Current state of practice in wide-field, low-frequency, high dynamic range imaging with contemporary radio interferometers

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ABSTRACT

This memo surveys the current state of practice in wide-field, high dynamic range imaging with current radio interferometers at frequencies under consideration for the mid-frequency Square Kilometer Array (SKA-mid). The primary aim is to confirm and identify instrumental calibration and processing issues affecting such observations at present, so as to inform the technical requirements for the dynamic range imaging regime anticipated for the SKA. Cross-cutting callibration and processing issues are identified from current practice and experience, and discussed in the context of SKA design and development.

1. Introduction

Deep, wide-field imaging at low frequencies is integral to the key science goals of the mid-frequency Square Kilometer Array (SKA). The array will have unprecedented sensitivity with a nominal $\frac{A}{T} \sim 10^4$ m^2 K^{-1} in current specifications (Schilizzi *et al.* 2007), and accordingly a very high target thermal dynamic range limit. Several key science projects will require deep imaging at frequencies $\nu < 2$ GHz; these imaging observations will need to achieve the theoretical thermal sensitivity of the array in representative deep field integrations without being limited by systematic errors due to inadequately accurate array calibration or sub-optimal imaging techniques. For the SKA, this problem is being addressed through multiple approaches, including: i) pathfinder demonstration of calibration and imaging techniques on prototype arrays similar to the target SKA design; ii) numerical simulation studies of the theoretical calibration and imaging performance of target array designs; and iii) statistical imaging techniques (Kemball *et al.* 2010). In this memo, we augment these approaches by surveying the current state of actual practice in deep, wide-field observations with contemporary operating radio-interferometer arrays using current calibration and imaging algorithms. Our goal here is to examine current experience in observations of this type with existing operating arrays, with a particular focus on assessing the actual limits encountered in reaching target thermal sensitivity or dynamic range in practice. The limits of numerical simulation of array performance are well-known; such work can only be as useful as the level of accuracy in the instrumental models adopted for array performance. We adopt a community and literature survey of current actual problems encountered in high-sensitivity and high dynamic-range observations as an independent exploration of these issues to augment and validate the main approaches to this problem for SKA-mid outlined above.

2. Dynamic range and sensitivity requirements for the SKA

Lazio *et al.* (2009) have published a Design Reference Mission (DRM) document for SKA-lo and SKA-mid that traces key SKA science case requirements through to their implied array technical specifications. We summarize quoted dynamic range requirements from the DRM in Table 1 below, organized by science use case, and in order of increasing dynamic range requirement.

Table 1: **Dynamic range and sensitivity requirements for SKA**

Science case	Sensitivity μJy	Dynamic range dB
Tracking Galaxy Evolution over Cosmic Time via H I Absorption		40
Resolving AGN and Star Formation in Galaxies	6	42
Wide Field Polarimetry	0.1	50
Neutral Gas in Galaxies: Deep H I Field	0.4	54
Tracking Cosmic Star Formation: Cosmic Magnetism Deep Field	0.050	63
Continuum Deep Field		74

3. Observational experience in low frequency wide-field observations

In this section, we summarize our current understanding of the state of practice in deep, wide-field low-frequency ($\nu < 1.5$ GHz) observations at contemporary radio interferometers in regular science operations. We sub-divide the results below by specific telescope for convenience of presentation alone; there is no implied prioritization or level of importance in the order of presentation. For reference, in this frequency range at current interferometers, and for representative bright sources, an off-source RMS noise of 1-10 μJy per beam translates approximately into a dynamic range of 10^{6-7} for the brightest pixels.

Historically, major advances in achieved dynamic range have advanced broadly in inverse proportion to the thermal sensitivity of arrays and their back-ends, receivers, and correlators available at any given epoch. However, the rate of advance is frequently episodic due to the irregular construction schedule of new telescopes and/or major upgrades of their receivers, back-ends, or correlators. These instrumental advances in sensitivity frequently prompt focused algorithm development during associated commissioning phases or early science operations. We focus in this memo on the current state of practice in wide-field, low-frequency imaging with contemporary arrays, as determined from a literature survey as well as discussions with senior scientists at several current arrays concerning the status of high dynamic range imaging at each telescope.

3.1. WSRT

This section describes wide-field, high dynamic range observational experience at the Westerbork Synthesis Radio Telescope (WSRT). The WSRT[1] is an E-W array of fourteen 25-m diameter, equatorially-mounted telescopes, operating in several frequency bands between 115 MHz and 8 GHz. The array started operations in 1970.

