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Traceability Model Design and Validation for Precipitation Radar

[1, 2] Kairang Wang, [1] Donglin Su, [3] Dangjun Zhao
[1] School of Electronic and Information Engineering, Beihang University, Beijing 100191, China
[2] Beijing Institute of Radio Metrology and Measurements, Beijing 100854, China
[3] School of Aeronautic and Astronautic, Central South University, Changsha 410083, China
[1] Tel.: +86 13366026139

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Abstract: The propagating process of data chain of a large instrument is usually indicated by the traceability model. In this paper, to enhance the measurement accuracy of the precipitation radar, we proposed a traceability mode design scheme for the power measurement internal the precipitation radar, which is the key parameter relating to the precipitation measurement. Unlike the conventional internal calibration, we design three additional circuits, including temperature compensation, sectional amplification, auto-calibration power source, according to the traceability model. By introducing three internal detection points, the online soft-calibration data package is obtained by using internal power meters and the environmental sensors. According to the measured power information and the temperature information, the calibration data package provides the online calibration and the attenuation control. Practical internal calibration and real-time online measurement experiments are conducted to validate the design scheme. The experimental results reveal the traceability model design and corresponding soft calibration strategy can improve the reliability of the dynamical measurement data and the dynamical performance of the radar measurement. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Precipitation radar, Traceability model, Power measurement, Traceability model design, Soft calibration.

1. Introduction

Radar plays a vital role in modern society ranging from civil to military applications. By using radio technology, modern radar can accurately detect, locate and recognize the remote objects [1]. The performance of radar measurement becomes more and more excellent, while the technologies concerned by radar become more and more complicated. The reliability of the radar equipment and the credibility of the measurement data are the critical consideration of the people who design and use the radar [2]. In order to guarantee the measurement consistency and reliability of radar, the measurement traceability is required. A common traceability method is sending the equipment to specialized laboratories for calibration [3]. However, a great deal of radars cannot be sent to laboratories for the reasons of huge volume, installment or combat duty. Further, the calibration results from the laboratory environment cannot directly reflect the performance of equipment working under the practical conditions. Especially, the static calibration in laboratory cannot guarantee the dynamical performance of the equipment.

In general, the term of traceability is the property of a measurement result whereby the result can be related to a reference standard through an unbroken chain of calibrations [4]. In this sense, the conventional traceability chain is hard to reach the final mile in radar measurement since of various unknown disturbances.

Radar traceability and calibration contains a great deal of aspects [5-6]. From the perspective of different types of calibration parameter, the calibration of radar can be divided into radiation calibration, geometric (spatial) calibration, polarmetric calibration, and movement state calibration etc. According to the characteristics of calibration, there have relative calibration and absolute calibration. While according to the different calibration object, radar calibration contains internal and external calibration. It is to note that, the diverse classification methods of calibration cause inconvenience to us while exploring the essence of radar calibration.

In this paper, from the perspective of radar traceability model, we aim to construct a demand-oriented traceability model for the precipitation radar, in which, internal and external calibration requirements, hardware and software realizabilitiy, and the overall performance of radar are integrally considered. By introducing additional internal test points, a soft calibration standard is developed for signal power measurement to improve the radar measurement performance. Static calibration and dynamic online calibration are well performed during the practical experiments. Hence the accurate measurement performance is achieved.

2. Radar Traceability Model

2.1. Hierarchical Traceability Model of Radar

Via measuring the echo reflected from the target object and properly processing procedure, the physical features of the target can be obtained by radar. Usually, the main features of the target measured by radar include dimension in space and physical characteristics. Dimensional measurement concerns the some parameters of the target, including three dimensional coordinate, velocity, acceleration and trajectory. The measurement of physical characteristic of the target focuses the parameters of radar cross section (RCS), statistical characteristics of RCS, angular glint and its statistical characteristics, polarization scattering matrix, and scattering center distribution, etc., from which, one can derive some physical characteristics of the target, such as, the shape, volume, attitude, and surface materials, roughness, and electromagnetic parameters. So it can archive the goal of object classification, identification and recognition.

Radar measurement is a kind of indirect measurement. To make the results of radar measurement reflecting the dimension and physical characteristics, the corresponding relationship between the measurement results and the target's characteristics should be constructed by quantitatively relating the measurement results to the true values of measurement. To obtain such quantitative relationship is relationship is the destination of radar calibration and traceability. In order to well indicate this relationship, the overall radar measurement process starting from the measured object to the result can be divided into multiple layers shown as Fig. 1, which is a kind of traceability model of radar.

