

Feedback-Controlled Beam Pattern Measurement Method Using a Power-Variable Calibration Source for Cosmic Microwave Background Telescopes

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Received September 11, 2025; Revised December 26, 2025; Accepted January 12, 2026; Published January 20, 2026

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We demonstrate a novel beam pattern measurement method for the side lobe characterization of cosmic microwave background telescopes. The method employs a power-variable artificial microwave source under feedback control from the detector under test on the telescope. It enables us to extend the dynamic range of the beam pattern measurement without introducing nonlinearity effects from the detector. We conducted a laboratory-based proof-of-concept experiment, measuring the H -plane beam pattern of a horn antenna coupled to a diode detector at 81 GHz. We gained an additional dynamic range of 60.3 dB attributed to the feedback control. In addition, we verified the measurement by comparing it with other reference measurements obtained using conventional methods. The method is also applicable to general optical measurements requiring a high dynamic range to detect subtle nonidealities in the characteristics of optical devices.
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Subject Index F10, F14, H52

1. Introduction

Precise measurements of degree-scale B-mode polarization patterns in the cosmic microwave background (CMB) provide information about inflation in the early universe [1,2]. The inflationary B-mode signal has not been detected yet, and further observations are ongoing or planned with ground-based or space-borne telescopes (e.g. Refs. [3–7]). These experiments aim to achieve sufficient statistical sensitivity to detect the B-mode signal by using arrays of highly

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sensitive detectors such as transition edge sensor (TES) bolometers, combined with multiyear observation campaigns. However, controlling systematic errors is crucial. A major source of systematic errors is the leakage of galactic foregrounds through side lobes, undesired gain outside the telescope's line of sight. These foregrounds are bright enough to leak into the B-mode signal, leading to a significant systematic error.

To avoid such contamination, it is necessary to precisely characterize the side lobes, in addition to using a telescope with inherently low side lobe levels. Comprehensive characterization is required to verify that the side lobe level meets design specifications and to enable accurate foreground removal during data analysis. Even extremely faint side lobes (e.g. those at 30 dB or more below the main lobe) must be identified prior to science observation; otherwise, they may introduce systematic errors in the B-mode search over long-term observations. In particular, space-borne telescopes must rigorously characterize their side lobes during prelaunch laboratory testing. For example, *LiteBIRD*, a future CMB observation satellite, requires far side lobe calibration down to -56 dB [7]. Thorough side lobe characterization during predeployment or prelaunch laboratory testing is important for future CMB telescopes to ensure high-quality B-mode observations.

Accurate characterization of such faint side lobes demands a high dynamic range measurement of the beam pattern, the telescope's angular gain profile. However, the TES bolometers employed in current- and next-generation CMB telescopes have dynamic ranges that typically fall short of this requirement. The dynamic range of a detector is defined as

$$\text{DR}_{\text{dB}}[P_r] = 10 \log_{10} \frac{\max P_r}{\Delta P_r} \text{ dB}, \quad (1)$$

where P_r denotes the power received by the detector and $\max P_r$ and ΔP_r represent the maximum measurable power¹ and the minimum detectable power within its linear response range, respectively. The maximum measurable power is significantly lower than the saturation power P_{sat} (typically on the order of pW in TES bolometers used in CMB telescopes [5,8–10]) due to detector nonlinearity, and the minimum detectable power is determined by the noise-equivalent power (NEP—typically tens of a $\text{W}\sqrt{\text{s}}$ level [11]) and signal integration time t . For example, assuming $\max P_r < 0.1P_{\text{sat}}$ and $\Delta P_r \sim \text{NEP}/\sqrt{t}$ and using the typical values above with an integration time of $t = 1$ s, the dynamic range is estimated to be less than 40 dB. It is also difficult to extend the dynamic range by using signals in the nonlinear region in practice. Correcting distorted signals requires characterizing and understanding the actual nonlinearity of each TES bolometer on the telescope [10]. The limited dynamic range hinders the detection of faint side lobes with the TES bolometers installed in the telescopes.

CMB telescopes commonly measure their beam patterns by scanning bright, point-like static sources in the sky (e.g. planets [12–14]). Repeating and averaging multiple measurements over the observation period improves the signal-to-noise ratio and extends the dynamic range. However, achieving a high dynamic range such as 60 dB using this method is impractical, as a 10 dB increase in dynamic range requires statistically 100 times more data. Additionally, long-term instabilities in the source or instruments can introduce significant systematic errors. A more practical approach is to combine multiple measurements using sources of varying intensities. Examples include celestial bodies such as planets, the Sun, and the Moon [14–17]. The BICEP/Keck Collaboration employed an artificial microwave source with several intensity levels

¹Commonly defined as the 1 dB compression point.

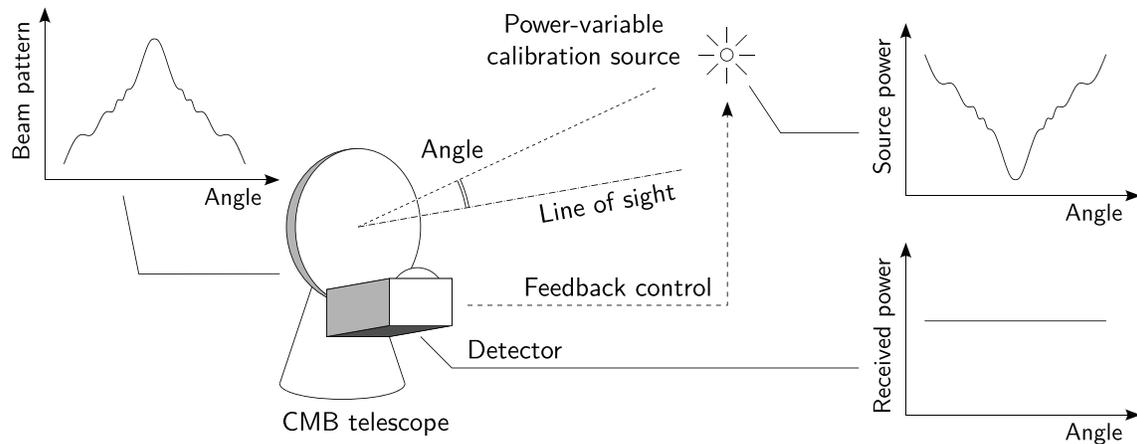


Fig. 1. Concept of the feedback-controlled beam pattern measurement method. The beam pattern measurement is conducted using the power-variable calibration source under feedback control from the DUT on the telescope. The feedback control keeps the power received by the detector constant to avoid detector nonlinearity during the measurement.

