Combined Calibration Method and its Realization for Direction Finding Antenna Systems with Patch Antennas

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Abstract. *A novel radio channel compensation method aiming to give optimal calibration for microstrip antenna array systems is presented in this paper, realized for an actual DOA measurement antenna system using microstrip antennas to sample the electromagnetic field, operating at 4.5GHz. This new approach considers mismatch between antennas and channel RF ports, channel transmission inequalities, and also decreases the effects of multipath propagation components of calibration reference signals by placing the calibration reference signal feeding network on the microstrip antenna array bearer, directly beside the antenna patches. It is combined with orthogonal spread spectrum calibration signal utility for continuous uninterrupted measurements. The spread spectrum calibration signal is orthogonal to the continuous wave (CW) signal to be measured, therefore, the 2 signals can be separated in the receiver, enabling them to be present simultaneously. DOA measurement results are shown, measured with the realized integrated microstrip patch antenna array with calibration network hardware.*

Keywords

Microstrip patch antennas, smart antenna systems, processing channel calibration, spread spectrum, Direction of Arrival (DOA).

1. Introduction

Antenna arrays are widely used today as smart antennas, with features like adaptive beam forming, adaptive interference reduction and electromagnetic (EM) spatial spectrum estimation, that is, for locating EM sources in the space. To achieve the latter, samples are taken of the EM field on the antenna array aperture. The signals obtained at the output of the antenna elements are fed into RF and digital electronics that perform signal processing. An antenna element with the corresponding electronics forms a signal processing channel in the antenna system. The analogue electronic components of these channels have varying electronic properties due to parameter scattering of manufacturing; electronic parameters can also vary with time, temperature, humidity and several other factors. These parameters together determine the transmission of the channel. Within the linear domain of such a channel, the channel can be described by its transfer function. Transmission can be defined as a complex value (magnitude and phase) which is the actual value of the transfer function at a specific frequency. During digital signal processing, these transmission differences have to be compensated to achieve uniform channel transmissions for spatial spectrum estimation. To obtain these transmission values, reference input signals can be fed into the system at several points. The optimal solution is to feed each channel at its input; in this case at the antenna, to compensate the whole analogue channel as one. Optimally, this requires a plane wave, perpendicular to the surface of the antenna array as a reference signal, which is hardly achievable in practical systems since it requires large free space in front of the antenna array for placing the EM source of the reference signal. If the reference signal source cannot be present during the measurements, the source has to be placed for calibration during the calibration process and removed afterwards, which means a relatively long pause between measurements. Multipath propagation components of the reference signal must also be dealt with in this case, as seen in [1]. This method is not appropriate for automated measurements, especially if compensation is to be done frequently. To optimally automate system calibration, the reference signals have to be emitted near to the antenna elements. Feeding reference signals after the antennas directly into the receiver RF input disregards matching inequalities between the antenna elements and the input of the RF electronics, as seen in a solution in [2]. Also, this solution is inapplicable at higher frequencies due to realization problems of calibration signal feeding: coaxial cables have position varying transmission properties, semi rigid cables are hard to re-mount.

Another problem of compensation is time variance. Due to the time-variance of several parameters that determine the transmission of an RF channel, frequent channel calibration is necessary. This multiple calibration process causes interruptions during measurements. To avoid these interruptions, low level code modulated orthogonal spread spectrum compensation signal is proposed to be used, orthogonal to the signal to be measured, which is a CW signal in this case. Compensation process can run simultaneously with measurements by separating the calibration signal at the receiver output by de-spreading.

2. Details of Our C Band Direction Finding System

Our measurement system contains RF receiver blocks, a DSP unit and the measuring software, running on a laptop computer. The RF receiver units with overall 16 RF input channels operate at 4.5GHz center frequency, baseband I-Q signals are produced by quadrature demodulation of the IF signal. The demodulated signals are sampled and converted to 12-bit digital data, which are transferred to the DSP unit. The DSP unit does sampling timing and data pre-processing by the calculation of the correlation matrix. The computed correlation matrix is sent to data processing software via USB connection to the PC. The software performs direction estimation and controls the calibration procedure. It is also capable to simulate. The structure of the system can be seen in Fig. 1 below.

