MeerKAT Primary-beam Measurements in the L Band

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Abstract

Full-polarization primary-beam patterns of MeerKAT antennas have been measured in the L band (856–1711 MHz) by means of radio holography using celestial targets. This paper presents the observed frequency-dependent properties of these beams and guides users of this 64 antenna radio telescope that are concerned by its direction-dependent polarization effects. In this work, the effects on the primary beams due to modeling simplifications, bandwidth averaging, gravitational loading, and ambient temperature are quantified within the half-power region of the beam. A perspective is provided on the level of significance of typical use case effects. It is shown that antenna pointing is a leading cause of inaccuracy for telescope users in the presumed beam shape, introducing errors exceeding 1% in power near the half-power point of beams, owing to a telescope pointing accuracy of $\sigma \approx 0\'6$. Disregarding these pointing errors, variability in the Stokes I beam shape relative to the array average is most commonly around 0.3% in power; however, the impact above 1500 MHz is on average triple that of the lower half of the band. This happens because the proportion of higher-order waveguide modes that are activated and propagate is sensitive to small manufacturing differences in the orthomode transducer for each receiver. Primary-beam correction verification test results for an off-axis spectral-index measurement experiment are included.

Unified Astronomy Thesaurus concepts: Radio interferometers (1345); Observational astronomy (1145); Polarimetry (1278)

1. Introduction

The MeerKAT telescope is a radio interferometer containing 64 antennas separated by up to 8 km and is situated in the Northern Cape Province of South Africa (see, e.g., Mauch et al. 2020). Holographic measurements of its 13.5 m diameter antennas have been performed in the Ku band (11.5–12.5 GHz) on satellite beacon targets as early as 2015. While excellent for collimation checks and dish surface accuracy measurements, such targets are not suitable for measuring full-polarization beam shapes. Not only do satellite targets provide beacons at limited frequencies, these signals are highly polarized, which renders the measurement equation (Smirnov 2011) not invertible and in turn leaves derived full-polarization patterns ill-defined. The high channelization required to observe a narrowband beacon signal could also be wasteful. Furthermore, as there exist only three Ku-band receivers and it is labor intensive to reinstall the units onto subsequent antennas, it is impractical to monitor and comprehensively characterize the 64 antenna array in the Ku band.

Holography was also performed in the L band (856–1711 MHz) around the same time to measure beam shapes for qualification purposes. The measurement techniques have been refined during the rollout, and since 2019 the beam shapes for all antennas have been monitored routinely under different environmental conditions for historical record. Diffraction effects make accurate dish surface and collimation measurements more challenging in the L band than the Ku band, but the full-polarization beams can be measured rapidly up to a few side lobes at all frequencies using unpolarized celestial targets. Similar measurements are performed in the UHF and S bands, but these fall outside the scope of this paper.

Of immediate interest to the community is the nature of the MeerKAT primary beams in the L band, which is its most popular observing band. The telescope was designed with the goal that tolerances be tight enough so that it would not be necessary to model any antenna differently from the array average. Individualizing the beams would have a computational cost implication, which is intentionally avoided. Equivalently, a cheaper mechanical structure could have been built if it was not for this design principle.

Unfortunately, design-stage fundamental mode electromagnetic (EM) simulations did not predict frequency-dependent pointing behavior that severely impacts primary beams in the upper half of the band. A recent study (de Villiers et al. 2021) uncovered that higher-order waveguide modes are activated by the orthomode transducer (OMT) within the operating band and are responsible for the effects observed. This paper communicates the measured properties of the primary beams in figures for reference and quantifies changes in the beam shapes that may occur. As a guide to telescope users, power levels are quoted of effects that would need to be taken into account in order to achieve the required level of accuracy.

2. Definitions and Measurement Technicalities

Only limited descriptions are provided here of the holographic measurement techniques used as this topic is adequately discussed in the literature (e.g., Popping & Braun 2008; Harp et al. 2011; Perley 2016, 2021; Iheanetu et al. 2019, and Asad et al. 2021). Some details that are peculiar to this work and relevant to telescope science users are discussed below.
Figure 1. A typical spiral scan pattern observed in the L band showing sampled and discarded slew points.

2.1. Scan Pattern

In the simplest case of a geostationary target, a beam pattern could be sampled by scanning in azimuth for a number of different elevations. However, some observation time is squandered on slewing motions because the on-target direction needs to be reobserved regularly for calibration purposes. Even worse, for an observation strategy where multiple rapid pointings are made in a grid, additional settling time allowances are needed at each pointing before capturing usable data. Overheads become costlier when larger angular distances are traveled at low frequencies, for relatively small-diameter antennas, or at high elevations. It is more efficient to scan in a spiral pattern where much less data are discarded. A practical spiral pattern as in Figure 1 scraps about 8 times less data than a raster pattern (with same scan speed, extent, and on-target regularity), while achieving scan spacings that are twice as dense.

A spiral scan pattern is preferred because it reduces the required observation time, has a circular rather than rectangular footprint, and offers variable control over the degree of sampling uniformity across the beam. It is useful for wideband beam measurements to sample the central part of the beam more densely to accommodate the narrowing of the beamwidth at higher frequencies. With an extreme twist factor of zero, a radial scan pattern would oversample the center and undersample the outer regions of the beam.

Since MeerKAT antennas can deform under environmental conditions, it is useful to minimize the observation time in order to distinguish effects especially when scanning celestial targets that move across the sky. The benefit of doing many shorter observations instead of fewer longer duration ones (that could individually attain higher signal-to-noise ratios (S/N)) goes beyond isolating environmental effects on the beam shape: radio-frequency interference can almost be eliminated given enough time and orientation variability, allowing excellent beam shape recovery over the full band.

Unlike most observation scripts, the holography script has a short minimum observation time and has no onerous restriction on minimum number of antennas, which allows it to be scheduled easily and regularly as a filler at any time. Targets are by default chosen automatically to maximize diversity in elevation among observations, and to avoid the Sun, when applicable.

Individual observations cycles are 10° in extent, 30 minutes in duration and captured at 1 s dump intervals, with 1024 channels across the band. However, at elevations greater than 60° the cycle duration is increased due to further distances that need to be traveled by the azimuth drive. When necessary, the array is unwrapped at the start of holography observations to ensure that each antenna has the same relative range of motion in azimuth. The ordering of the scan pattern arms are chosen to reduce the elevation extent to less than what is possible for geostationary targets.

Usually, half the antennas in the array are scanned while the remainder tracks the target for reference. These groups are alternated in subsequent cycles; however, antennas under investigation can be selected to be scanned consecutively.