selectable using built-in attenuators, achieving a dynamic range of ~ 70 dB in their on-site side lobe calibration [5,18].² In this multisource approach, however, the TES bolometer's nonlinearity can distort the united beam pattern when stitching multiple measurements together. This concern is particularly significant in laboratory testing for predeployment or prelaunch characterization. Since bolometer conditions, such as optical loading or noise level, in the laboratory may differ from those in situ, the bolometers may exhibit greater nonlinearity than expected.

This study presents an advanced measurement method for high dynamic range beam pattern characterization. The concept of the proposed method is illustrated in Fig. 1. The method employs a power-variable artificial microwave source. Feedback control from the detector under test (DUT) on the telescope is applied to the source, dynamically adjusting the source power during measurement to maintain the received power at a constant level within the detector's linear response range. This approach renders the measurement results insensitive to detector nonlinearity. It effectively extends the dynamic range of the beam pattern measurement regardless of the detector's intrinsic dynamic range.

Section 2 describes the methodology of the proposed approach. Section 3 presents a laboratory-based proof of concept, demonstrating that the method achieves high dynamic range beam pattern measurement as intended. Finally, Section 4 summarizes the conclusions and discusses the prospects of the method. We also mention broader applications of the method to general optical measurements beyond beam pattern characterization of CMB telescopes.

2. Methodology

Figure 2 shows a high-level illustration of the general system used for a beam pattern measurement in the proposed method. A microwave is generated by a power-variable source and is transmitted from a feed horn into free space. After passing through an optical system (e.g. a compact range) or over a far-field distance, the microwave is well-approximated by a plane wave and illuminates the antenna under test (AUT) at an angle (θ, ϕ) . The AUT is coupled with

²Note that their TES bolometers had a special operation mode for calibration only, in which the bolometers were biased at a higher transition point and extended the saturation power and dynamic range [5,18].

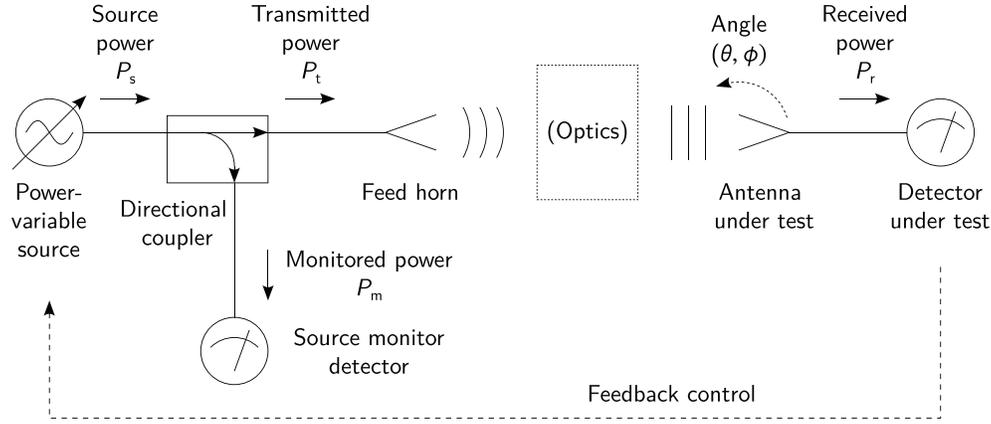


Fig. 2. General model of the feedback-controlled beam pattern measurement system. The microwave generated by the power-variable source propagates from the feed horn to free space, passes the optics (e.g. a compact range or a far-field distance), and illuminates the AUT coupled to the DUT. The source monitor tracks the source power through the directional coupler. The closed-loop feedback control from the DUT adjusts the source power during the measurement.

an amplitude detector (referred to as the DUT) to measure the received power P_r . A second detector, referred to as the “source monitor,” is connected to the source via a directional coupler. The source monitor tracks the source power P_s during the measurement by sampling it through the coupler and measuring the monitored power P_m . This is essential because the source may exhibit nonlinearity or lack calibration in practice.

The system incorporates closed-loop feedback control from the DUT to the source. The control loop dynamically adjusts the source power during measurement to maintain the received power at a constant target level, $P_{r,\text{target}}$, set within the DUT’s linear response range. This measurement scheme excludes distortion due to DUT nonlinearity from the measurement by keeping the received power constant during the measurement. In effect, the method transfers the linearity requirement from the DUT to the source monitor detector. By selecting a source monitor detector with better linearity than the DUT, the overall linearity of the measurement is improved. This approach is particularly helpful when the DUT is a nonlinear detector, such as a TES bolometer.

The adjustable power range of the source is constrained by the linear response range of the source monitor or the emissible power output range of the source. When the source power reaches the upper limit of the adjustable power range, the measurement is conducted within the DUT’s own dynamic range, as in a conventional static source measurement.