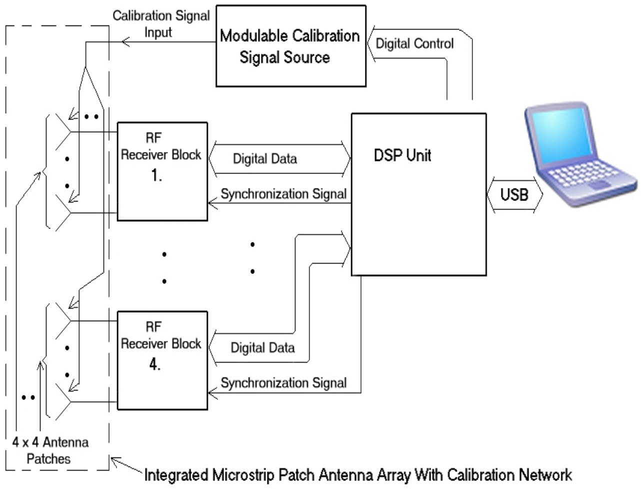

Fig. 1. System block diagram: 16 channel direction finding measurement system, including calibration network, digital quadrature receivers and data processing computer.

The estimated far-field power distribution is calculated by using the estimated correlation matrix $\hat{R}$ of the electromagnetic environment of the antenna array**,** the calculation depending on the estimation method. More detailed information about our system can be found in [3].

The elementary antennas are elliptically polarized microstrip patch antennas. General design considerations for high gain microstrip patches according to which the patches were designed and realized (also with the help of simulation software) can be found in [4]. The antennas can be placed at the minimal distance of 2/3 wavelengths in a rectangular grid. This distance yields about ±45° grating-lobe free angular measuring range in azimuth and elevation. The ambiguity caused by the grating-lobes is reduced significantly by the directional characteristics of the elementary antennas.

In the described system, calibration is needed to eliminate the effects of antenna mismatching, as well as manufacturing parameter scattering and temperature variation of the transfer functions of the receiver channels containing RF filters, amplifiers and mixers.

3. Solution and Design Considerations

Reference signals can be supplied with an integrated system: *feeding circuit for antenna elements with antenna patches on the same Printed Circuit Board (PCB).* The schematics of the realized system for a single patch with a reference signal feeding microstrip wave guide line can be seen in Fig. 2 below.

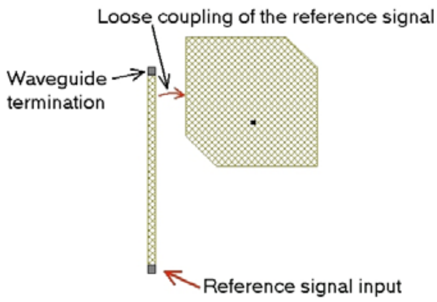

Fig. 2. Schematics of an elementary patch antenna and a microstrip line placed on the same layer, loosely coupled to the patch. The calibration signal is injected by the microstrip stub.

This planar feeding structure, unlike previous solutions seen in [1] [2], meets the requirements that are discussed in the introduction: compensation of mismatch between antennas and channel RF ports and channel transmission inequalities. Multipath propagation components of the reference signal are also negligible since the feed network is close to the antenna elements and is far from possible reflecting surfaces.

Requirements. Coupling between the feed line and the antenna patch should be enough to feed the antenna output with appropriate, stable signal levels. Magnitudes of coupled reference signals have to be in the same limited range in order to achieve the same compensation conditions (same sampling resolution of A-D conversion, same range of the transfer characteristics of the RF electronics) for each channel. Coupling between a feed line and another patch should be negligible. Coupling between the feed line and its patch should not influence the microstrip antenna radiation patterns significantly. Mutual coupling between antenna elements should either be low, or be compensated later. If continuous wave sinusoidal calibration signal is used, the measured source signal levels should be significantly below calibration signal levels in order to enable calibration with present sources to be measured. Spread spectrum signal can also be used for the calibration of the system; see more details in section 4. Matching: in order to achieve linear frequency dependence of reference signal phases, matching requirements have to be fulfilled: the reference input of the system as well as the feed lines have to be matched. Waveguide termination, seen in Fig. 2, serves to adjust appropriate coupling level between the feed line and its patch as well as to match the feed line for low reflection levels at the input of the reference signal.

