Analysis of Noise Injection Calibration Method for K-band Room-Temperature Receivers - Postprint

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Abstract

The noise injection calibration method is widely employed as a conventional intensity calibration technique in the centimeter-wave band. A K-band room-temperature receiver and its calibration platform were constructed to calibrate the receiver noise temperature and noise source temperature using the traditional hot/cold load method at 20°C indoors, and subsequently recalibrated at -7°C outdoors using the same approach. The indoor-calibrated noise source was then utilized to further calibrate the receiver noise temperature in the outdoor environment. Test results demonstrate that with an ambient temperature variation of approximately 27°C, the calibration discrepancy for receiver noise temperature is about 50.5%, while that for the standard noise source is about 41%. Consequently, it is evident that applying the noise injection method to room-temperature receiver calibration necessitates first considering thermal stabilization of the receiver. Furthermore, implementing temperature compensation for the injected standard noise source would enable its more accurate application in secondary calibration, which constitutes the planned future work of this paper.

Full Text

Preamble

Analysis and Research on Noise Injection Calibration Method for K-Band Ambient Temperature Receiver

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Abstract: The noise injection calibration method is widely used as a conventional intensity calibration approach in centimeter-wave receivers. By establishing a K-band ambient temperature receiver and its calibration platform, we first calibrated the receiver noise temperature and noise source temperature using the traditional cold/hot load method at an indoor temperature of 20°C. The same method was then applied at an outdoor temperature of -7°C to calibrate these parameters again. Subsequently, the noise source calibrated indoors was used to further calibrate the receiver noise temperature in the outdoor environment. Test results demonstrate that when the ambient temperature changes by approximately 27°C, the difference in receiver noise temperature calibration is about 50.5%, and the difference in standard noise source calibration is about 41%. Therefore, if the noise injection method is to be applied to ambient temperature receiver calibration, it is first necessary to consider thermal control of the receiver. Additionally, temperature compensation for the injected standard noise source can be implemented to make it more accurately applicable to secondary calibration. This represents the planned next step of our research.

Keywords: Calibration; Receiver; Noise temperature; Cold/hot load method; Noise injection
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Radio astronomy is an observational discipline that utilizes radio telescopes to receive microwave signals from radio sources. The microwave receiver is a critical piece of equipment in radio astronomy observations. After being received by the radio telescope, the radio signal is first reflected and converged onto the phase center of the receiver system' s feed, then amplified by a low-noise amplifier, filtered by a bandpass filter to select the required operating frequency band, mixed with a local oscillator signal in the mixer, and finally transmitted as an intermediate frequency signal to the digital backend for storage, where it is made available for astronomers to process. The basic composition of a receiver system is shown in Figure 1 [Figure 1: see original paper].

Figure 1. Receiver system

Receiver calibration establishes a temperature scale that equivalently converts the receiver' s intensity response to a radio source into a temperature value, which is then combined with antenna parameters to ultimately convert it into the astronomical quantity of flux density. The general method involves using the cold/hot load method to obtain the receiver' s intensity-to-temperature response ratio g (Formula 1), where T_amb is the ambient blackbody load temperature, T_cold is the cryogenic blackbody load temperature, V_amb is the power output with the ambient blackbody load, and V_cold is the power output with the cryogenic blackbody load.

Using this intensity-to-temperature response ratio g, ON/OFF observations of the radio source are performed to obtain the equivalent temperature T_A of the source (Formula 2), where V_ON is the power output when pointing at the source and V_OFF is the power output when pointing off-source.

Finally, combining the antenna aperture A_p and efficiency $\_A$, the flux density S_v of the radio source can be obtained (Formula 3), where k is the Boltzmann constant.

As the core signal reception equipment in a radio telescope system, the most important receiver performance metric is sensitivity, typically characterized by noise temperature. Higher sensitivity means the receiver can detect weaker radio signals. The thermal noise generated by the receiver itself is referred to as the receiver noise temperature, which is essentially the equivalent temperature value after calibrating the receiver’ s own intensity response.