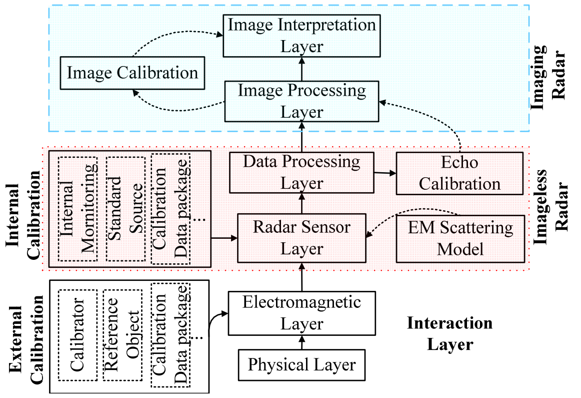

Fig. 1. Radar traceability model.

The first level is the physical layer which indicates the characteristics of object, such as dimension, physical characteristics of the object. The main goal of radar measurement is to most accurately obtain the desired characteristics of the object via the measurement data. The second level is the electromagnetic interaction layer, in which, the interaction between object and electromagnetic waves occurs. Due to the bandwidth limitation of radar itself, only a part of the electromagnetic scattering characteristics can be measured. The third level is radar sensor layer, in which the conversion process from electromagnetic waves to electrical signal is accomplished. It is to note that this conversion process relates to not only the geometric position relationship between radar and object but also the bearing platform, antenna characteristics and radio wave propagation effects. The forth level is the radar processing layer, in which, the signal manipulations, such as signal sampling, A/D, and data storage, are made by the radar receiver.

The four layers above mentioned are included in normal radars, while the imaging radar contains additional layers, i.e., image processing and image interpretation layers. Image processing layer is the fifth level, in which the radar echo signals are processed via different focusing algorithms to form an image relating to the target. The hardware structure of the processor and software of processing algorithm should be paid more attentions in radar system development. The top level is the image interpretation layer containing the processes of target detection, identification and recognition based on the image data [7]. After the image interpretation, the physical characteristics in the physical layer can be obtained from image, such as position, geometric structure, motion and material types, etc.

To enhance the measurement performance, the calibration is essentially necessary. According to the types of radar, the calibration process can be divided into echo field calibration and image calibration. Actually, in the traceability model of radar, the echo field calibration locates between the fourth and fifth level, while the image calibration locates between the fifth and sixth level. In general, the calibration data including echo data file is offline obtained and is stored in the local disk. The calibration strategies come in the following subsections.

2.2. Strategies of Radar Calibration

The strategies of radar are often made in accordance with the hierarchical traceability model. Firstly, the system error sources must be identified. In order to make the image interpretation in the top layer accurate as far as possible, we should identify the system errors and minimize the errors' influences.

The error sources locate in second, fourth and fifth layer of the radar traceability model. In the electromagnetic layer, the system errors mainly include movement errors in radar platform, the errors caused by the distortion of antenna pattern, and the errors resulted from atmospheric propagation. The errors in forth layer are mainly contributed by the imperfect characteristics of radar receiver, and the nonlinearities of AD sampling etc. The error sources in fifth layer mainly refer to the parameter distortions in the various Auto-focus algorithms.

The measurement and evaluation for the errors aforementioned can be performed in each layer of the radar traceability model. For instances, the movement errors can be evaluated by using inertial navigation system and positioning system. Antenna pattern can be measured during the antenna design process. The operation characteristics of the radar receiver can be tested before flying. However, it is hard to calibrate and correct the errors in each layer due to the imperfection of measurement. For examples, the variation of environmental parameters, such as temperature, humidity, will cause the change of the system performance. Further, some parameters like antenna pattern are hard to be directly measured by presently available instruments. Hence we should make the calibration strategies from other views.

In general, the calibrations of radar contain the internal calibration and external calibration. The internal calibration starts with the third layer shown in Fig. 1, in which, by using internal monitor equipment and standard calibrator and calibration data, the transmission characteristics of the fourth and fifth layers can be evaluated. So it could do the calibration or correction for the radar measurement. The most advantage of internal calibration lies in the realization of real-time monitoring, compensation and calibration for improving the system performance. However, the external units, such as antenna, can't be measured and calibrated by the internal calibration method, consequently, to realize the calibration and correction in each layer is not realistic.