2.2. Direction Cosine Feed Plane Coordinates

In order to command the azimuth-elevation-driven antennas to follow a desired scanning pattern when sampling the beam, feed plane coordinates must be converted to requested azimuth elevation coordinates.

The forward equations for mapping a scanning antenna’s measured azimuth and elevation coordinates (\(\phi_{\text{scan}}, \theta_{\text{scan}}\)) to the beam plane are

\[
\begin{align*}
  l &= \cos(\theta_{\text{target}})\sin(\phi_{\text{target}} - \phi_{\text{scan}}), \\
  m &= -\cos(\theta_{\text{target}})\sin(\phi_{\text{scan}})\cos(\phi_{\text{target}} - \phi_{\text{scan}}) \\
  &+ \sin(\theta_{\text{target}})\cos(\theta_{\text{scan}}), \quad (1) \\
  n &= \sqrt{1 - l^2 - m^2}, \quad (2)
\end{align*}
\]

where \(l, m,\) and \(n\) are the direction cosines of the scanning antenna’s feed orientation with respect to the target at \((\phi_{\text{target}}, \theta_{\text{target}})\). These equations differ from the standard orthographic projection in that the role of the reference coordinate is exchanged with that of the object coordinate. This in turn results in disparate inverse equations,

\[
\begin{align*}
  \phi_{\text{scan}} &= \phi_{\text{target}} - \sin^{-1}(l/cos(\theta_{\text{target}})), \quad (4) \\
  \theta_{\text{scan}} &= \sin^{-1}\frac{n \sin(\theta_{\text{target}}) - m \cos(\theta_{\text{target}}) - l^2}{1 - l^2}, \quad (5)
\end{align*}
\]

which are used to determine the requested coordinates in an observation. Note that at high elevations, scanning must extend further in the azimuthal direction to capture the same beam extent in feed plane coordinates.

2.3. Feed Phase Center Offset

A geometric phase difference transpires in the correlation product between two antennas when the orientation of one antenna is rotated relative to that of the other, around a point that is not the antenna’s feed phase center. It is necessary to correct holography visibility data between scanning–tracking baselines for the effect of this phase center offset relative to the antenna mount phase center. The phase adjustment

\[
\Delta \phi = \frac{2\pi}{\lambda} (\Delta x l + \Delta y m + \Delta z n) \quad (6)
\]

is added to the measured visibility data phase where the offset is \(\Delta x = 0\) sideway, \(\Delta y = -1550\) mm downward, and \(\Delta z = -2476.2\) mm backward, according to design drawings.
The adjustment has the effect of centering the aperture around the origin.

2.4. Error-beam Power Metric

Throughout this paper, the error-beam power metric is used to compare corresponding beam shapes quantitatively against each other. This metric is chosen over the more familiar root mean square (rms) error because MeerKAT per-antenna primary beams are specified to have an error-beam power of less than 4% relative to the array average over the 900–1670 MHz range. The use of this metric makes it easier to see how various effects measure up against this qualification limit.

When comparing beams, the rms error metric is sensitive to the area size of the beam being evaluated because larger errors tend to exist where the beam has more power. If evaluation is dynamically restricted to the half-power region of the beam, then the rms error estimates an average error over this region while the error beam quotes the worst case. Because the beam shape errors vary relatively slowly over the half-power region, these metrics are about equally informative.

While other definitions exist, in this paper, the error-beam power is a function of frequency, is distinguished among polarization types $p$, and is expressed in units of percentage power. The error-beam power, $P_{EB}$, is defined as follows:

$$P_{EB,p}(f) = 100 \max_{l,m} |E_p(f, l, m)|^2 - |E_{p,h}^0(f, l, m)|^2,$$

(7)

for $|E(l, m)|^2 > 0.5$ only, where $E$ is a complex voltage beam response per feed and polarization type that is being compared to a reference $E_{p,h}^0$ of the same kind, each of which is normalized to unity maximum of the corresponding copolarization beam. Normally, $p$ refers to the horizontal (H) or vertical (V) feed response to a horizontal or vertical polarized wave front, $f$ is the frequency, and $l$ and $m$ are the direction cosine coordinates of the beam relative to the frequency-independent pointing direction of the antenna. For Stokes IQUV error beams ($P_{EB,I}, P_{EB,Q}, P_{EB,U}, P_{EB,V}$), the following definitions apply assuming an unpolarized source:

$$|E_I|^2 \triangleq \frac{1}{2}(|E_{HH}|^2 + |E_{HV}|^2 + |E_{VH}|^2 + |E_{VV}|^2),$$

(8)

$$|E_Q|^2 \triangleq \frac{1}{2}(|E_{HH}|^2 + |E_{HV}|^2 - |E_{VH}|^2 - |E_{VV}|^2),$$

(9)

$$|E_U|^2 \triangleq 2(E_{HH}E_{VH} + E_{HV}E_{VV}),$$

(10)

$$|E_V|^2 \triangleq 2(E_{HH}E_{VH} + E_{HV}E_{VV}).$$

(11)

It is important to emphasize that some studies remove any pointing errors before drawing comparisons among beams when evaluating an error-beam metric. Great consideration should be given to the appropriateness of whether the pointing error should be included or not when evaluating the error-beam metric for any given use case because, as seen in Section 3.2.2, this has a dominating impact on the results.

2.5. Cosine-tapered Beam Model

The cosine-tapered field pattern, derived in Section 3.2.5 of Condon & Ransom (2016), shares a remarkable resemblance to the MeerKAT beam shape, particularly at 1500 MHz and in the horizontal direction only, more so than other simple mathematical formulations, as pointed out by Mauch et al. (2020). It can be shown that a perfectly cosine-tapered aperture transforms to a voltage beam pattern of the form

$$E_{CT}(r) = \frac{\cos(\pi r)}{1 - 4r^2},$$

(12)

where $r_0 = 1.1889647809329453$ ensures that the half-power beamwidth (HPBW) occurs predictably at $E_{CT}(0.5) = \sqrt{0.5}$. The publicly available katbeam module constructs simplified MeerKAT beam patterns using this function in conjunction with offset ($l_0, m_0$) and beamwidth ($HPBW, m_{HPBW}$) measurements as follows:

$$r = \sqrt{\frac{(l - l_0)^2}{HPBW^2} + \frac{(m - m_0)^2}{m_{HPBW}^2}}.$$  

(13)

In this simple module, the Stokes I beam is composed of the copolarization models only, and the cross-polarization beams are approximated to zero.

2.6. Array Average Concepts

The array average beam shape may draw great interest; however it is often poorly communicated by telescope users which kind their reduction software requires. It may be best to define some options explicitly.