A notable early result in WSRT high dynamic range imaging was reported in the immediate post-self calibration era by Noordam *et al.* (1982), describing 21 cm observations of 3C84 at a dynamic range of 10,000:1; this dynamic range was achieved by imposing redundant baseline constraints during antenna-based gain and phase calibration (which reduces the number of independent degrees of freedom) and by correcting non-closing, interferometer-based errors. Prior WSRT observations had been limited to a dynamic range of 100-1,000:1 (Noordam *et al.* 1982).

Contemporary results in WSRT high dynamic range imaging are summarized by de Bruyn (2006). This paper lists contributing causes of dynamic range limitations as understood at WSRT, and more broadly in interferometry, as comprising: i) pointing errors; ii) ionospheric non-isoplanatism; iii) ionospheric or tropospheric decorrelation; iv) baseline-based, non-closing errors; v) non-linear effects (such as RFI); vi) Gibbs phenomena, band-edge effects, or sideband image rejection problems; vii) time-variability of polarization leakage terms; vii) limitations in deconvolution algorithms, especially for extended sources; viii) source variability, and ix) software inadequacies.

WSRT results, organized by source, are presented in the following sub-sections. For the high dynamic range observational results considered in this memo, the $uv-$coverage is generally as complete as possible for the array - as observed by full synthesis observations in multiple configurations - and this condition is generally implicit in what follows, unless stated otherwise.

3.1.1. 3C343/3C343.1

The sources 3C343 and 3C343.1 serve as good test for peeling at WSRT as they have similar flux densities (∼5 Jy at 21 cm wavelength) and are separated by approximately a beam-width at 21 cm wavelength. de Bruyn (2006) report observations of 3C343/343.1 at 1175 MHz of 12-h duration,

[1]http://www.astron.nl

correlated over 64 channels in a bandwidth of 10 MHz, with a predicted thermal noise limit of 30 μJy. The resulting target dynamic range for this source of 100,000:1 can only be achieved however using direction-dependent calibration, in this instance, peeling (implemented using a NEWSTAR script). The resultant differential gain and phase solutions reveal a systematic pointing drift of 42" over the 12 h observation (de Bruyn 2006). For the purposes of this memo, we classify both the correction for the primary beam response pattern and antenna pointing errors as direction-dependent error corrections.

3.1.2. Abell 2255

WSRT observations of the cluster Abell 2255 at a wavelength of 92 cm (328 MHz) are described by de Bruyn (2006). In the analysis, bright off-axis sources show a ring-shaped, position-dependent polarization error pattern. An analysis of the errors using a MeqTrees self-calibration solution for the voltage beams (S. Yatawatta) suggests that the polarization artifacts at the off-axis source positions are explained by feed response errors at individual antennas that introduce closure errors in parts of the array. These data also show ionospheric scintillation errors (de Bruyn 2006); these ionospheric disturbances similarly introduce direction-dependent errors.

Multi-band WSRT observations of Abell 2255 at 25 cm, 85 cm, and 2m wavelength are reported by Pizzo and de Bruyn (2009). These data are similarly affected by direction-dependent errors, visible as artifacts at the position of the off-axis sources or, in the case of the 25-cm wavelength observations, also cumulatively at the center of the field. The authors use peeling (implemented as a sequence of NEWSTAR tasks) to calibrate the off-axis errors for the data at 25 cm wavelength. The data at this wavelength are also affected by strong RFI (causing at 25% data loss); in addition peeling could only be used effectively at the lower three frequency bands due to SNR constraints imposed by the steep spectrum of the off-axis source 4C+64.21 (Pizzo and de Bruyn 2009). The data in each of the three bands are limited by classical confusion at the field center.

3.1.3. Perseus cluster / 3C84

The dynamic range of 10,000:1 obtained by Noordam *et al.* (1982) for 3C84 at 21 cm wavelength using redundant baseline calibration is noted above. Intervening high-dynamic range observations of the Perseus cluster during ths 1990s and 2000s at WSRT in multiple bands are reported by Sijbring (1993), Sijbring and de Bruyn (1998), de Bruyn and Brentjens (2005), and de Bruyn (2006).