The external calibration of radar system located in the physical layer can be accomplished by introduction of calibrators therefore the end-to-end performance evaluation. Here, we should make an assumption that the physical characteristics of the calibrator are well known, otherwise, the electromagnetic scattering model in the second layer should be carefully computed. In this case, we compare the data of auto-calibrator generated by the electromagnetic scattering model and the practical measurement thereby the performance evaluation of the third, fourth, and fifth layers. Such calibration method is called external calibration. In the contrast with the internal calibration, the supreme advantage of the external calibration is the capacity of measuring the whole system performance. But this calibration method can't guarantee the real-time evaluation for the system performance. A practical way to evaluate the system performance is to combine both the internal and external calibration.

2.3. Particularities of Radar Measurement Traceability Chain

During the making of radar calibration strategies, we should consider some particular factors as follows.

1) Environmental effects.

Environmental factors, such as temperature, humidity, atmosphere pressure, vibration, illumination, acceleration, electromagnetic field, wind effect, sunlight etc., more or less affect the measurement results of radar. Especially, the temporal change of the environmental factors will result in the variation of measurement results, mechanism failure and position changing, which directly lead to measurement errors. Hence, careful consideration of the measurement dynamic performance in the varying environment should be firstly made while constructing the traceability chain of radar system.

2) Traceability design.

It is well know that the effective traceability chain must be uninterrupted. In order to guarantee the continuity of the traceability chain, the traceability must be efficiently extended from the conventionally typical examination to the design process of radar therefore a traceability design. Such extension contains the recognition of measurement parameter, the measurable design (auto-calibration, measurement accessibility) and the construction of traceability chain.

3) Soft link and hard link.

During the value transfer, two types of link can be used to construct traceability chain, i.e., soft link and hard link. Hard link refers to use an object with known specific characteristics as a standard reference, such as a fundamental physical constant, or a standard object, etc. In general, the reference object is often with a specified uncertainty. Soft link means to take the well-known physical laws or basic principles as the basis for comparison, calibration and measurement. The conceptualization and realization of such physical laws and principles in the measurement model via software algorithms are necessary for the soft link construction. With the development of computer technology, digital systems are widely used in modern radar design. It not only perfected the data transmission and exchanging performance, but also made constructing system more flexible and simple. Besides many software are playing roles which were played by hardware at one time. It leads to cutting lots of possible time shift, separate simulating hardware needed periodic calibration. With the wide use of standard bus, the system accuracy, measurement accessibility and reproducibility are largely improved.

3. Implementation of Radar Traceability Model Design

In this section, the traceability model design is applied in a type of precipitation radar therefore an online calibration strategy to improve the power measurement accuracy.

Precipitation radar is a kind of weather radar to forecast and locate precipitation in accordance with the radar wave echo, whose power should be accurately measured. The inaccurate measurement of signal power will lead to a seriously wrong result of precipitation forecast. Hence we should make proper calibration strategy to enhance the measurement performance.

3.1. Calibration Strategy

According to the radar traceability model, we should first identify all of error sources in the precipitation radar system. Then the accuracy of radar calibration is guaranteed by external and internal calibration.

The absolute calibration of radar measurement results, the calibration of radar pattern, of gain, and of transmitting power are accomplished by external calibration to achieve the desired accuracy of radar measurement. Internal calibrations calibrate the absolute gain of receiver channel and linearity. Further, the output signal powers of frequency conversion and of mid-frequency combinations are calibrated by removing the variations of receiver channel gains therefore the desired accuracy of radar calibration.

External calibration mainly depends on active radar calibrator, whose accuracy can be calibrated by standard instruments with higher-level accuracy. The quantity to be calibrated can be traced back to the specialized calibration organization. Actually, there have numerous researches (see [8-10] and references therein) on active radar calibrations which are not the main concern of this work. We focus on the traceability model design in the following subsection.

3.2. Traceability Model Design

It is to note that the signal power is the key parameter of precipitation radar for evaluating the amount of precipitation. Hence the traceability model design mainly focuses on the signal power measurement. The conventional scheme of power measurement and internal calibration is shown in Fig. 2, in which two points of power measurement guarantee the accuracy of precipitation measurement, meanwhile, the temperature sensor is used to obtain the operational condition of radar. The power measurements and the temperature sensor output are sent to the building-in-test unit of radar or to the equipment of external calibration while leaving factory. However, such off-line calibration scheme fails to satisfy the requirements of high accuracy of radar which is operated with wide-range of temperature and measurement scope, and the online calibration is hard to be implemented. Hence, the traceability model design is necessary. The traceability mode design of radar power measurement is presented in Fig. 3.