1.1 Cold/Hot Load Method

The cold/hot load method is considered the most classical approach for receiver calibration. According to Planck’ s blackbody radiation principle, any object at different temperatures emits thermal radiation externally, and the radiation intensity has an approximately linear relationship with the object’ s temperature within a certain range. The cold/hot load method is based on this principle. Specifically, when testing receiver noise temperature, two broadband blackbody radiation sources at different physical temperatures (such as a cryogenic blackbody load in 80 K liquid nitrogen and an ambient blackbody load at 300 K room temperature) are placed at the receiver feed aperture (in front of the first-stage amplifier or mixer). This allows the blackbody loads to absorb microwave radiation from outside the feed while injecting radiation from the different temperature blackbody loads into the receiver for noise calibration. The cold/hot load method test is shown in Figure 2 [Figure 2: see original paper].

Figure 2. The test of cold and hot load method

Formula 1 is expanded into Formula 4, where T_rec is the receiver noise temperature. After completing receiver noise calibration, ON/OFF observations of radio sources are performed using the radio telescope to obtain the equivalent temperature of the source, which is then combined with antenna efficiency and aperture to obtain the flux density.

Although the cold/hot load method is recognized as the best receiver calibration approach in the industry, it has certain limitations. Since receiver systems are generally installed in the receiver cabin of a radio telescope and rotate in azimuth and elevation during observations, engineers cannot use cold/hot loads to calibrate the receiver while the antenna is moving, especially since it is impossible to provide a cold load for calibration. Consequently, the response ratio g cannot be obtained.

1.2 Noise Injection Method

Given that the cold/hot load method cannot be performed for real-time calibration during antenna observations, a method of injecting standard noise from the receiver end has been proposed. This approach involves injecting a standard noise signal (a pulsed noise diode, also called a noise source) into the receiver signal chain. Before observations, the cold/hot load method is first used to calibrate the standard noise source. After obtaining the equivalent temperature value of the standard noise source, this calibrated source is then used for secondary calibration of radio sources during observations. Since the standard noise source can be conveniently turned on or off at any time during observations, this method is widely used for centimeter-wave receiver calibration.

Formula 5 shows the calculation formula for the receiver' s standard noise source temperature T_cal, where V_cal_ON is the power output with the blackbody load when the noise source is on, and V_cal_OFF is the power output with the blackbody load when the noise source is off.

After completing receiver noise calibration, ON/OFF observations of radio sources are performed using the radio telescope to obtain the equivalent temperature of the source, as shown in Formula 7, thereby enabling further calculation of flux density.

The noise injection calibration method is generally divided into two types: free-space noise injection and waveguide noise injection. Figure 3 [Figure 3: see original paper] shows a schematic diagram of the free-space noise injection method. The standard noise source is placed at the antenna' s subreflector position, facing the receiver beam direction, and the calibrated noise signal is injected into the receiver feed through free space for calibration.

Figure 3. Free space noise injection mode

Due to the susceptibility of free-space noise sources to changes in external ambient temperature and spatial signal attenuation, the waveguide noise injection method is more commonly used for centimeter-wave receiver calibration. This involves injecting the standard noise signal into the receiver interior via a directional coupler located behind the receiver feed, thereby establishing a temperature scale for calibration. Figure 4 [Figure 4: see original paper] shows a schematic diagram of the waveguide noise injection method.

Figure 4. Waveguide noise injection mode

The noise injection method effectively solves the problem of real-time calibration that the cold/hot load method cannot address. However, it introduces additional components into the receiver system, such as the directional coupler required for noise injection, which adds extra noise to the entire system.

Additionally, for ambient temperature receivers, the *T_cal* value calibrated at one temperature will introduce a certain degree of difference during secondary calibration due to temperature variations.

2 System Setup, Testing and Analysis

To conduct research on intensity calibration of centimeter-wave receivers (including atmospheric opacity measurements in the short centimeter-wave band), a K-band ambient temperature receiver with noise injection capability and its test platform were built to carry out research on receiver noise injection calibration methods.