This method requires appropriately determining the minimum source power, $\min P_s$, and the coupling factor, C , of the directional coupler. Assuming the loss of the coupler is negligible, the requirements are

$$\min P_s \leq \frac{1}{\eta} P_{r,\text{target}}, \quad (2a)$$

$$C \leq -10 \log_{10} \left(\eta \frac{\Delta P_m}{P_{r,\text{target}}} \right) \text{ dB}, \quad (2b)$$

where $\eta = P_r(\theta_0, \phi_0)/P_t(\theta_0, \phi_0)$ represents the total optical efficiency from the feed horn to the DUT at the beam center, where P_t is the transmitted power from the feed horn and ΔP_m is the minimum detectable power of the source monitor. The optical efficiency depends on the

optical system configuration. These requirements ensure that the source and monitored powers remain sufficiently high at the beam center. The coupling factor is optimal when equality holds in Eq. (2b), where the total dynamic range of the beam pattern measurement is maximized.

The normalized power beam pattern at an angle (θ, ϕ) is given by

$$G_n(\theta, \phi) = \frac{1}{G_0} \frac{P_r(\theta, \phi)}{P_m(\theta, \phi)}, \quad (3)$$

where $G_0 = P_r(\theta_0, \phi_0)/P_m(\theta_0, \phi_0)$ is the normalization factor and (θ_0, ϕ_0) denotes the angle at which the beam pattern reaches its maximum (typically at the beam center). By the feedback control, the beam pattern measurement obtains an additional dynamic range, in which the systematic error due to the DUT's nonlinearity is excluded. This additional dynamic range is gained independently of the DUT's own dynamic range. Assuming that the coupling factor is optimized as previously described and that the adjustable power range of the source is limited by the linearity of the source monitor, the additional dynamic range corresponds to that of the source monitor detector, $\text{DR}_{\text{dB}}[P_m]$, which is defined consistently with Eq. (1). Therefore, a detector with good linearity and a high dynamic range is suitable as a source monitor in high dynamic range measurements. The whole measurement can be performed independently of the DUT's dynamic range, provided that the source monitor offers a higher dynamic range than required.

In some cases, the source may saturate in a high-power region and run short of power during the feedback control. When this happens, the adjustable power range of the source is limited by its maximum emissible power, $\max P_s$, rather than by the maximum measurable power of the source monitor. Then, the additional dynamic range gained by the feedback control reduces to $10 \log_{10} \left(\eta \frac{\max P_s}{P_{r,\text{target}}} \right)$ dB. However, commercial artificial microwave sources can typically emit 10 dBm or more, which is sufficient in most cases, including the demonstration shown in Section 3.

3. Proof-of-concept test

To demonstrate proof of concept, we applied this method to a laboratory optical system and measured the H -plane beam pattern³ of a W-band (75–110 GHz) standard gain pyramidal horn antenna (Millitech SGH-10-RP000) coupled to a commercial diode amplitude detector (Eravant SFD-753114-103-10SF-P1). We set the target dynamic range of the measurement at 60 dB, which satisfies *LiteBIRD*'s calibration requirement of 56 dB [7].

3.1. Test setup

We constructed a feedback-controlled beam pattern measurement system in our laboratory, as shown in Figs. 3 and 4. A power-variable continuous wave (CW) generator (Agilent Technologies E8247C) combined with a W-band frequency multiplier (Eravant SFA-753114616-10SF-E1-1-ET) was used as the source. The generated microwave was pulse-modulated at 10.0 Hz using a radio frequency (RF) switch (Analog Devices ADRF5045-EVALZ), driven by a square wave from a function generator. An isolator was attached to the output port of the multiplier for protection from unexpected microwave reflection. The source monitor was connected to the source via a 20 dB directional coupler (Coupler A in Fig. 3). The coupling factor satisfies

³The 1D beam pattern taken in the plane that contains the main lobe axis and the magnetic field vector. We chose the H -plane over the E -plane because the horn antenna's side lobe level is lower in the H -plane, which is suitable for demonstrating a high dynamic range measurement.

