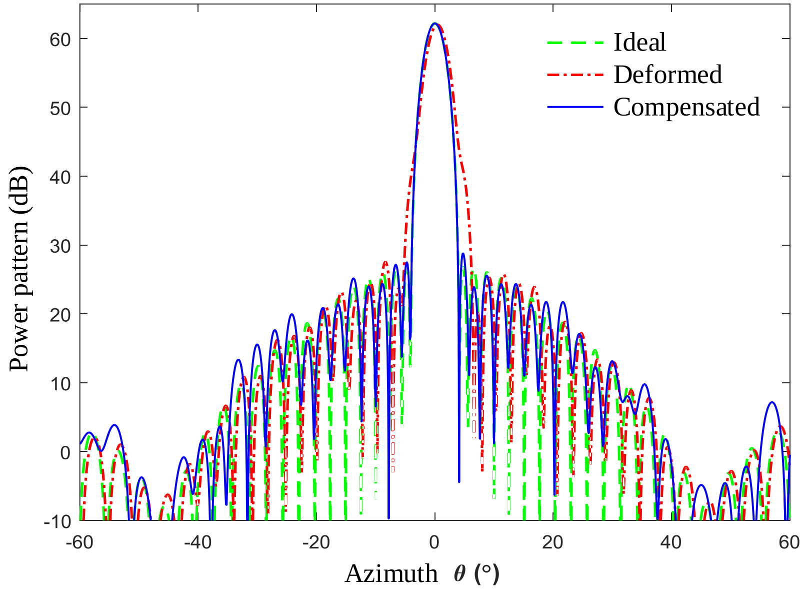
Experimental Verification

Electromagnetic performance comparison

The electromagnetic performance of phased array antenna before and after compensation, with and without consideration of structure deformation are shown as below.



In $\phi = 0^{\circ}$ plane



In $\phi = 90^{\circ}$ plane

1. The gain loss is 0.37dB and fully compensated with the phase compensation method.
2. The maximum sidelobe levels in $\phi = 0^{\circ}$ and $\phi = 90^{\circ}$ planes are raised by 3.72dB and 3.32dB, respectively. The former is decreased by 1.99dB, and the letter is decreased by 1.94dB.
3. The boresight error and 3dB beamwideth are both compensated at the same time.

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Summary and Outlook

- **Present a compensation method for reducing structural deformation based on the electromechanical coupling model.**
- **Verify the compensation effect under the effect of the typical type of distortion form based on an APAA experimental platform.**

Widely applied active phased array antenna can be inevitably affected by complex environmental loads, the electromechanical coupling theory and compensation way for array antenna are very important, need to be studied in-depth constantly.

Future works

- **To do more analysis on different amplitude attenuator and bit of phase shifter to obtain more application results**
- **To study in-depth in the structural-electromechanical coupling theory for more effective compensation**
- **Compensate more error sources, such as element failure, element mutual coupling and so on**

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Thanks for your attention