2.1 K-Band Receiver

The built K-band ambient temperature receiver consists mainly of a feed network, noise source, low-noise amplifier, bandpass filter, mixer, dielectric local oscillator, and intermediate frequency amplifier, as shown in Figure 5 [Figure 5: see original paper]. The RF operating bandwidth of this receiver is the same as that of the Nanshan 25 m telescope' s K-band cryogenic receiver (22-24.2 GHz, and the band includes the Nanshan station water vapor radiometer test frequency point of 23.8 GHz). It adopts a superheterodyne design, where the RF signal is amplified, filtered, and mixed to ultimately output an IF signal of 3.95-6.15 GHz. To reduce costs, the test system only processes and performs power acquisition on the left-hand polarization signal output from the receiver' s polarizer, while the right-hand signal is directly connected to a matched load after the waveguide-to-coaxial converter. Therefore, all subsequent test data in this paper are from the left-hand signal.

Figure 5. The schematic diagram of K-band receiver

The directional coupler in the feed network of the above K-band ambient temperature receiver is a microwave component specifically designed for injecting standard noise signals. The standard noise source selected is the NOISEWAVE NW18G-15-CS, as shown in Figure 6 [Figure 6: see original paper].

Figure 6. Directional coupler and noise source

The physical implementation of the K-band receiver is shown in Figure 7 [Figure 7: see original paper]. The low-noise amplifier in the left-hand polarization chain and its subsequent microwave components are mounted on an aluminum plate, which not only facilitates overall fixation behind the feed network but also aids in heat dissipation for each active component.

Figure 7. K-band receiver

2.2 Noise Injection Method Testing

First, based on the cascaded noise calculation method, the theoretical noise temperature of the K-band receiver at 22°C (room temperature) is calculated to be 406.5 K (sum of Eff.T), as shown in Table 1 .

Table 1. Theoretical calculation of noise temperature of K-band receiver

In the room temperature environment, five sets of tests were conducted using the cold/hot load method to calibrate the noise temperature and standard noise source temperature of the K-band ambient temperature receiver. The test data and calculation results from the five sets of noise injection method tests, along with the comparison errors relative to the theoretically calculated noise temperature (the theoretical receiver noise temperature at 20°C is 403.7 K), are shown in Table 2 . Here, *V_amb_cal_ON* is the power output of the receiver when the ambient blackbody load covers the receiver feed aperture and the noise source is on, and *E_rec* is the relative error between the *T_rec* measured by the cold/hot load method and the theoretically calculated noise temperature of the K-band receiver at the corresponding ambient temperature.

Table 2. Test data and comparison results for indoor

In the outdoor environment, five sets of tests were also conducted using the cold/hot load method to calibrate the noise temperature and standard noise source temperature values of the K-band ambient temperature receiver. The test data and calculation results from the five sets of noise injection method tests, along with the comparison errors relative to the theoretically calculated noise temperature (the theoretical receiver noise temperature at -7°C is 366.5 K), are shown in Table 3 .

Table 3. Test data and comparison results for outdoor

2.3 Test Data Analysis

First, the measurement precision of the cold/hot load method for testing receiver noise temperature was evaluated using the five sets of indoor test data from Table 2. The five measurement precision values are 4.71%, 5.06%, 5.06%, 5.01%, and 5.07%. Subsequently, by comparing the receiver noise temperature measured by the cold/hot load method with the theoretically calculated values, the indoor test errors are found to be between 1.2% and 5.1%, while the outdoor test errors are between 0.5% and 1.6%, thereby verifying that this classic calibration method fully meets the noise temperature test requirements (error within 10%).

Formula 7 shows the calculation method for solving the receiver noise temperature when the standard noise source temperature value is known. From the formula, we can see that in addition to the *T_cal* value, the temperature and corresponding power output of the ambient (or cryogenic) blackbody are also required.

Using the ambient blackbody calibration test data from Table 3 and the standard noise source temperature value calibrated in the indoor environment (20°C) (taken as the average T_cal value of 162.6 K from Table 2), the receiver noise temperature in the outdoor low-temperature environment was secondarily calibrated. The test differences in the standard noise source temperature and receiver noise temperature in the outdoor low-temperature environment are shown in Table 4 .