2.6.1. Half-array Average

The beam patterns of only about half of the array are scanned during a typical individual holography observation, because the other half is used for reference. A half-array average would differ systematically by some margin from that of the subsequent observation cycle where the alternate set of antennas are scanned. Environmental factors such as changed gravitational loading may further render alternate observation cycles incomparable at some level of accuracy.

2.6.2. Composed-array Average

A full-array average can be composed using results from more than one comparable holography observation cycles, by first removing any pointing errors prior to averaging applicable beams together. Technically, an array average could be tailored for a particular science observation from only the antennas actually used, at a given elevation and ambient temperature. Most commonly, an average is composed from an equal weighting per antenna over the full array at an elevation of 60° and ambient temperature of 15 °C. Such an average may resemble a high-quality idealized result that eliminates antenna-specific assembly imperfections and is referred to as the array average throughout this paper when not explicitly qualified differently.

2.6.3. Widened-beam Array Average

Image-plane primary-beam corrections are performed after the image has been generated. The applicable primary-beam pattern that should be used to normalize the flux across the image would be an average effect of the particular antennas used to produce the image, where the beams are offset, rotated, and smeared by the corresponding parallactic angle rotation over the sky. Furthermore, for continuum imaging, the applied
beam would be an average over the band. The antenna pointing errors, which for MeerKAT are substantial (see Section 3.2), should be included in such a computation because it has the effect of broadening the array average beam wider than that of individual antennas, and also offsets the array average beam. The error beam deteriorates more than expected because the pointing error of the array average beam is also large. Depending on the application, it may be preferable to widen a composed-array average beam by convolving it with a pointing uncertainty distribution. Although the factor by which the beam widens is small relative to the beamwidth in the L band, it could impact the accuracy of sensitive spectral-index calculations.

3. Results

This section presents measured properties of the MeerKAT primary beams in the L band and quantifies its variability. As a summary preceding the conclusion, a more technical perspective on the power levels at which common effects start playing a role is also provided. Some larger figures and tables referenced in this section are appended at the end of the article to improve the flow of reading. Data sets and selected data products related to this work will be made available electronically\(^4\), and primary-beam-model updates will be distributed through the public facing katbeam module.

3.1. Measurement Accuracy

The accuracy of beam shape measurements depends on the S/N of the visibility data, which directly relates to the flux of the target observed. In addition, the scan pattern used, observation duration, missing data, presence of other targets in side lobes, and radio-frequency interference (RFI) also affects the quality of the beam measurement. These circumstantial factors contribute to nonzero Fourier transform components that lie outside the footprint of the aperture. Relying on Parseval’s theorem, the effective S/N of a measurement, representative of its overall quality, is estimated from these components in the aperture plane. Figure 2 illustrates how the error-beam power relates to the quality of the measurement, per observation. The figure is produced by quoting half the error-beam power between two successive and comparable beam measurements, indexed by the average aperture-plane-based S/N estimate for that measurement pair. All measurement pairs are comparable in the sense that beams of the same antenna, with the same receiver installed, are being compared, and the observations differ by less than 3° in elevation and less than 5 °C in ambient temperature, within a variable yet relatively short period of time. Each channel in the 900–1670 MHz range is evaluated separately, where those affected by RFI, for example, would yield a poor S/N. The spread of results is only illustrated for the per-antenna case to avoid clutter.

Since roughly half (typically 25–32 antennas) of the array is used as scanning antennas per observation cycle, a half-array instead of a full-array average is also computed for each measurement. If these half arrays are compared indiscriminately, i.e., different groups of antennas exist in each half array, then the resultant error beam is worse than if the results are consolidated, i.e., half-array pairs are composed of the same antennas. The improvement in the error beam resulting from averaging over multiple \((N)\) consolidated scanning antennas seems to follow a \(\frac{1}{\sqrt{N}}\) rule.

Table 1 summarizes the error-beam power that can be expected in measured beam patterns from individual observations. On average, a typical holography observation using a target such as PKS 1934-63 yields a per-antenna beam measurement that is accurate to about 0.29% in power. Furthermore, the table reads that the error could be as much as 0.55% within the 84th percentile of variability among antennas and channels. The flux densities of targets are quoted from Tingay et al. (2003).

Table 1. Error-beam Power Dependence on Measurement S/N for Individual Holography Measurements

| S/N (Ratio) | Target (Name) | Flux Density (Jy 1.4 GHz) | Stokes I Error-beam Power (%) | Horizontal Copolarization Error-beam Power (%) | Vertical Copolarization Error-beam Power (%) |
|------------|---------------|---------------------------|-------------------------------|-----------------------------------------------|---------------------------------------------|
|            |               |                           | Median 16–84th Percentile     | Median 16–84th Percentile                    | Median 16–84th Percentile                   |
| 30 J1924-2914 | 12            | 0.55                      | 0.31–1.63                    | 0.62                                          | 0.35–1.74                                  |
| 60 PKS 1934-63 | 15            | 0.29                      | 0.17–0.55                    | 0.34                                          | 0.20–0.63                                  |
| 100 3C 273   | 36            | 0.17                      | 0.11–0.29                    | 0.19                                          | 0.12–0.33                                  |

\(^4\) doi:10.48479/s9nh-3e43.
Pointing errors occur when a beam is assumed to be steered precisely toward a certain direction, but in reality it is not. Despite routine pointing calibrations, the MeerKAT telescope operates on a σ = 0.64 uncertainty in its pointing accuracy. As seen in Figure 3, individual antenna pointing errors are seldom worse than 4°, but errors up to a degree have been detected. Reference pointing, where a small update is made based on a nearby target immediately before a target field is observed, is hardly ever used during science observations due to onerous scheduling. While it has shown some improvement in repeatability tests, it is still unclear how well it improves absolute alignment among different antennas. System level work on tilt meter sensors is currently being done with the goal to improve the pointing accuracy, although simplifying assumptions in system-pointing calibration algorithms and outstanding fine-tuning also play a role.

While some authors (Cotton & Mauch 2021) recognize the importance of accurate pointing, it is nevertheless common to assume that the pointing errors are negligible. Science users have limited means to detect pointing errors from their observations, and if left unaccounted, seemingly small pointing errors could result in intolerable beam shape errors near the half-power point of the beam in wide-field imaging projects. Such misalignment may render the need for high-accuracy beams useless.