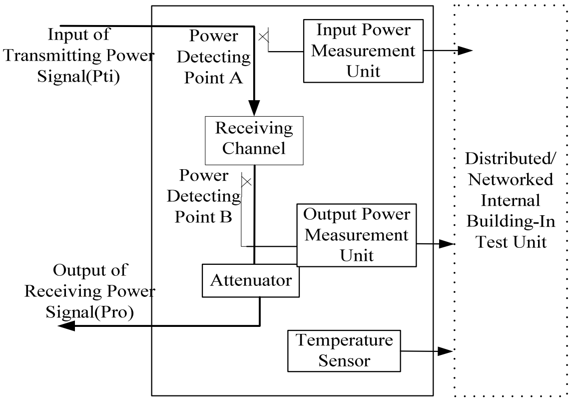

Fig. 2. Conventional Scheme of Internal Calibration.

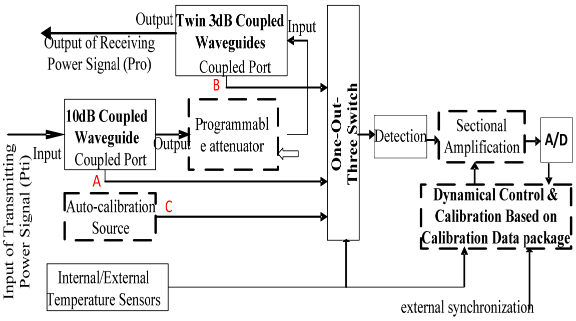

Fig. 3. Traceability Model Design.

Considering the particularities of precipitation radar, we add four additional units, including a temperature compensation unit, a sectional amplification unit, an auto-calibration source, and a dynamical programmable attenuator. On the basis of these additional units comparing with the conventional calibration scheme (shown as Fig. 2), we design three additional detecting points (A, B, and C), and a one-out-three switch to facilitate the internal calibration. According to the measurement on A point, we can obtain the power of the input Pti of the transmitting signals, then the signal power on B point demonstrates the powers of the calibrator R and the output Pro signal. The power of Pro and The calibrator R can be controlled by the programmable attenuator. Further, the power variations of the auto-calibration source (50 MHz) throughing the measurement circuit can be observed on the power detection point C, therefore the long-term characteristics of the power detection circuit.

Note that the power on three detection points closely relates to the environmental temperature, hence the temperature compensation should be carefully considered in the calibration scheme. In the proposed scheme, the temperature compensation is accomplished by the programmable attenuator, whose output is based on a lookup table driven by the internal and external temperature and the corresponding power measurements. The table is called a calibration data package, whose acquisition is presented in the next subsection. The main units of the proposed calibration scheme are explained as follows.

1) Temperature compensation.

The operation temperature of internal calibration equipment ranges from -20 ºC to 60 ºC. It is well known that the performance of some main components of internal calibration, such as demodulator, calibration source, switch, and attenuator, etc., deeply relates to the environmental temperature. Hence, the temperature compensation module based on the internal/external temperature sensors' output signal and the calibration data package is constructed during the internal calibration. The acquisition of the calibration data package will be presented in the following subsection.

2) Sectional amplification.

Even for the coaxial GaAs (gallium arsenide) microwave detector, the nonlinear output-voltage sensitivity of the detector with respective to the input signal power is still a serious problem. To achieve high voltage sensitivity, meanwhile, to alleviate the pressure of the resolution of AD converter, the sectional amplifier is used in the proposed traceability model design.

3) Auto-calibration source.

To reduce the influences of the new circuits, an auto-calibration source of 50 MHz designed by us is introduced. Apart from utilization of voltage reference with high stability, some diodes, which have the similar functions of detector diodes, are cascaded with the voltage reference to compensate the temperature drift and ageing characteristics of the detector diodes. The practical experiment of 10-days constant-temperature test reveal the power variation of the auto-calibration source is bounded in ±0.02 dBm. In different environmental temperature, the maximum fluctuation of the output power is 0.055 dB. These test results reveal the designed auto-calibration source is with high stability with respect to temperature.