4. Realization

Simulations to realize the hardware were made with Microwave Office simulation software. Feed lines were of 100Ω; to achieve matching within the feed circuit Wilkinson-hybrids were used. Due to loose coupling between the feed lines and their patches, isolation enhancing resistors were not required. The PCB type is RO4003, with 1.6 mm thickness.

With the help of a network analyzer, the reference signals that appear at the output of the antenna patches were measured at the operating frequency and are stored in the calibration software. The photo of the realized hardware can be seen below in Fig. 3.

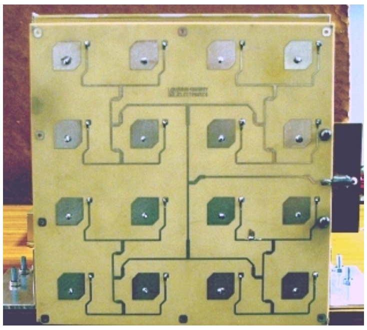

Fig. 3. The realized antenna array and the calibration network integrated onto one PCB.

According to our simulation and measurement results, coupling between the antenna patches did not exceed -20dB in any case, which is negligible in this application, therefore, compensation of mutual coupling was not necessary. Another way of planar feeding is to couple the reference signal to the antenna patch by a slot aperture underneath the patch on the ground plane, influencing the properties of the antenna array to a smaller extent and more uniformly. This solution is yet to be realized.

4.1 Algorithms in the System

The calibration-error-free estimated correlation matrix is calculated from the electric field distribution on the antenna array aperture. If the complex representation of the k-th electric field vector on the aperture of the antenna array is:

$$\mathbf{z}_k = [r_{1k}\exp(j\varphi_{1k}) \ \cdots \ r_{ik}\exp(j\varphi_{ik}) \ \cdots \ r_{nk}\exp(j\varphi_{nk})] \quad (1)$$

where r_{ik} and φ_{ik} are the actual amplitudes and phases of the incoming EM wave at the place of antenna element i, then the estimated correlation matrix, constructed of k pieces of sampled R_k correlation matrices, where

$$R_k = \left[r_{ik}\exp(j\varphi_{ik}) \quad r_{jk}\exp(-j\varphi_{jk})\right]_{ij}, \quad (2)$$

$$\hat{R} = \frac{1}{M}\sum_{k=1}^{M} z_k * z_k^{H} = \frac{1}{M}\sum_{k=1}^{M} R_k \quad (3)$$

where M is the number of samples taken in time domain.

The real correlation matrix of the EM environment of the antenna array is:

$$R = E\{\hat{R}\}. \quad (4)$$

The estimated correlation matrix impaired with calibration error $\hat{R}'$ is calculated from the measured electric field distribution influenced by the different transmission values of the RF channels.

If the complex representation of the k-th *measured* electric field vector is:

$$\mathbf{z}_k = [a_1 r_{1k}\exp j(\varphi_{01}+\varphi_{1k}) \ \cdots \ a_i r_{ik}\exp j(\varphi_{0i}+\varphi_{ik}) \ \cdots \ a_n r_{nk}\exp j(\varphi_{0n}+\varphi_{nk})] \quad (5)$$

where φ_{0i} is the static phase error of the channel i and a_i represents the amplification coefficient of the corresponding analogue RF channel of the antenna array hardware, then:

$$R'_k = \left[a_i r_{ik}\exp j(\varphi_{0i}+\varphi_{ik}) \quad a_j r_{jk}\exp - j(\varphi_{0j}+\varphi_{jk})\right]_{ij}$$

$$\hat{R}' = \frac{1}{M}\sum_{k=1}^{M} z'_k * z'^{H}_k = \frac{1}{M}\sum_{k=1}^{M} R'_k. \quad (7)$$

The transmission of an analogue RF channel is:

$$a_i \exp(j\varphi_{0i}). \quad (8)$$

If we provide known reference signals to the input of the RF channels while measuring their outputs, transmission values of the channels can be calculated by the division of the output and the input signals, assuming that sinusoidal signals are used.