Deep polarization observations of the cluster at a wavelength of 81-95 cm (315-350 MHz) are described by de Bruyn and Brentjens (2005). These observations detect a diffuse polarized component in the cluster, and use an innovative rotation measure synthesis technique to derive rotation measures within the cluster. The authors report the following issues or mitigating measures related to achieving high dynamic range: i) Approximately 25% of the data are lost due to RFI or back-end problems. Sharp interference spikes introduce ringing in the band - these were mitigated by averaging odd and even channels, reducing the frequency resolution by a factor of two; ii) Gibbs phenomena at the video edge and low SNR at the upper end reduced the effective width of each band by 12.5%; iii) The total intensity images, which are limited by classical confusion to a dynamic range of 20,000:1, show evidence of direction-dependent calibration errors, caused by ionsopheric scintillation, and pointing errors, both affecting off-axis sources. The pointing errors do not strongly affect the inner cluster region, the primary science goal of this paper, and were not accordingly corrected; iv) The authors report the use of peeling (over four source positions) to solve for direction-dependent polarization leakage corrections on a channel-by-channel basis.

The cube produced by rotation measure synthesis achieves a net noise level of 70-100 μJy in Stokes Q and U over a net bandwidth of 50 MHz, which translates to a dynamic range of 200,000-400,000:1 relative to the peak in Stokes I (de Bruyn and Brentjens 2005; de Bruyn 2006). The authors report residual systematic polarization errors primarily concerned with uncorrected direction- and frequency-dependent instrumental polarization errors. They note that the instrumental polarization response of parabolic dishes increases a function of distance from the optical axis and that this is the primary source of residual direction-dependent polarization errors. They also note a clear frequency dependence of the unocorrected polarization with a period of approximately 17 MHz - this is possibly due to standing waves between the dish surface and the focus box, and/or scattering from focus box support legs. They also report an unexplained radial "whisker" error pattern surrounding the strongest sources, 3C84.

de Bruyn (2006) reports on 1994 and 2003 polarization observations at 21 cm, achieving a net polarization dynamic range of $1-2\times10^6$, corresponding to a Stokes Q, U noise of $10-25\mu$Jy. These observations show the same 17 MHz frequency dependence in residual polarization response noted by de Bruyn and Brentjens (2005).

3.1.4. 3C147

de Bruyn (2006) reports observations of 3C147 at 21 cm (1.4 GHz) and 2 m wavelength (150 MHz) that have dynamic ranges of $10^6:1$ and $10^4:1$, respectively. The 21 cm observations conducted in 2003 yield a dynamic range of 1.5×10^6 on the central pixel, but this decreases steeply to 1000:1 with distance from the field center. The data also show the impact of non-linearity due to an interfering radar signal, and evidence of pointing errors. These effects were diminished in subsequent re-observations in 2006, but the new observations do not remove all direction-dependent residual errors (de Bruyn 2006).

The 2 m wavelength observations (de Bruyn 2006; de Bruyn *et al.* 2009) span a full-beam $6^\circ\times6^\circ$ field of view with a peak flux density of 56 Jy in the field and an achieved rms noise of 3 mJy. This translates to a dynamic range of $2\times10^4:1$. The observations are limited by classical confusion. Observations at 163 MHz suggest that the isoplanatic patch exceeds 20 degrees in favorable ionospheric conditions.

3.1.5. 3CR196

de Bruyn *et al.* (2009) describe high dynamic range, full polarization observations of 3CR196 at 150 MHz. The authors report an achieved image rms noise in Stokes I of 3 mJy (limited by classical confusion); for a peak flux density of 81 Jy, this produces a dynamic range of 27,000:1. The data are affected by satellite RFI, which was mitigated by excision - make possible by high time- and frequency-resolution. The authors used peeling (over three sources), removed the brightest sources (Cas A, Cyg A, Tau A, and Vir A - all sufficiently bright to be visible in outlying grating lobes), and undertook a single direction-independent self-calibration using a source model containing the brightest 200 sources to achieve the reported dynamic range. Ionospheric conditions were good, but for nights with poor conditions, residual direction-dependent errors were clearly visible surrounding off-axis sources.

In related 2 m wavelength WSRT observations, Bernardi *et al.* (2009) describe observations of the Fan field, and de Bruyn (2006) report observations of Cyg A. For the latter source, extended-source deconvolution errors are encountered at a dynamic range of 5000:1.