3.3. Acquisition of Soft-standard Calibration Data Package

In the above traceability model design, the power measurement results should be online calibrated, meanwhile, to alliviate the influences of the temperature variation, the signal attenuation gain should be controlled in accordance with the temperature variation. Obviously, the quality of the calibration data package directly effects on the performance of internal calibration.

In order to obtain a high-quality soft-standard calibration data package, we proposed a method shown in Fig. 4, in which, the main aim of calibration is to correct the error caused by the temperature variations. Hence, the acquisition of the soft-standard calibration data package is based on the test experiments performed in the automatic thermostat. The test experiment is performed as the following steps.

Step 1: Connections are made according to Fig. 4. The signal source is connected with the input port of 10 dB coupled waveguide via 6 dB coupled waveguide and waveguide connector. The power meter 1 is connected to the coupled port of 6 dB coupled waveguide therefore the power of the 10 dB coupled waveguide input port via calibrations.

Step 2: The gain of the programmable attenuator is set to 0. The output port of twin-3 dB waveguide is connected to the 50 Ω load and the power meter 2.

Step 3: Control the temperature increasing from -20 ºC to +65 ºC with a step of 5 ºC (or 2 ºC). Meanwhile, let the signal power of Pti change from +17 dBm to -13 dBm with a step of 0.1 dBm. Then measure the corresponding power of the detection point A and C.

Step 4: Similar to the configuration of Step 3, obtain the corresponding power magnitude on the point C of the 50 MHz calibration source.

Step 5: Similar to the configuration of Step 3, calibrate the combination of input power and output power by using the power meter 1 and power meter 2, therefore the attenuation gain in different temperature.

After the above steps, we henceforth have the calibration data package on the power of transmitting signal Pti. Similarly, we can obtain the calibration data package on the power of receiving signal Pro through controlling the one-out-three switch.

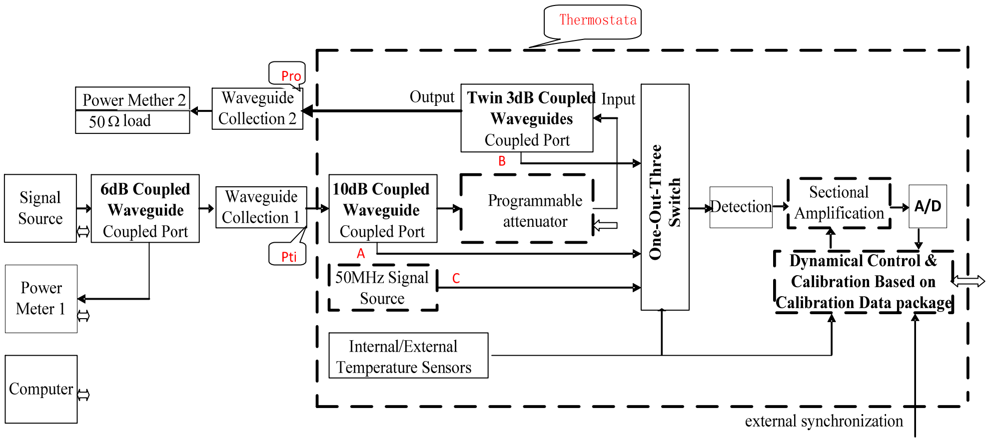

Fig. 4. Acquisition of Soft-Standard Calibration Data Package.

4. Experimental Validations

In this section, we performed the offline and online experiments to validate the efficiency of the proposed radar traceability model design and the corresponding soft calibration strategy.

4.1. Offline Experimental Test

The power measurement results of the radar internal calibration device directly affects on the reliability of the radar measurement, while the power measurement is dramatically influenced by the operational temperature. Thus, we need to control the attenuation gain of the signal attenuator in accordance with the environmental temperature, and the control accuracy will act on the final measurement results. Consequently, the power measurement and the attenuation control of the internal calibration device are the emphasis of the experimental validation.

1) Performance validation of internal calibration device.

Let the standard signal source as the excitation whose power decreased from 16 dBm to -13 dBm. The decrement step is set as 1 dBm. During the experiment, the standard signals were measured by the standard power meter and the internal calibration device, respectively. The measurement results are illustrated by Fig. 5 which reveals the readings by the internal calibration device closely approx that of the power meter. The difference of two types of readings is demonstrated in Fig. 6. It is obvious that the errors of two types of reading are bounded in ±0.15 dBm. This numerically reveals that the proposed traceability model design and the soft calibration strategy render high accuracy of signal power measurement.