The effect of pointing errors on the error beam can readily be computed using Equation (7) for arbitrary beam shapes by

| Description                                      | Median | 16–84th Percentile | 2–98th Percentile |
|--------------------------------------------------|--------|--------------------|-------------------|
| Measurement accuracy                              |        |                    |                   |
| Antenna, individual, S/N 60                       | 0.29   | 0.17–0.57          | 0.11–2.59         |
| Half array, indiscriminate, S/N 60                | 0.14   | 0.08–0.26          | 0.05–1.26         |
| Half array, consolidated, S/N 60                  | 0.05   | 0.02–0.10          | 0.01–0.32         |
| Antenna, composite                                | 0.05   | 0.03–0.09          | 0.02–0.14         |
| Array average, composite                          | 0.02   | 0.01–0.04          | 0.01–0.05         |
| Modeling simplifications                         |        |                    |                   |
| EM simulations, fundamental mode, five channels only | 0.88   | 0.55–2.89          | 0.41–4.39         |
| EM simulations, high order, five channels only     | 0.75   | 0.53–1.57          | 0.43–2.60         |
| Cosine taper, array average squint, >1500 MHz     | 0.87   | 0.55–1.39          | 0.36–2.32         |
| Cosine taper, array average squint                | 0.44   | 0.30–0.86          | 0.23–1.67         |
| Cosine taper, array average squint, <1284 MHz     | 0.37   | 0.28–0.50          | 0.23–0.94         |
| Cosine taper, per-antenna squint                  | 0.25   | 0.21–0.37          | 0.18–0.84         |
| Array average, >1500 MHz                          | 0.78   | 0.48–1.35          | 0.28–2.20         |
| Array average                                     | 0.34   | 0.19–0.77          | 0.11–1.62         |
| Array average, <1284 MHz                         | 0.25   | 0.16–0.40          | 0.09–0.97         |
| Array average shape, per-antenna squint           | 0.17   | 0.10–0.33          | 0.06–1.14         |
| Use cases                                         |        |                    |                   |
| Feed indexer slippage, 3°2 †                      | 1.83   | 1.3–2.18           | 1.17–3.31         |
| Antenna pointing accuracy, σ = 0.64 †             | 1.16   | 0.59–3.03          | 0.26–4.55         |
| Array pointing accuracy, σ = 0.25 †               | 0.39   | 0.19–0.70          | 0.07–1.06         |
| Bandwidth averaging, 10 MHz                       | 0.08   | 0.03–0.17          | 0.01–0.29         |
| Gravitational load, 70°–80° elevation †           | 0.11   | 0.07–0.17          | 0.05–0.23         |
| Gravitational load, 20°–70° elevation †           | 0.05   | 0.02–0.09          | 0.00–0.14         |
| Nocturnal thermal contraction, Δ10°C †            | 0.03   | 0.02–0.03          | 0.02–0.04         |
| Feed indexer consistency, σ = 0.62 milidegrees     | 0.01   | 0.00–0.02          | 0.00–0.04         |

Note. Statistics are evaluated over Stokes I beams for all antennas, except for items marked with † where only the array average is considered. Antenna pointing errors are removed in all cases except for the two items that quote errors due to the pointing accuracy. Performance outside the 900–1670 MHz system specification range deteriorates and is excluded.

accuracy to which the beams are known, is quoted in Table 2 amongst other quantities discussed later in Section 3.12.

3.2. The Effect of Pointing Errors on Error Beam

Figure 3. A historic record of antenna pointing errors measured by means of holography shows occasional large errors for few antennas. Pointing errors of array average beams are shown using dots. Antenna pointing errors are determined by the weighted fit of phase gradients across the aperture plane. See also Figure 12 for more details.
offsetting the beam, e.g., $E_p(f, l, m) = E_p(f, l + \Delta l, m)$. If the applied offset is expressed in terms of the half-power beamwidth, then the frequency dependence is almost eliminated, and the effect on the error beam can be graphed compactly, as in Figure 4. Barely distinguishable from the performance of a cosine-tapered beam shape, on average, the Stokes I error-beam dependence is $1.47 \pm 0.02$ times the horizontal pointing error, when expressed as a percentage of the half-power beamwidth. Likewise, the average Stokes I error-beam dependence is $1.49 \pm 0.02$ times the vertical pointing error percentage. Because the measured beam changes in shape over the frequency, and not only in scale, the narrow margin of variation is also illustrated.

Beam shapes with broader peaks relative to the beamwidth, and hence steeper falloff at the half-power point, have a worse error-beam dependency on the pointing error. Results for a Gaussian-shaped beam is included for reference. The strong dependency of the error beam on the pointing errors (for any beam shape) plays a dominant role in the usage of high-accuracy beam shapes and is therefore of significant importance. This is shown later in Table 2.

3.3. The Half-power Beamwidth

Figure 11 shows the measured HPBW of the copolarization beams for the MeerKAT antennas expressed in degrees as a function of frequency. Results for the Stokes I beam are essentially midway between that of the horizontal and vertical copolarizations. Throughout this paper, certain angular distance quantities are conveniently expressed as a percentage of the Stokes I measured HPBW in order to normalize the scale across frequency. There is very little variation among different antennas in their half-power beamwidths: these are within $\sigma = 0.1\%$ of the HPBW.

Note that HPBW equals the more familiar FWHM when referring to a power quantity, which is the case here. Reference is also made to the half width at half maximum (HWHM = $\frac{1}{2}$ FWHM) in some figures to express the radial offset more intuitively.

3.4. Frequency-dependent Pointing

In addition to antenna pointing errors, MeerKAT beams exhibit frequency-dependent pointing errors, which also differ per polarization (referred to affectionately as squint). This means that if an antenna is optimally lined up to receive maximum power and least cross-polarization impurity from a target at one frequency, for one polarization, it will not be optimally lined up at other frequencies nor for the other polarization.

These squint profiles as a function of frequency relate to the OMT of the receiver, rather than the antenna onto which the receiver is installed. These squint measurements are repeatable and are insensitive to collimation effects but deteriorate in the presence of RFI, degraded calibration due to poor S/N, or data-loss effects. Observing the squint is an excellent way to diagnose manufacturing issues internal to the OMT.

Figure 12 summarizes measured frequency-dependent pointing profiles for all of the 70 possible receivers that might be installed (there are six spares). Significant pointing errors exceeding $2\%$ of the half-power beamwidth at 1500 MHz is noted in the array average for the copolarization beams relative to the nominal pointing direction. These would result in more than $3\%$ error-beam power near the half-power point if the beam is naively assumed to be centered around the pointing center instead of being offset as a function of frequency, as indicated in the figure. The situation is worse at the uppermost end of the band. Although the trend follows the array average, deviations can be substantial for outlier receivers like 1.4046, which is responsible for the case that draws attention in the vertical copolarization results.