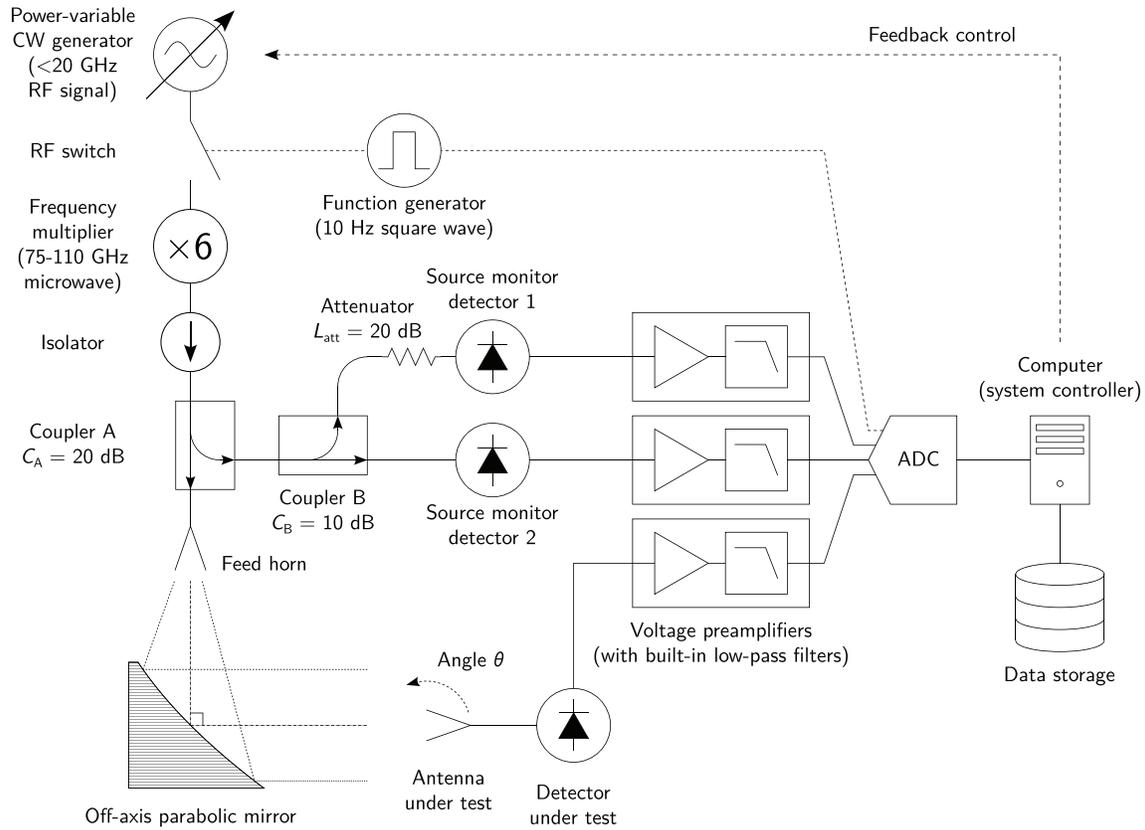


Fig. 3. Block diagram of the feedback-controlled beam pattern measurement system used for the proof-of-concept demonstration. The power-variable CW generator and frequency multiplier produce a W-band (75–110 GHz) microwave, which is pulse-modulated at 10 Hz by the RF switch. The 20 dB directional coupler (Coupler A) transmits the microwave to the feed horn attached to the through port, and two source monitor detectors (diode amplitude detectors) via the 10 dB directional coupler (Coupler B) attached to the coupling port. One of the source monitor detectors is given a 30 dB attenuation by Coupler B and the 20 dB attenuator. The feed horn feeds the compact range optics, which consists of the off-axis parabolic mirror, and illuminates the AUT connected to the DUT. All detector outputs are amplified, low-pass-filtered, digitized, and processed in the system-control computer, which also runs the feedback control.

Eq. (2b). The source monitor comprised two diode amplitude detectors (Eravant SFD-753114-103-10SF-P1, the same model as the DUT), which are common linear microwave detectors with output voltage proportional to the incident power. Their typical sensitivity and maximum measurable power in their linear range were 1000 mV/mW and -30 dBm, respectively.⁴ The noise level was ~ 200 nV \sqrt{s} when combined with the voltage preamplifier described later, allowing the detection of a power of approximately -70 dBm at a minimum over a signal integration time of 10 s. Because a single diode detector cannot monitor source power variation over a 60 dB dynamic range, two detectors were combined: one (Source monitor detector 1) included a 30 dB attenuation via another directional coupler (Coupler B) and an attenuator, whereas the other (Source monitor detector 2) was unattenuated. The feed horn (a W-band standard gain pyramidal horn antenna, Millitech SGH-10-RP000, the same model as the AUT) transmitted the

⁴Based on the specifications and calibration provided by the manufacturer. Although the typical input power is specified at -20 dBm, we conservatively assumed the maximum measurable power to be -30 dBm to ensure sufficient linearity.

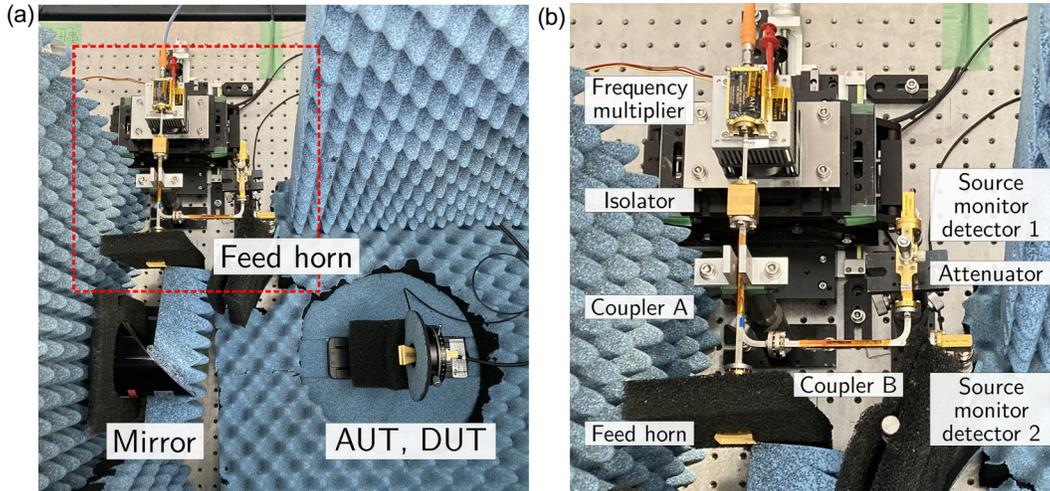


Fig. 4. Photographs of the feedback-controlled beam pattern measurement system. Left: Compact range. It was fully shielded by microwave absorbers during the measurement to suppress unexpected stray lights. Some absorbers have been temporarily removed for the photograph. The AUT and DUT are mounted on an automatic rotation stage to change the AUT angle. Right: Close-up of the source and source monitor (the part framed with red dashed lines in the left panel). The CW generator and RF switch are not shown in this photograph.

microwave across a compact range. The compact range consisted of an off-axis parabolic mirror (Edmund Optics #36602), with a diameter of 101.6 mm, offset angle at 90° , and an effective focal length of 152.4 mm. The AUT was coupled to the DUT and mounted within the compact range on an automatic rotation stage that changed the angle of the AUT azimuthally. The DUT's characteristics are identical to those of the source monitor detectors described above. The distance from the mirror to the AUT's aperture was about 390 mm. The optical efficiency of the compact range was $\eta \sim -10$ dB. We carefully aligned the entire optics using visible lasers. The H -plane of the rectangular aperture of the feed horn and the AUT were aligned horizontally. The aperture center of the AUT was also aligned with the rotation axis of the rotation stage so that the aperture was illuminated on the optical axis of the compact range at any angle. The alignment accuracy of the position and the horizontal angle of each optical component are estimated to be ~ 1 mm and $\sim 2^\circ$, respectively.