2) Experiment on the attenuation control.

In order to validate the performance of attenuation control provided by the internal calibration device, the vector network (VN) analyzer is used to measure the attenuation produced by the internal calibration device. In the experiment, let the attenuation gain of the calibration device varying from 42 dB to 85 dB by a step of 1 dB. Fig. 7 presents the errors between the VN measurements and the given attenuation. The control accuracy of the attenuation lies in the scope of ±0.2 dB.

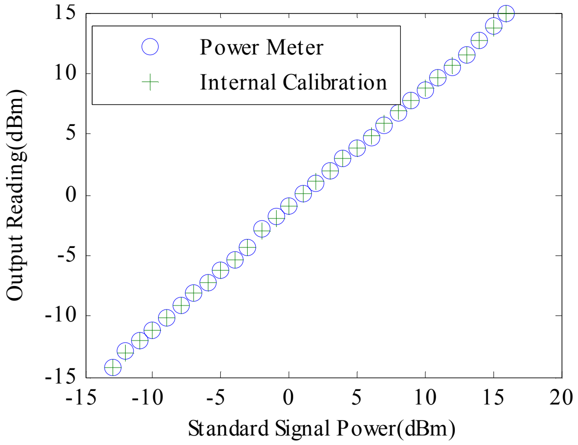

Fig. 5. Power measurement results.

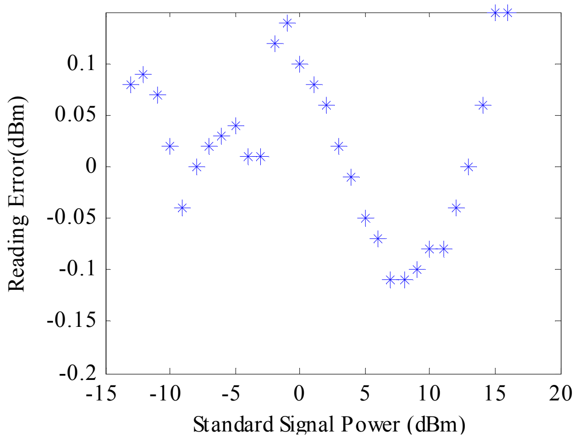

Fig. 6. Reading errors of power measurement.

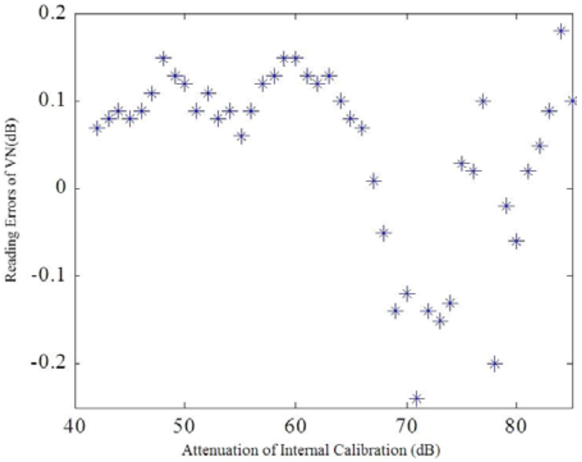

Fig. 7. Validation results of attenuation control.

4.2. Online Experimental Test

After the performance validation of the internal calibration device, we need to validate the overall performance of the precipitation radar measurement by online experiment. In this work, we carried the precipitation radar on an airplane to perform a real-time measurement experiment, which is start from eight o'clock to near twelve o'clock in a certain day. During the experimental flight, the temperature of the radar operation varies with respect to time, and the temperature curve is depicted as Fig. 8.

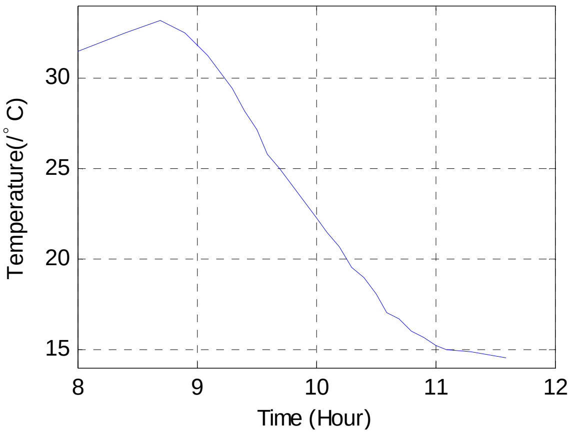

Fig. 8. Curve of temperature versus time during the flight operation.