As for traditional pointing errors, the effect of frequency-dependent pointing errors on the error-beam power can be overwhelming. Therefore, it is important that any reduction software that relies on the beam shape be mindful of this characteristic, perhaps more so than the shape itself. In fact, MeerKAT’s poor system-pointing performance is in part due to the fact that pointing calibration algorithms currently are agnostic to the frequency-dependent pointing behavior.

3.5. The Measured Copolarization Beams

Measured MeerKAT beam shapes have been analyzed by fitting elliptical contours through main lobes at various power levels. Doing so, reveals center offsets, semimajor and minor axes as well as orientation angles. Of immediate interest are the results at the half-power point, which can be used to normalize a measured beam geometrically into a radial function, approximately.

As illustrated in Figure 5, the radial profile of the geometrically normalized measured MeerKAT beam shape at 1500 MHz resembles the cosine taper. Even somewhat beyond the half-power point, for all frequencies, this simple mathematical form seems to approximate measurements well at this scale. However, over the range of frequencies in the band and at different tangential locations in the beam, the cosine taper may misrepresent the first side lobe by about 0.5\% of the on-axis power, which equals the side-lobe power level of this cosine taper itself.

Tangential cuts through the Stokes I main lobe are shown in Figure 6, along the loci of best-fit ellipse contours to the 10%,
Figure 5. This figure shows the radial profiles of measured Stokes I primary beams in the L band that have been geometrically normalized by translation, rotation, and radial scaling using the parameters of the best-fit ellipse through the half-power point of the main lobe. The average value over the tangential angle for selected frequencies are indicated using black lines. Despite variations in the side-lobe levels of the profiles at different frequencies, the main lobe remains remarkably stable after the geometric normalization procedure and can be well modeled using the cosine taper function. Note that at 1500 MHz, the first side lobe almost matches the cosine taper function, and at 1670 MHz, the second side lobe cannot be distinguished from the first side lobe. The darker gray envelope indicates the extent of variation over the 900–1670 MHz bandwidth and full-polarization angle of the array average Stokes I beam. The lighter gray envelope shows a small widening due to antenna disparities. Results in this figure are for 60° elevation and 15°C ambient temperature.

Figure 6. This figure shows variations in the power of the Stokes I beams around elliptical loci that are best fit to the half-power point contour. Three panels are shown corresponding to the 10%, 50%, and 80% power levels. The envelope thicknesses are due to variations over the 900–1670 MHz bandwidth and not due to measurement inaccuracy. A straight flat line at 0.5 cannot be achieved because the half-power point beam contours are not perfectly elliptical. A narrow envelope (0.5% peak to peak) is found for the array average case using an elliptical contour, and only a modest widening occurs (0.9% peak to peak) when considering individual antenna peculiarities. A significant deterioration (3.7% peak to peak) is observed if a circular contour is assumed for the Stokes I beam, and an even greater deterioration (6.8% peak to peak) occurs if frequency-dependent centering is not done.

50%, and 80% power levels. Cuts along best-fit circular loci, including circular loci around the pointing direction (origin) instead of the center offsets individually best fit per frequency channel, are also shown. The significant fluctuations above and below the 50% power level along the circular loci shows that a naive assumption that the beam is circular is false and would result in a ±2% error in power estimation, which would be increased to ±3% if it is also assumed that the beam centering does not change with the frequency. Fluctuations along the 50% power elliptical contours are much smaller, indicating that the shape is quite elliptical. The 360° tangential period fluctuation along the 80% power elliptical contours is due to a slight vertical shift of the beam centering, relative to that of the 50% power elliptical contour. The same phenomenon is seen as fluctuations in the opposite direction, at the 10% level. Further departures at the 10% level suggests that the contours appear slightly more triangular.

Although not explicitly depicted in another figure due to its subtle nature, the main lobe has a skewness in the vertical direction such that the beam centering of the peak power differs by about 2% of the half-power beamwidth from the centering at the 10% power level and by about 0.5% at the half-power level. This is due to the offset Gregorian design of the reflector optics and is consistent with simulations.

Due to a horizontal broadening of the main reflector design, the Stokes I primary beam is elongated vertically with approximately 4% ellipticity, as shown in Figure 13. At the half-power level, the horizontal polarization is elongated horizontally around 1550–1670 MHz only, indicated using negative ellipticity values in this figure. Some further elongation in the horizontal direction occurs at low-power levels of the horizontal copolarization main lobe. Little variation in ellipticity is observed among different antennas.

The rotational orientation of the Stokes I beams for the antennas are within $\sigma = 1.8°$ from the axes, except for a few outliers. There is a strong correlation between the feed indexer alignment and copolarization power beam orientation, which differs from the actual dipole orientation discussed in the next subsection. The indexer encoder mountings for antennas M023, M024, M033, and M054 have slipped significantly over time. In the worst case, the indexer slippage of 3°2 over $2\frac{1}{3}$ yr resulted in a 19° rotation of the Stokes I beam on M054. This rotational effect on the beam tapering also stems from the offset Gregorian reflector optics design.

Telescope users should be aware of a far out side lobe approximately 72° overhead from the boresight direction at the 0.01% power level. This side lobe can pick up interference when it unexpectedly aligns toward a satellite, or the Sun during daytime. At high elevations, this lobe is known to pick up terrestrial interference.

3.6. The Measured Cross-polarization Beams

The measured MeerKAT cross-polarization beam patterns agree fairly well with design stage simulations in the lower half of the band only. In the upper half of the band, systematic features appear that break the symmetry, which is presupposed by the reflector optics design. Even with perfect reflector collimation and despite meticulous symmetry of the feed horn and dipoles within the feed, asymmetry exists in beam patterns above 1284 MHz. This effect is consequent to the activation of higher-order waveguide modes within the OMT that extends behind the dipoles in the receiver unit. The OMT contains small, unavoidable asymmetries that can only be compensated for electromagnetically at limited frequencies, and this causes activation of the TE21 asymmetric mode, increasingly noticeable above its theoretical cutoff frequency of 1387 MHz for the given waveguide diameter. However, MeerKAT’s wideband specification up to 1670 MHz extends well beyond the cutoff
frequency of both the TE21 and TM11 modes resulting in these two modes significantly affecting the beam patterns in half of the operating range of the antennas.

While the antenna-to-antenna variations in the cross-polarization beam shapes could be explained by collimation effects in the lower half of the band, this is not true in the upper half of the band. Because the OMT mode effects are much greater than the collimation effects at higher frequencies, antenna-to-antenna variations in these beam patterns are associated with the receiver installed, rather than the antenna onto which it is installed. The higher-order waveguide modes are very sensitive to the manufacturing accuracy, which means that receivers are identifiable by the cross-polarization beam pattern they produce irrespective of on which antenna they are installed. While both have an impact, the effect of collimation is dwarfed by that of the OMT in the upper half of the band. This can be seen qualitatively in Figure 7 and is expressed more quantitatively later in the next subsection. It does not make sense to use per-antenna beam patterns, unless they are dated, because receivers are exchanged from time to time.