Signals measured by the two source monitor detectors and the DUT were amplified by voltage preamplifiers, filtered by built-in 100 Hz low-pass filters within the preamplifiers, and simultaneously read out by a multichannel analog-to-digital converter (ADC) at a sampling frequency of 1 kHz. The voltage gain of the preamplifiers was set to 2×10^3 . To obtain the voltage amplitude of the modulated signal measured by each detector, coherent demodulation was performed using custom software on the system-control computer, employing the reference signal from the function generator to the ADC. The demodulated signals from the two monitor detectors were merged by scaling with the “intermonitor coefficient,” defined as the ratio of their sensitivities to the source power. Signals from Source monitor detector 2 were used when its received power was within its linear response range (less than -30 dBm); otherwise, signals from Source monitor detector 1 were used. The intermonitor coefficient was determined by feeding a test microwave from the source to the two detectors and measuring the ratio of their output voltages. The determined intermonitor coefficient was $c_m = 8.484 \times 10^{-4} = -30.7$ dB at 81 GHz.

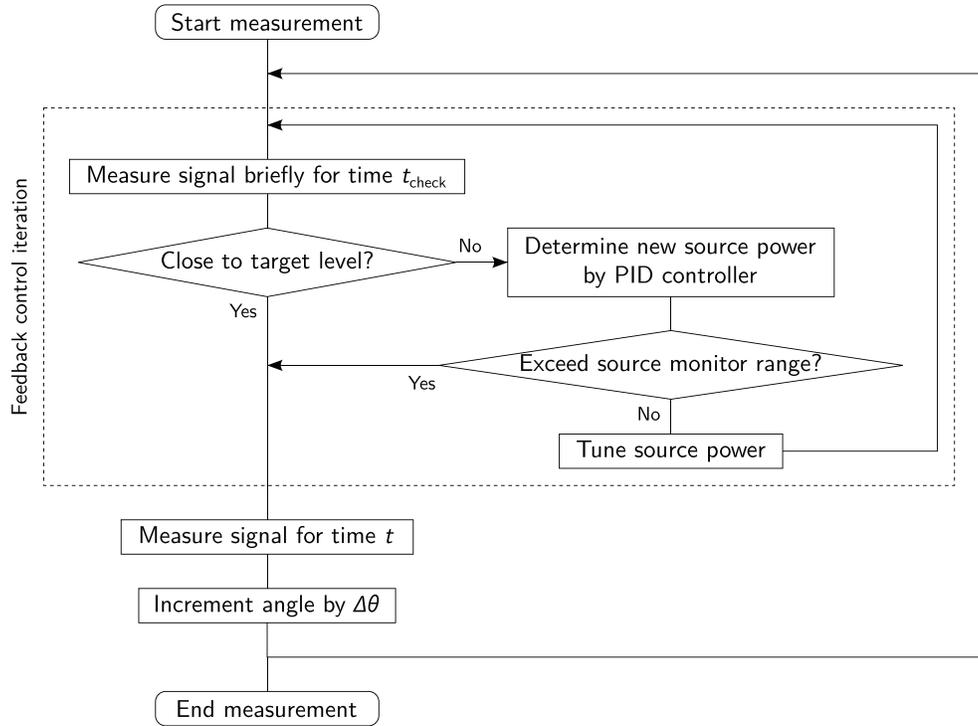


Fig. 5. Flowchart of the routine in the feedback-controlled beam pattern measurement. The routine was repeated until all the angular points were covered. The subroutine boxed in the dashed lines is the closed-loop feedback iteration adjusting the source power.

3.2. Procedure

The beam pattern was measured at discrete angular points over the angular range of -10° to 180° to the beam center. The angular interval (i.e. the angular resolution of the measured beam pattern) was $\Delta\theta = 1.0^\circ$. At each point, the feedback control tuned the source power according to the routine shown in Fig. 5. The DUT signal was briefly measured ($t_{\text{check}} = 1$ s) to assess its current amplitude. The source power was adjusted by a proportional-integral-derivative (PID) controller until the DUT signal amplitude reached within $\pm 10\%$ of the target signal level, which corresponds to the target level of the power received at the DUT. We set the target level at $P_{r,\text{target}} = -50$ dBm, intentionally set much lower than the DUT's maximum measurable power of -30 dBm to demonstrate a test with a low dynamic range DUT. The PID controller gains were manually tuned in advance. When the monitored power reaches the maximum measurable power of the source monitor (-30 dBm at Source monitor detector 1), the system terminates feedback control and maintains the source power at this limit. This tuning algorithm was performed using custom software on the system-control computer. After adjusting the source power, signals from the source monitor and the DUT were measured over a signal integration time of $t = 10$ s.

The beam pattern was estimated using Eq. (3).⁵ The main lobe in the angular range of $|\theta| \leq 10^\circ$ was fitted using a model described in Ref. [19] to determine the normalization factor and

⁵The calculation used measured detector voltages, whereas Eq. (3) is expressed in terms of the measured powers. The two formulations are equivalent.