If the complex representation of the k-th reference signal on channel i is

$$R_{ik}\exp(j\phi_{ik}). \quad (9)$$

Then, the output will be

$$a_i R_{ik}\exp j(\phi_{0i}+\phi_{ik}). \quad (10)$$

The channel transmission of channel i can be obtained by the following division:

$$a_i \exp j\varphi_{0i} = a_i R_{ik}\exp j(\varphi_{0i}+\phi_{ik}) / R_{ik}\exp j\phi_{ik}. \quad (11)$$

During measurements the measured output of a channel is divided by its obtained channel transmission. If the measu red output on channel i is

$$a_i\, r_{ik}\, \exp j\left(\varphi_{0i} + \varphi_{ik}\right) . \tag{12}$$

Then the signal to be measured will be obtained by the following division:

$$r_{ik} \exp j\varphi_{ik} = a_i\, r_{ik} \exp j\left(\varphi_{0i} + \varphi_{ik}\right) / \; a_i \exp j\varphi_{0i} \; . \tag{13}$$

Calibration process in case of sinusoidal (CW) reference signal:

1. Setting the calibration mode in DSP from the PC.
2. Turning on the reference signal source that distributes reference signals to each patch.
3. Measuring the reference signals and calculating complex transmissions on the PC.
4. Loading compensation data into the DSP unit for measurements.

Calibration signals are fed to the calibration signal input of the integrated microstrip patch antenna array via a calibration network (see *Fig. 1.*). These can either be continuous wave signals or, to achieve orthogonality, phase modulated signals. Continuous wave signals have at least 20dB higher level than the measured signals in order to achieve correct calibration with present sources whose directions are to be measured. Signals, arriving from the environment of the antenna array, may interfere with the sinusoidal calibration signal in case they correlate, hence, correlation reduction is advisable, which can be achieved by utilizing orthogonal calibration signals. One of the simplest spectrum spreading techniques that realizes this orthogonalization is BPSK modulation. This phase modulated signal is used as a low level signal in our system, providing calibration under measurement signal levels, which enables continuous calibration, without the interruption of measurements. The phase modulated calibration reference signal, whose phase is controlled by the DSP, is fed into the system at the calibration signal input, propagating through the PCB and the RF channels, sampled then by ADCs and it is then finally demodulated by the DSP unit. The length of the modulating code is determined by the levels of the measured signal sources. According to practical observations, the calibration signal has to be 20 dB weaker than the average measured signal source level, however after integration (de-spreading of its spectrum) the calibration signal level should be around 20 dB higher than the average measured signal source level. That is, a code length of minimal 10,000 bits is needed to achieve the required 40 dB processing gain. The used code, in order to achieve calibration in few seconds, is a maximum 8,191 elements long pseudo-random code. In case spread spectrum BPSK code is used, the calibration process can be continuous during measurements, which means that the BPSK calibration signal is always on.

Measurement:

The DSP automatically compensates the measured data with the channel transmission results, achieving uniform transmissions on all channels.

5. Simulation and Measurement Results

Simulations made with Microwave Office included the simulation of coupling between the feed line and its antenna patch, as well as the effect of the feed line on the antenna radiation pattern.

The achieved coupling between the input of the feed network and the output of the patches is between -26dB and -31dB at 4.5GHz for each channel (achieved with the proper selection of feed line terminations). Reflection at the input of the feed network is -12dB at 4.5GHz. Coupling between a feed line and its patch is 10dB higher than between the feed line and the closest neighbouring patch. Patch coupling simulation and measurement results are shown in Fig. 4 below.

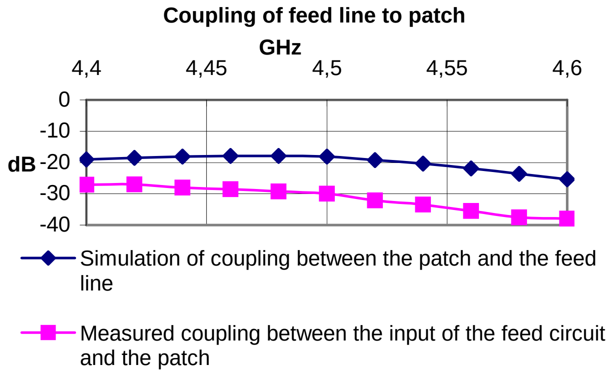

Fig. 4. Simulation of coupling between the patch and the feed line, and the measured coupling between the input of the feed circuit and the patch. NOTE: The measured coupling between the input of the feed circuit and the patch is about 12dB less than between the feed line and the patch, due to the 16 patch elements to be fed at the same time with reference signals.