Independently of the copolarization power beam rotational orientation, which is determined largely by collimation effects and is therefore antenna specific, the cross-polarization pattern is rotated by the dipole orientation and is receiver specific. The dipole assembly orientation error in the OMT can be estimated by fitting a hyperbolic function to the cross-polarization pattern in the vicinity of the zero crossings, over the frequency range that is unaffected by higher-order waveguide modes. The angle of the hyperbole asymptotes follows the rotation error. For MeerKAT, the dipoles are on average aligned to the axes within $\sigma = 0.7^\circ$, except for receiver 1.4002, installed on antenna M006 since 2019 August, which is in error by about $3^\circ$. Receiver-specific features follow when a serviced receiver is installed onto another antenna. Both the dipole orientation and the copolarization beam orientation will jointly affect high-precision wide-field polarimetry; however, the errors are zero mean and small, so will not impact common primary-beam correction strategies that apply corrections after the image is formed.

3.7. Power Levels of the Error Beam, Side Lobes, and Cross Polarization

Figure 14 shows the power levels of the error beam in comparison to the side lobe and cross-polarization levels, as a function of the frequency, for the horizontal and vertical feeds in separate columns. Here the error beam is calculated for all
antennas, relative to the array average at 60° elevation and 15 °C.

The horizontal copolarization error beam for various antennas differ most commonly from the array average by 0.9% in power in the 1500–1670 MHz range. Within the 16–84th percentile group (equivalent to one standard deviation), antennas differ by up to 1.5%, and in the worst case up to 5% in this frequency range. In contrast, at the lower half of the band, antennas differ from the array average most commonly by only 0.3% and 0.5% within the 16–84th percentile group, and at worst 1.4%. The copolarization beam can therefore be approximated 3 times more reliably by the array average in the lower half, than in the upper half of the band.

Except for the first side lobe of the vertical copolarization in the upper half of the band, there is little variability among different antennas in their peak side-lobe levels, compared to its frequency dependence. The first side-lobe level reaches about 1% at the middle of the band and tapers off to about 0.4% toward both ends of the band. For the horizontal polarization the second side-lobe level is fairly consistently about 0.2%, whereas for the vertical polarization this ranges between 0.1 and 0.3%.

The cross-polarization power levels have a great dependence on the frequency as well as the elevation, the latter being especially apparent at the lowest end of the band. Per-antenna deviations from the array average are small in the lower half of the band and much larger in the upper half of the band. The array average makes a better approximation for each beam in the lower half of the band than the upper half. For the lower half of the band, it would be more sensible to make provisions for the gravitational loading effect on the cross-polarization pattern, rather than per-antenna differences.

Illustrated in the first row of Figure 15, gravitational loading has a small effect on the copolarization power compared to antenna-to-antenna variations. Most commonly, gravitational loading introduces an error of 0.05% over the 20°–70° elevation range relative to the shape at 60°. At higher elevations, an asymmetrical weight distribution appears to introduce an error of 0.05% over the 20°–70° elevation range. At higher frequencies (indicated for 900 MHz) are much larger than antenna-to-antenna variations, for the cross-polarization patterns. At high frequencies (indicated for 1670 MHz), the gravitational loading effect is hardly noticeable against antenna-to-antenna variations.

The first two rows in Table 3 show the maximum power levels of the Stokes Q, U, V response to an unpolarized source within the half-power region of the Stokes I beam for all the antennas over the frequency ranges indicated. The polarization response above 1500 MHz is more than 2 times larger than in the lower half of the band. Error-beam results in rows three and four show differences among antennas against the array average. While it is feasible to model the direction-dependent polarization response using the average array in the lower half of the band to the 0.12%–0.18% level, on average, this can only be done to almost a factor of 3 times worse above 1500 MHz without taking into account receiver-to-receiver differences. Gravitational loading effects seem to be operating around similar power levels for these Stokes parameters as mentioned for Stokes I.

Figure 8 shows how the instrumental polarization deteriorates radially away from the beam center, particularly at higher frequencies, and toward the first null (which occurs radially at about 250% of the HWHM). Within the half-power region of the beam, the instrumental polarization is less than 2.5% in the lower half of the band but approaches 10% in the upper half. Only in the lower half of the band is this performance comparable to that reported for the Very Large Array by Cotton (1994). At much higher operating frequencies and narrower fractional bandwidths, Hull et al. (2020) measured up to 0.5% instrumental polarization for the high-precision Atacama Large Millimeter/submillimeter Array telescope near the half-power level.

![Diagram](attachment:diagram.png)
The distribution of the error and cross-polarization power along radial extent is shown in Figure 16. For various frequencies and antennas, the peak error beam is reached just before the half-power point, while the peak cross-polarization power is reached just beyond the half-power point. These effects are symptomatic of frequency-dependent squint variations among individual antenna beams relative to the array average.

3.8. Bandwidth Averaging

Interpolation of primary-beam shapes across frequency is a task commonly performed by image-correction algorithms and is linked to a science project’s frequency resolution requirements and computer resource footprint. There are many ways in which a beam could be interpolated across frequency, and the effect on accuracy for each method may differ significantly. Although it is recommended and would be more accurate to interpolate the shape independently of its frequency-dependent pointing offsets, doing so is unusual.

To provide some guidance to the normal use case, i.e., without processing the pointing behavior separately, the effect of bandwidth averaging on the error beam is shown in Figure 9. Here primary beams of all antennas at all frequencies in the band are compared to their average over a given bandwidth, using the error-beam metric. For 10 MHz of bandwidth averaging, in most cases there is a maximum of only 0.08% power introduced into the Stokes I beam. However, in the worst case for some antennas at some frequencies, the maximum error could slightly exceed 0.4%.

3.9. Cross Polarization Phase Residuals

Over a timescale of 2–6 months, it is very likely that an event happened where the digitizers of all antennas were power cycled. On shorter timescales of days to a month, digitizers might be reset during maintenance for some individual antennas. Whenever a digitizer starts up, a random delay of between −4 and 4 samples may occur in the alignment of one polarization signal relative to the other polarization of the same antenna (and other antennas). This is an expected behavior based on how the phase lock on the maser timing signal is implemented in hardware and is generally inconsequential because user level calibration methods should eliminate these. However, polarization calibration that constrains the absolute position angle of a source is expected to yield multiples of 90° jumps in the leakage phase solutions per affected antenna from one data set to another as a result of this effect, possibly causing some confusion.