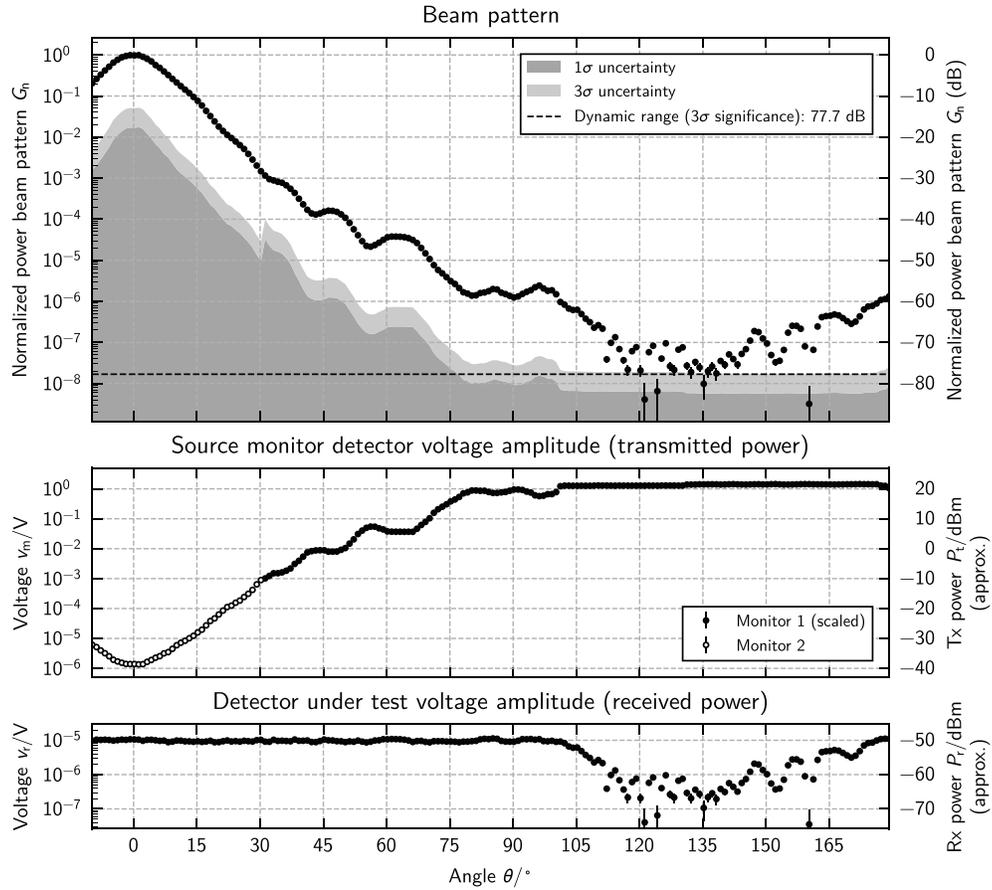


Fig. 6. *H*-plane beam pattern of the W-band standard gain pyramidal horn antenna at 81 GHz measured in the feedback-controlled measurement method (top), with the corresponding voltage amplitudes of the source monitor detectors (middle) and the DUT (bottom). The estimated transmitted (Tx) power from the feed horn and the received (Rx) power at the DUT are also shown on the right axis of the middle and bottom panels, respectively. The dark- and light-shaded areas in the top panel show the magnitude of the 1σ and 3σ uncertainty. The dashed line in the top panel shows the minimum detectable level at the 3σ significance, indicating the achieved total dynamic range of the measurement. The filled and unfilled points in the middle panel are from Source monitor detectors 1 and 2, respectively. The former is scaled using the intermonitor coefficient (the ratio of their sensitivities to the source power) and is stitched to the latter.

to correct the angle of the beam center.⁶⁷ The uncertainty at each point of the beam pattern was derived by propagating the uncertainties in the DUT voltage amplitude, source monitor voltage amplitude, normalization factor, and intermonitor coefficient.

3.3. Results and discussion

Figure 6 shows the *H*-plane beam pattern at 81 GHz measured using the feedback-controlled method. The corresponding source power, measured by the source monitor, and the power received at the DUT are also shown. During the measurement, the feedback control adjusted the source power over a range of 60.3 dB, as measured by the source monitor. As a result, the sys-

⁶⁷We fitted only the main lobe region, in which the measurement and the model agreed sufficiently. The model cannot precisely describe the actual side lobes, mainly due to diffraction effects.

⁷The angle correction of the beam center was performed for possible misalignment of the AUT with respect to the optical axis of the compact range.

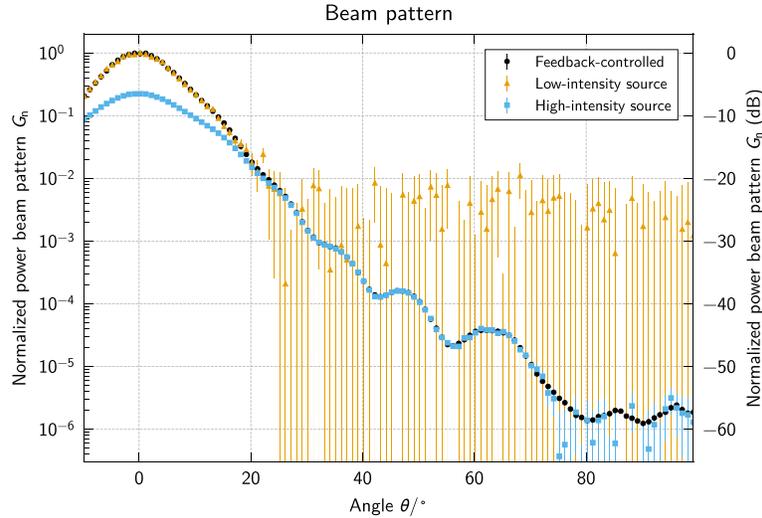


Fig. 7. Comparison of the H -plane beam patterns of the W-band standard gain pyramidal horn antenna at 81 GHz measured using the feedback-controlled source (black circle), the low-intensity static source (orange triangle), and the high-intensity static source (sky blue square). The last one is not normalized at the beam center but is scaled to the feedback-controlled measurement at $\theta = 45^\circ$ because it is compressed at the main lobe due to the saturation of the DUT.

tem successfully maintained the power received at the DUT near the target level of -50 dBm throughout the measurement. The measurement gained an additional dynamic range of 60.3 dB by using the feedback-controlled method, achieving a total dynamic range of 77.7 dB by including the DUT's dynamic range. We performed the same measurement at several W-band frequencies and achieved similar dynamic ranges. These high dynamic ranges enabled the detection of very faint side lobes.