The resonance of the realized antennas with the feed lines was at 4.45 GHz according to our measurements.

Simulated patch antenna radiation patterns are shown in Fig. 5 in planes that are in the domain where the feed line influences the patterns the most significantly, first without, then with feed line. Respectively to Fig. 2, the horizontal axis pointing to the right is Phi=0°, the positive angles (30°, 45°, 60° and 90° in this case) are measured downwards from the horizontal axis.

Only slight differences can be observed between patterns, due to loose coupling between the feed line and its patch. Radiation pattern differences in other planes were negligible according to the simulations. The advantage of the realized feed network construction is that feed lines influence the radiation patterns of their patch antennas nearly uniformly, resulting that elementary radiation pattern errors do not appear significantly in the results of Direction of Arrival (DOA) algorithms.

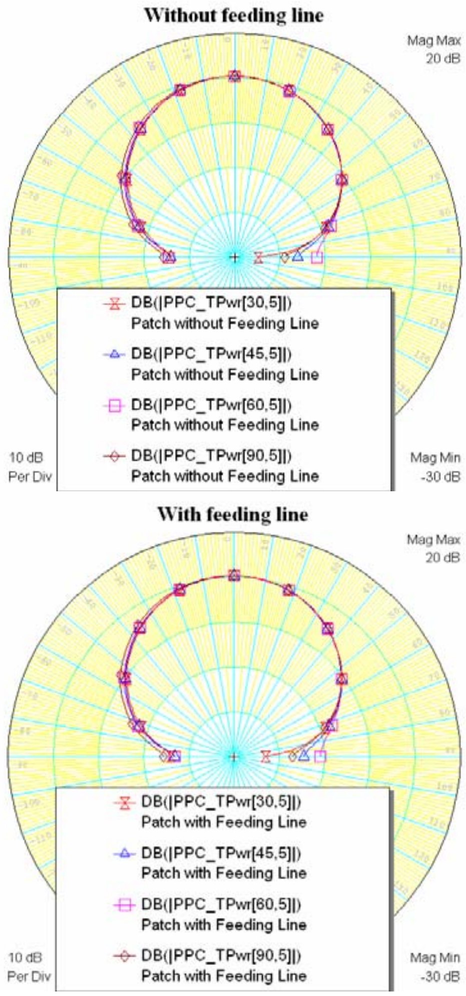

Fig. 5. Simulated patch radiation pattern without feed line and with feed line in planes 30°, 45°, 60° and 90°.

Changes in matching between a patch and its RF sampler electronics, caused by the feed line, were also measured and found negligible.

DOA measurements no. 1:

Measurements were performed on a low reflection open area. Continuous wave was used as calibration signal. If calibration and measurements are performed with different non-synchronized sources emitting at different frequencies, measurement errors will occur. In our system the relative frequency difference was less than 1ppm causing minor errors in our measurements. Other errors in the measurement: compass, used to read elevation and azimuth angles, reading (±0.5° both in elevation and azimuth) and positioning relative to the array center error (less than 1° perpendicular to the plane of the array in azimuth). According to the measurements the system has an approximate ±1° accuracy both in elevation and azimuth.

Measurement results can be seen in Fig. 6 for a source at 0° elevation (Theta), 20° azimuth (Phi), read with a compass; measurement distance: 30 m. Fig. 6 shows estimated 2D spatial EM spectra, where the brighter shades represent greater power values (the darkest grey is zero signal power and the whitest is the maximum, see Color Map, which applies to all DOA estimation figures). First, results are shown without calibration (Fig. 6a), then with calibration (Fig. 6b), both with Bartlett-method (conventional Fourier-method) and with MUSIC (MUltiple SIgnal Classification) algorithm. In case of MUSIC, in order to enhance measurement reliability (stability of the DOA algorithm, good measurement performance), spatial averaging correlation cancellation method was used to eliminate the negative effects of multipath propagation such as instability of the DOA algorithm and degraded DOA measurement performance, seen as subaperture averaging in [5]. The 4×4 antenna matrix was split up to 4 pieces of 3×3 overlapping matrices.