In addition, there is a receiver-specific frequency-dependent residual in the phase alignment between polarizations. Its effect on polarization calibration is still under study.

3.10. Geometric Delay Correction

Prior to 2019 August and given sufficient S/N, visibility data captured by MeerKAT exhibit a distinctive sawtooth pattern in phase with a period of 5 s. This happens because geometric delay corrections (needed for ephemeris tracking) are interpolated and applied in hardware over this time period and have a quantized delay rate resolution. Initially, the phase of the visibilities could drift by up to about 6° within 5 s, depending on the baseline. Despite the fact that the biasing effect of the phase per baseline is small and is hard to identify in long-dump-rate observations, the quantization resolution has since been increased by 16 bits. A future release of the telescope’s data access layer katdal5 intends to alleviate this issue retrospectively.

On a related note, it may be worth cautioning that the standard system delay calibration performed when the array is prepared for an observation occasionally fails to determine delay offsets accurately for some antennas. It also happens (more rarely) that operators neglect to address this condition or do not mark such antennas as faulty. While the holography reductions check for and eliminate affected data, this could be a cause of degraded performance in other use cases.

3.11. Spectral Index Example

One of the cases where having an accurate beam shape is most critical is that of estimating spectral indices from primary-beam-corrected subband images. Since this involves data across the entire bandwidth, variations in antenna gain must be accurately and consistently applied. An example case comparing the cosine taper and a widened array averaged beam is shown in Figure 10.

This figure shows the same source, J0038−7422 (Vollmer et al. 2010), observed in extended (∼8 hr) L-band observations at three different offsets from the nominal pointing. The offsets cover the range from inside the half power of the beam to well outside it. Subband flux densities of J0038-7422 are primary-beam corrected and have a power-law spectrum fitted (weighted by the inverse variance of the subband rms). The left panel shows the result of using the simple cosine beam, and the right panel uses an array average beam including pointing offsets. For the 0°.12 offset (black stars), the two beam shapes give nearly identical results. At an offset of 0°.65 (dark gray stars), the results are still quite similar; however, the spectrum corrected using the array average beam is closer to the 0°.12 offset spectra than the one corrected using the cosine beam. At an offset of 0°.88 (light gray stars), the cosine-beam-corrected spectrum is very wrong, rising sharply at higher frequencies, even though the fitted spectrum does not clearly indicate this. The spectrum corrected using the array average beam is a bit steeper than the 0°.12 spectra and with considerably more 5 https://github.com/ska-sa/katdal
scatter but is much closer to the correct one than the cosine-corrected spectrum. The S/N of these data are all high enough that deviations from a power law are due to inaccuracies in the assumed beam shapes. The array average beam shape is clearly preferred away from the center of the beam. A simple power-law fit to a grossly distorted spectrum may give misleading results. The cosine beam used does not include the effects of pointing errors, which cause the array beam to broaden at higher frequencies where the pointing errors are a larger fraction of the beam size. The underestimate of the beam size inherent in this cosine beam causes the overcorrections at high frequencies far from the nominal pointing.

3.12. A Perspective on Use Cases Affecting the Error Beam

Table 2 summarizes the various effects on the Stokes I beam accuracy to express their relative magnitude and hence importance. Although most of these items have already been discussed earlier in this section, details about the statistics provided are expanded, and the results are collated for a more meaningful comparison. Reference is made to values quoted from Table 2 throughout this subsection to abet interpretation when read in a side-by-side fashion. The intent is to assist telescope users in estimating which effects need to be taken into account for a given level of beam accuracy that is appropriate to their project. Implications of the required primary-beam accuracy may be far reaching on computing resources.

Measurement accuracy statistics introduced in Section 3.1 are summarized in the first set of rows. In results of a typical single holography observation, corresponding to 30 minutes of observation time, most commonly there exists a maximum measurement error of about 0.29% in power in the beam shape that is largely due to the S/N of the measurement. If beam patterns for a single observation are averaged together into a half-array average, the measurement error of this
The estimate of the array average is about 0.14%. When combining results from multiple observations, the net per-antenna beam shape estimate is believed to be accurate to 0.05% while the net array average is accurate to 0.02%. These values give a sense to what degree of accuracy the beams are known currently.

**Figure 12.** Frequency- and polarization-dependent pointing errors are observed in measured primary-beam patterns. The range of variation among different receiver units are significant in the upper half of the band. These profiles are independent of the antenna onto which the receiver is installed. Antenna pointing is aligned at 1420 MHz for the L band, in the horizontal direction using the vertical copolarization beam and in the vertical direction using the horizontal copolarization beam.

**Figure 13.** The ellipticity of MeerKAT beams at 60° elevation, 15°C are shown at three power contour levels, with envelopes that indicate little variability over all antennas.
Results quoted in the remaining rows of Table 2 are derived from comparisons against measured primary-beam patterns for all antennas, or the array average (when thus indicated by †), at an elevation of 60° and ambient temperature of 15 °C, over the 900–1670 MHz frequency range. Antenna pointing errors are removed except in the two cases that deal with the antenna pointing accuracy, while frequency-dependent squint errors are retained.

Although higher-order mode EM primary-beam simulations from de Villiers et al. (2021) are more exemplary than fundamental-mode simulations, they too cannot compete with measurement-based modeling alternatives. This is because error-beam results are sensitive to the actualized frequency-dependent squint, which cannot be predicted by simulations conclusively because of simulation approximations and manufacturing tolerances. The error-beam valuations of EM simulations against all antennas in Table 2 are done only over five channels (at 900, 1100, 1350, 1500, and 1670 MHz), but these make up a representative sample. Note that the performance of these simulations are comparable to that of measurement-based modeling methods above 1500 MHz, discussed next.

Figure 14. The levels of power in antenna-to-antenna variation in the copolarization beams are compared against side-lobe levels and cross-polarization power as a function of the frequency.
Figure 15. Both the error-beam and cross-polarization levels as functions of the elevation show deterioration above 70°. At the lowest frequencies, cross-polarization patterns are more distinguished by the elevation than to which antenna they belong.

Figure 16. The error-beam and cross-polarization powers are illustrated as functions of the radial distance from the beam center, collapsed tangentially, for all antennas and the restricted 900–1670 MHz frequency range. The styled lines indicate the median cases at specified frequencies. Note that the Stokes I beam incurs half power at the normalized radius value of 100%.
Basic modeling of the beams can be done using a simple mathematical formula, as in Section 2.5. If a cosine taper function, with frequency-dependent pointing and beamwidth derived from the array average, is used to approximate all beam patterns, then errors of 0.87% can be expected above 1500 MHz, while only 0.37% in the lower half of the band, or 0.44% on average. If instead frequency-dependent pointing is tailored separately for each antenna from per-receiver squint measurements, then the error across the band reduces to only 0.25%.