To highlight the advantages of the proposed method, the same beam pattern was measured without feedback control, i.e. with the source power fixed at certain levels. Two cases were demonstrated: one using a static source with appropriate intensity that did not saturate the DUT and another with higher intensity that intentionally saturated the DUT. The received power at the DUT at the beam center was approximately -50 and 0 dBm in each case, respectively.⁸ These values correspond to transmitted powers from the feed horn of -40 and 10 dBm, respectively. In the high-intensity source measurement, the voltage gain of the DUT's preamplifier was reduced to avoid exceeding the maximum voltage range of both the preamplifier and the ADC; otherwise, the exceeding signals would be clipped at their voltage limit.

Figure 7 shows the beam patterns measured with the low-intensity and high-intensity sources, compared to the result obtained using the feedback-controlled method. The low-intensity source measurement achieved a dynamic range of only ~ 20 dB, which was insufficient to detect the side lobes. The high-intensity source saturated the DUT around the main lobe (in the angular range of $|\theta| < 30^\circ$) and caused a compression of up to 6.5 dB. Additionally, faint side lobes below -50 dB remained undetectable because the low voltage gain of the DUT's preamplifier caused the noise floor to be dominated by their internal noise. The feedback-controlled method effectively avoids both low signal-to-noise ratio and distortion from saturation or nonlinearity.

We verified the feedback-controlled beam pattern measurement by evaluating its consistency with two reference measurements using conventional methods. The first reference was a long-

⁸0 dBm stays safely below the 17 dBm handling power limit of the DUT.

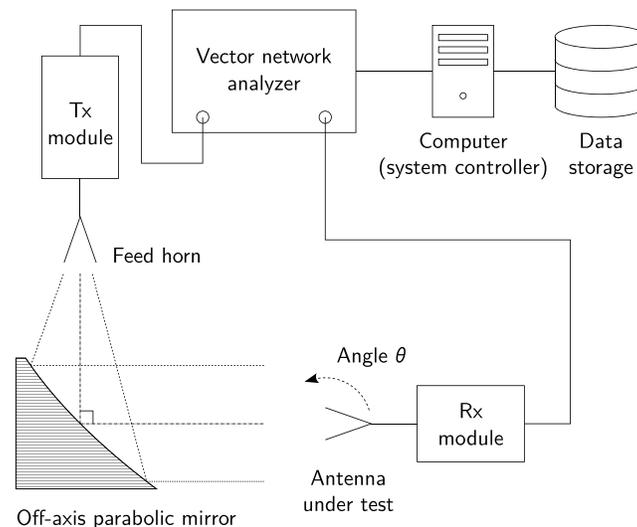


Fig. 8. Block diagram of the beam pattern measurement system using the VNA. The frequency extender transmitter (Tx) module feeds the compact range with a microwave via the feed horn. The receiver (Rx) module receives the microwave through the AUT. The feed horn, optics geometry, and AUT are the same as in the feedback-controlled system shown in Fig. 3. The VNA measures S_{21} (the scattering parameter from Tx to Rx) at every angular point.

time integration measurement, in which a low-intensity static source measurement with a longer signal integration time was repeated and averaged. A signal integration time of 100 s, which is 10 times longer than in the previous measurement, was allocated at each angular point, and the measurement was repeated accordingly. Due to time constraints, the measurements were sparsely done, at 5.0° angular intervals. A total of 1207 measurements were finally selected based on the noise level and system temperature fluctuation. This corresponds statistically to a $\sqrt{1207 \times 10} = 15.4$ dB extension of the dynamic range compared to the previous measurement. The second reference was a measurement using a vector network analyzer (VNA), a standard instrument in microwave engineering for characterizing microwave components.⁹ A separate test system was constructed, as shown in Fig. 8. This system included a VNA (Keysight Technologies N5225B) along with a pair of W-band frequency extender transmitter and receiver modules (Virginia Diodes Inc. WR-10 VNAX). The beam pattern was obtained by normalizing the angular pattern of S_{21} , the scattering parameter from the transmitter to the receiver, computed by the VNA. The same feed horn, optical configuration, and AUT were used as in the feedback-controlled test system.

Figure 9 shows the comparison of the feedback-controlled measurement with the two reference measurements. The fractional differences are also shown to evaluate their consistency. The fractional difference between two beam patterns is defined as their fraction G'_n/G_n , which corresponds to their difference on a logarithmic scale. The long-time integration measurement achieved a dynamic range of ~ 35 dB and agreed with the feedback-controlled measurement within 2σ uncertainty at most of the 5° -step angular points. However, the long-time integration measurement lacked sufficient angular resolution to resolve fine side lobe structures and a sufficient dynamic range to verify the faint side lobes. In contrast, the VNA measurement provided the same angular resolution as the feedback-controlled measurement and a sufficiently high dy-

⁹VNAs are utilized for component- or optics-only beam pattern measurements, but are unavailable for measurements in TES-bolometer-installed telescopes.