Under the operation condition, let the detection point A be chosen therefore the power magnitude of A. Based on the power of A point and the current temperature obtained by the temperature sensors, the power of transmitting signal Pti is obtained by looking up the soft calibration data package. Then, choose two mid-frequencies f_1 and f_2 and control the gains of mid-frequency by the programmable attenuator in accordance with the temperature and the measured power, therefore curves of two mid-frequency gains versus to the temperature (shown as Fig. 9).

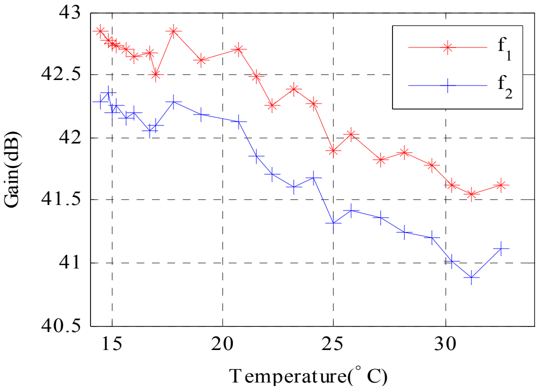

Fig. 9. Mid-frequency transmitter gain versus temperature.

Then change the one-out-three switch to the detection point B, in the same time, let the attenuation gain be 0. Similarly, based on the measured power of point B and the current temperature, we can obtain the power of receiver signal Pro by looking up the calibration data package. Again, control the power of Pro by the programmable attenuator therefore the variation curve of the mid-frequency gains versus to the temperature (shown as Fig. 10). It is obvious that the variation of receiver gain and the temperature have an approximately linear relationship, which well satisfies the requirement of online calibration. Finally, the curves of the mid-frequency gains versus the attenuation are presented in Fig. 11.

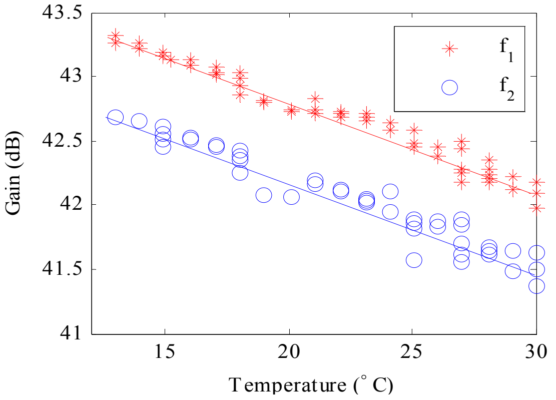

Fig. 10. Receiver gain versus temperature.

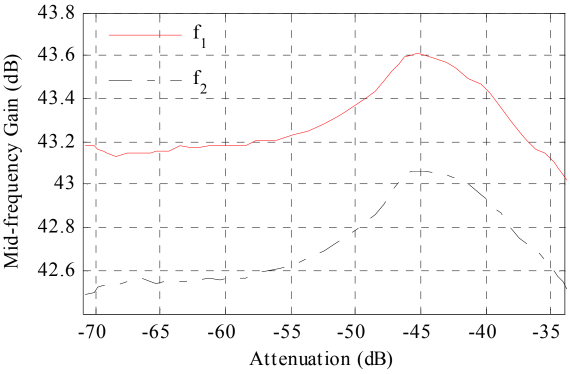

Fig. 11. Mid-frequency gain curve of internal calibration.

5. Conclusions

Measurement traceability is a main concern in almost all instrumentation design. In radar system design, the final measurement results relate to the unified standard by uninterrupted data chain of comparison to guarantee the traceability. To enhance the performance of radar measurement, various error sources should be identified and traced, and their effects on the measurement result should be accurately calibrated. Hence, the traceability model design is a nice choice to obtain soft-calibration data packages, which easily facilitate the online calibration to improve the measurement accuracy.

In this work, to enhance the performance of the precipitation radar, we proposed a novel traceability model design method by introducing additional circuit units, which include a temperature compensation unit, a sectional amplifier, and a programmable attenuator. The three internal detection points are set for the acquisition of soft calibration data package and the online calibration. The static calibration experiments and real-time online calibration tests reveal the proposed method is efficient to perform the online calibration for the power measurement in the precipitation radar.

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