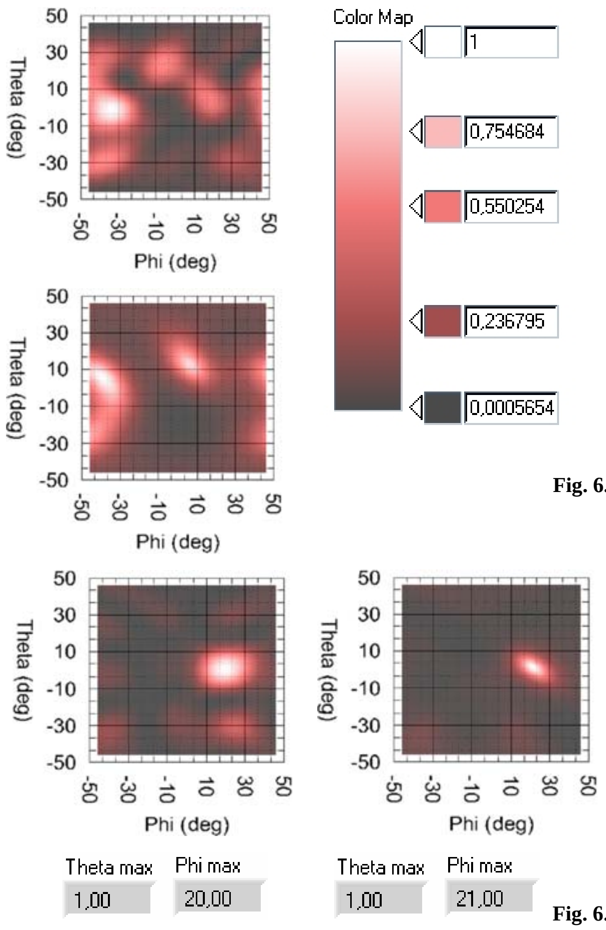

Fig. 6.a

Fig. 6.b

Fig. 6. CW-signal calibration measurement results: relative estimated power versus angle of arrival (Bartlett and MUSIC with spatial averaging with 4 pieces of 3x3 overlapping arrays): **Fig. 6a** Non-calibrated system, Bartlett and MUSIC respectively and Color Map. **Fig. 6b** Calibrated system, Bartlett and MUSIC respectively.

DOA measurements no. 2:

Measurements were performed in another open area, with greater reflection from the ground. BPSK modulated signal was used for calibration. Approximately the same error conditions were present as during the measurements of the continuous wave calibration signal measurements.

Measurement results can be seen in Fig. 7 for a source at –4° elevation (Theta), –20° azimuth (Phi), read with a compass; measurement distance: 15 m.

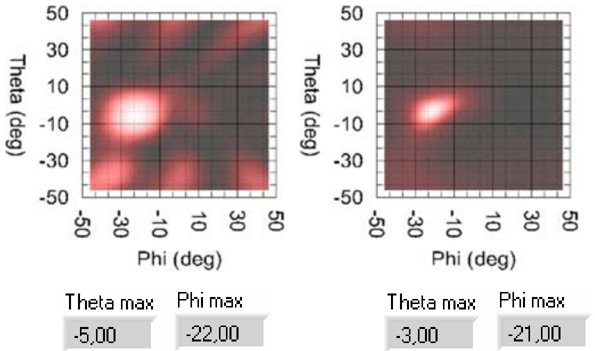

Fig. 7. BPSK spread spectrum signal calibration measurement results (Bartlett and MUSIC with spatial averaging with 4 pieces of 3×3 overlapping arrays).

Due to the good linearity of the RF channels that are to be compensated, signal level differences caused by different measurement distances do not represent a significant effect from the aspect of the comparability of the 2 measurements with different calibration methods.

6. Conclusion

An automatic signal processing channel compensation method was developed and realized for a C-band, 4×4 array, adaptive spatial spectrum estimator antenna system with microstrip patch antennas. The method compensates both mismatch between antennas and channel RF ports and channel transmission inequalities, also solving the problem of multipath propagation components of the calibration signal.

Two kinds of calibration algorithms are possible with the system: continuous wave high level (for short calibration interruptions between measurements) and spread spectrum (phase modulated) low level reference signal feeding algorithm (for continuous measurement with calibration, without the interruption of measurements). In case of continuous wave calibration, this method enables system calibration in shorter time than the duration of a measurement.

Approximately ±1° measurement accuracy was achieved both in elevation and azimuth in the ±45° measurement range.

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