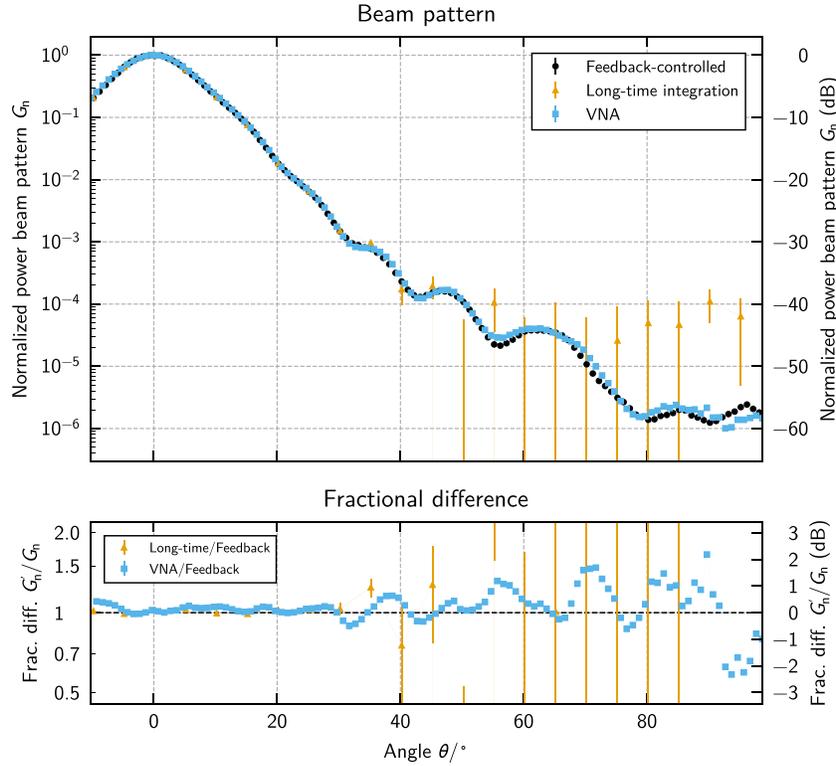


Fig. 9. Comparison (top) and the fractional difference (bottom) of the H -plane beam patterns of the W-band standard gain pyramidal horn antenna at 81 GHz obtained from the feedback-controlled measurement (black circle), the long-time integration measurement (orange triangle), and the VNA measurement (sky blue square). The long-time integration measurement shows the unweighted, averaged beam pattern over 1207 repeats of the measurement with the low-intensity static source, each of which was conducted with a 10 times longer signal integration time and at 5 times sparser angular intervals than the previous measurement shown in Fig. 7. Its error bars show the standard error of the mean.

dynamic range to see faint side lobes. It also showed good agreement with the feedback-controlled measurement at the ~ 2 dB level or better in terms of fractional difference. The systematic difference at that level, particularly noticeable in the side lobe region, is attributed to differences between the feedback-controlled measurement system and the VNA-based measurement system. As the two measurements were conducted using different systems, stray light, standing waves, and alignment are likely to differ, resulting in the slight disagreement.

4. Conclusion

In this study, we proposed a feedback-controlled beam pattern measurement method for CMB telescopes that extends the dynamic range of the measured beam pattern by using a power-variable calibration source. As a proof of concept, we demonstrated the method by measuring the beam pattern of a horn antenna in a laboratory environment and showed that the measurement successfully obtained an additional dynamic range of 60.3 dB attributed to the feedback control of the source power. We also verified that the feedback-controlled measurement yielded results consistent with those obtained using standard methods without feedback control.

The proposed method can be utilized to characterize the beam pattern of current- or next-generation CMB telescopes. In particular, the method is expected to be powerful in laboratory testing of future CMB telescopes since it can exclude the systematic effects caused by the TES

bolometer's nonlinearity, which is of concern as discussed in Section 1, from the beam pattern measurement. Since TES bolometers have significantly lower saturation power than the diode amplitude detector used in this study, the transmitted power level may require adjustment. This can be achieved by optimizing the source system, e.g. by inserting an attenuator at the feed horn. Differences in optical efficiency can also be canceled in a similar manner. It should be noted that, unlike conventional methods, the proposed method cannot simultaneously measure the beam patterns of multiple detectors within the same telescope, as the feedback control operates on only one detector at a time. In recent CMB telescopes, which have a large focal plane with >1000 detectors, we would perform feedback-controlled beam pattern measurements on some typical detectors, such as those at the center or edges of the focal plane, rather than on all the detectors. These selective measurements are still valuable for characterizing telescope side lobes. For instance, the measurements are useful to reveal the agreement of beam patterns between multiple pixels on the focal plane and to validate the telescope's physical optical model. In addition, the combination with measurements in conventional methods allows us to discuss potential systematic errors in the beam pattern characterization. For example, we can verify whether the beam patterns measured using conventional methods are distorted due to the nonlinearity of TES bolometers.

Beyond CMB telescope side lobe characterization, the method is applicable to a broad range of optical measurements since the methodology we presented in Section 2 does not rely on any specific antenna design, detector type, or testing frequency. As demonstrated in this study, it enables high dynamic range side lobe measurement of general antennas across a broad frequency range, which was previously difficult to perform without a VNA. The same principle can be applied to other measurements, including band-pass, transmittance, and reflectance measurements of linear optical devices. By enabling the detection of faint nonidealities, the proposed high dynamic range approach enhances the understanding of the instrument's optical characteristics and contributes to the suppression of systematic errors in CMB B-mode polarization searches.

Data availability

The data underlying this article will be available upon reasonable request to the corresponding author.

Acknowledgements

Calculations were performed on the KEK Central Computing System (KEKCC), owned and operated by the Computing Research Center at KEK. We thank Shogo Nakamura for giving useful suggestions on the experiments and data analysis. We thank Shuhei Kikuchi for providing the temperature monitoring device for the test setup. We thank Yuji Chinone for the useful discussion to improve the manuscript. We thank Enago (www.enago.jp) for English language editing.

Funding

This work was supported by Japan Society for the Promotion of Science (JSPS) KAKENHI grant numbers 19KK0079, 20H01921, 22H04945, 25H00403, JSPS core-to-core program number JPJSCCA20200003, and the World Premier International Research Center Initiative (WPI) of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

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