Error-beam results improve by between 10 and 50% if the array average pattern, instead of the cosine taper function, is used to approximate beam patterns for all antennas. By using the array average shape, but additionally tailoring the frequency-dependent pointing separately for each antenna, then the error across the band reduces to 0.17% on average.

Beyond this level of modeling accuracy, there is a small margin of benefit using individualized antenna beam shapes before elevation-dependent effects demand consideration at 0.05% power on average (Section 3.5). In terms of cross-polarization, there is more variability due to elevation than per-antenna differences in the lower half of the band. In the upper half of the band, beam patterns are associated more representatively by which receiver is installed on the antenna regardless of the antenna. Using beams at this level of accuracy necessitates more complex bookkeeping, and it may be computationally demanding to apply in imaging software.

By far the most striking outlier effect encountered is due to feeder indexer slippage that happened to four antennas to a significant degree discussed toward the end of Section 3.5. Slippage causes devastating pointing errors that reoccur despite being compensated by routine system-pointing calibration. Apart from resulting pointing errors, the loss in collimation also affects the beam shape with coma distortion, which in the tabulated case reads a 1.83% error due to the gradual change in shape alone for M054 over 2$^\circ$ to 4$^\circ$ relative to its position at assembly, sparked a thorough investigation and subsequent mechanical fix by early July. In some applications, it may be more sensible to reject data from antennas that differ by much from the array average, instead of individualizing beam patterns.

As indicated in Section 3.2, for typical observations the system is unable to point antennas with an accuracy closer than $\sigma = 0.64$ to an intended target. This has the consequence that telescope users cannot align beam patterns accurately, resulting in 1.16% errors in the applied beam patterns if no additional provisions are made. This hurdle may be the stumbling block for most telescope users, making it pointless in this case to use high-accuracy beams.

Those users that perform post-imaging primary-beam corrections should be aware that there remains a larger than expected $\sigma = 0.25$ inaccuracy to the array average pointing. The assumption that the array average primary beam has no pointing error would typically introduce an error of up to 0.39% in the assumed beam power near the half-power point. Refer to Figures 3 and 4.

The compounding of lesser effects such as bandwidth averaging from Section 3.8, gravitational loading, and nighttime ambient temperature could easily induce deviations in the beam shape above the 0.1% power level. Because the receiver-to-receiver deviations from the array average in the lower half of the band is also at that level for Stokes Q, U, V beams according to Table 3, polarimetry studies will not benefit from per-antenna patterns in the lower half of the band, unless these lesser affects are also included. However, above 1500 MHz, it is necessary to regard receiver dependence in order to achieve an accuracy below the 0.3% power level for Stokes Q, U, V beam models.

It is advisable that investigators first achieve satisfactory results in the lower half of the band, where possible, before attempting the upper half, which is more challenging due to effects of the activation of higher-order waveguide modes.

4. Conclusion

A great level of detail and accuracy is provided on the measured characteristics of the MeerKAT primary-beam shape. These are presented as figures for reference. Perhaps the polarization- and frequency-dependent pointing behavior is the most interesting feature, which is due to the activation of higher-order waveguide modes in the OMT. Receiver-to-receiver variations in the beam shape are significantly boosted in the upper half of the band by this unexpected effect. However, this is currently not the biggest factor that limits the accuracy for most users.

The most important consideration in utilizing MeerKAT primary beams effectively is the manner in which pointing errors are dealt with. If the model beam is not aligned accurately to where the antenna is truly pointing, then it introduces an error in the presumed beam shape that could quickly overwhelm any other effect on the beam that may occur during normal telescope operations. Given the pointing calibration accuracy that MeerKAT is currently capable of, the assumption that the beams are mechanically aligned toward the intended pointing center of a target field, is roughly a two times poorer assumption (in terms of maximum error power introduced into the beam) than using a well-oriented cosine taper to approximate the beam shape. It is crucial that MeerKAT’s system pointing be improved or augmented in order to make effective use of beam patterns that exceed an accuracy of 1% in power.

There are two distinct categories of use for the primary beams in imaging. In the case that is by far more common, a widened array average beam pattern is required to correct attenuation in final images so that more accurate flux densities and spectral indices can be derived across the field of view. Alternatively, in the case of improving image quality instead, specialist imaging deconvolution algorithms that iterate between the modeled sky and visibilities using accurate beam models, can estimate pointing errors at an enormous processing expense. The accuracy to which the beam pointing can be estimated depends on source locations in the field, uncertainties of source fluxes, and the beam model; still that solution may be entangled with other calibration parameters.

Pipeline imaging and common telescope usage rely more heavily on the system-pointing accuracy because the computational overhead of the alternative is largely prohibitive. It is up to the telescope science user to assess the available resources and intricacies of their software to determine what effects are feasible to be taken into account and to estimate what level of accuracy can be achieved. In some cases, the pointing error will remain the limiting factor rather than the accuracy of the beam model used.
At a level secondary to ordinary antenna pointing, the frequency-dependent nature of the pointing errors or simplifying assumptions regarding its variability may limit the accuracy to which telescope users can utilize accurate beam patterns. In the lower half of the band, antenna-to-antenna variations in the beam pattern shape are about 3 times smaller than above 1500 MHz. For the copolarization beams, this is largely accounted for by frequency-dependent pointing differences linked to the receivers installed, rather than shape differences due to collimation. In most cases, it is possible to represent antenna beam patterns to less than 0.2% maximum error in power by recentering the array average beam shape using frequency-dependent pointing details peculiar to specific receivers installed. Without tailoring frequency-dependent pointing errors per antenna, an array average beam shape would mostly be 0.3% in error but around 0.8% above 1500 MHz.

At a third level of accuracy, beam shapes are affected by gravitational loading due to the antenna elevation. Cross-polarization beam shapes are more affected by gravitational loading than antenna-to-antenna differences in the lower half of the band where only the fundamental waveguide mode propagates. Computational provisions need to be expanded to use different beam shapes based on the antenna and elevation, and depending on the requirements also the temperature, for the highest-accuracy beam corrections. At this level of accuracy, dated beam patterns are needed because receivers are exchanged, and feed indexer encoder slippage and collimation adjustments occur over a period of time. Alternatively, in some applications, data from antennas that are not well represented by the array average could be eliminated.

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