Table 4. Test data and comparison results of noise injection method for outdoor

This paper establishes a K-band ambient temperature receiver and its calibration platform to conduct analysis and research on receiver noise injection calibration methods. First, in an indoor environment at 20°C, the traditional cold/hot load method was used to test the receiver noise temperature and calibrate the standard noise source temperature of the K-band receiver. The K-band receiver was then placed in an outdoor environment at -7°C, and after the receiver' s physical temperature equilibrated with the ambient temperature, the classical calibration method was again used to obtain the receiver noise temperature and noise source temperature. Subsequently, using the noise source temperature calibrated in the indoor environment, combined with switching the noise source on and off under the ambient blackbody, the receiver noise temperature tested using the noise injection calibration method in the outdoor environment was obtained. Test results show that when the ambient temperature changes by nearly 27 K, the difference in standard noise source temperature is about 41%, and the difference in the secondarily calibrated receiver noise temperature is about 50.5%. Therefore, it is concluded that the noise injection calibration method for ambient temperature receivers should be performed under relatively stable ambient temperature conditions, such as by adopting a constant-temperature treatment for the receiver, similar to the cryogenic dewar approach used for cryogenic receivers, to maintain constant temperature for the low-noise amplifier and its front-end components. When the ambient temperature variation range is large, real-time calibration methods such as the chopper wheel method should be considered to reduce errors. Future work will focus on error analysis of the noise injection method under different ambient temperatures, with the expectation of compensating for the temperature of the injected standard noise source to reduce the error in the secondarily calibrated receiver noise temperature or the equivalent temperature of radio sources to an acceptable range. Ultimately, it is hoped that this research can provide technical references for the calibration of centimeter-wave receivers for the Xinjiang Astronomical Observatory' s QTT project.

References

[1] WANG Na. Xinjiang Qitai 110 m Radio Telescope [J]. Scientia Sinica (Physica, Mechanica & Astronomica), 2014, 44(8): 783-794.
[2] CHEN Maozheng, LIU Qi, MA Jun, WANG Na. Development of Ultra-Wideband Receiver Technology for Large Aperture Radio Telescopes [J]. Scientia Sinica (Physica, Mechanica & Astronomica), 2017, 47(05): 35-47.

[3] XIANG Binbin, WANG Congsi, WANG Wei, et al. Subreflector Position Adjustment Method for Reflector Antenna Based on Electromechanical Coupling [J]. Systems Engineering and Electronics, 2018, 40(3): 489-497.
[4] MA Jun, PEI Xin, WANG Na, LI Jian, WANG Kai, LIU Yanling. QTT Ultra-Wideband Multi-Beam Signal Reception and Processing System [J]. Scientia Sinica (Physica, Mechanica & Astronomica), 2019, 49(09): 6-18.
[5] ZHANG Hailong, ZHU Yan, NIE Jun, YUAN Jianping, WU Gang, LIU Jun, WANG Jie, WANG Wanqiong, YE Xinchen, TUHOTINUR, ZHANG Meng. Xinjiang Astronomical Observatory NSRT Observation Data Storage System [J]. Astronomical Research & Technology, 2018, 15(02): 181-187.
[6] WANG Kai, CHEN Maozheng, LI Xiaofei, LI Jian, XIANG Binbin, YAN Hao, WANG Yang. Noise Temperature Test and Analysis of Ku-Band Receiver [J]. Electro-Mechanical Engineering, 2018, 34(06): 13-16+21.
[7] WANG Kai, CHEN Maozheng, MA Jun, LI Xiaofei, YAN Hao, XIANG Binbin. Intensity Calibration of Radio Astronomical Millimeter-Wave Receivers [J]. Acta Astronomica Sinica, 2018, 59(05): 3-16.
[8] HAN Kezhen, GENG Xue, ZHANG Fang, GE Xiaolu, LIU Xiaojuan, QIN Hua. Discussion on the Vertex Problem of Blackbody Radiation Curve [J]. Physics Bulletin, 2018(10): 115-118.
[9] CHEN Yong, SUN Zhengwen, YAN Hao, LI Jian, LI Dalei, LI Xiaofei, LIU Feng. Conversion of Linear-Circular Polarization for Xinjiang Astronomical Observatory 26 m Telescope L-Band Receiver [J]. Astronomical Research & Technology, 2019, 16(03): 262-267.
[10] CHEN Maozheng, MA Jun, QIN Lü, et al. Design of Q-Band Ridge Transition Orthomode Transducer [J]. Journal of University of Electronic Science and Technology of China, 2018, 47(2): 178-182.

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Note: Figure translations are in progress. See original paper for figures.