3.1.6. Conclusions from WSRT

As described above, the WSRT produces very high dynamic range images in frequency range considered in this memo. Specifically, for 3C84 on-axis at 21-cm wavelength, the achieved dynamic range is of order several million to one. As evident from the results presented above and discussions with WSRT scientists (de Bruyn, private communication), the dominant calibration challenges are perceived to lie in the area of direction-dependent terms, including pointing (and the interaction of pointing errors with ionospheric and tropospheric phase errors), and the direction- and frequency dependence of the full primary beam response. The associated high frequency-sampling required to mitigate these effects have serious implications for data set sizes and associated processing requirements. In addition, software for direction-dependent calibration can be a limitation or productivity bottleneck, in common with other arrays. Traditional self-calibration without direction dependence typically produces images limited to a net dynamic range of only several thousand to one.

In high dynamic range imaging, the WSRT benefits from redundant-baseline calibration and from the equatorial antenna mounts. The latter allows longer integrations when solving for direction-dependent effects (de Bruyn, private communication).

As noted above, RFI is a practical concern, and improved deconvolution algorithms for extended emission are regarded as a need.

Results on 3C84 and 3C147, discussed above and referenced to de Bruyn (2006), are planned for full later publication (de Bruyn, in preparation).

3.2. VLA and EVLA

Recent high dynamic range observations using the Very Large Array (VLA[2]) and EVLA in the frequency range under consideration here, $\nu < 2$ GHz, have been reported by R. Perley (private communication). These include recent observations of the 3C147 field at an observing frequency near 1460 MHz using array antennas outfitted with the new EVLA receivers and electronics; these observations have been correlated with both the old VLA correlator and the new WIDAR EVLA correlator (in separate observing sessions). The observations with the old VLA correlator achieve a dynamic range of $\sim 200,000 : 1$ and the WIDAR observations $\sim$ 850,000:1, both in Stokes I, relative to off-source noise measurements. These results are recent however and have not yet been compared to the expected thermal noise limit predicted for the bandwidth, exposure time, and system performance parameters applicable to the two observing runs. To achieve these dynamic ranges, the data require correction for baseline-based closure errors (arising partly from residual parallel-hand instrumental polarization errors, but likely with contributions from other causes also); these baseline-based corrections were performed in individual frequency channels of $\sim$ 10% fractional bandwidth each - this provides a first-order correction for frequency-dependence of these errors. A full non-linear polarization calibration is required for all cross-correlation polarization pairs in this dynamic range regime. In addition, off-axis sources show associated artifacts due to unmodeled direction-dependent calibration errors in amplitude and phase including non-azimuthal symmetry across the antennas in the array. Direction-dependent calibration tests on these data, including, for example, the peeling method, are under evaluation at present. It is believed that direction-dependent calibration (which is made more complicated by the rotation of the antenna beam pattern on the sky for the az-el VLA antenna mounts), and the requirement for full non-linear polarization calibration (with an associated assumption that Stokes $V \neq 0$, throughout the reduction) are limiting factors in the achieved dynamic range. Higher dynamic range results are expected in the future from the EVLA, the perceived limit is the removal of variable, non-isoplanatic errors (R. Perley, private communication).

The wide-field NVSS survey, conducted using the VLA at 1.4 GHz is described by Condon *et al.* (1998). Although these are not pointed single-field observations aimed at producing the highest dynamic range possible, the survey does require sophisticated wide-field reduction processes, including a correction for the direction-dependent polarization primary beam response and related calibrations. The NVSS catalog extends down to 2.5 mJy and reports a typical Stokes I dynamic

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[2]http://www.nrao.edu

range of 1,000:1 for the snapshot observing strategy used for the survey.

Richards (2000) reports deep VLA observations of the HDF-N at 1.4 GHz, that achieve an image rms of $\sim 7.5\mu$Jy, but with an estimated dynamic range limit of 5,000:1. The data were reduced by imaging and removing all confusing sources out to the first sidelobe of the primary beam, and imaged using facet-based wide-field imaging. A joint deconvolution across all facets was not possible due to computational costs. Residual artifacts associated with point sources suggest residual uncorrected direction-dependent errors - which are attributed to likely uncorrected pointing errors at individual VLA antennas.

High dynamic range VLA observations of the gravitational lens 0957+561 over a range of wavelengths between 2 cm and 20 cm are reported by Harvanek et al., (1997). This is a complex lensed image, with significant source structure. We consider only the 20 cm wavelength observations here, given the primary focus of this memo on frequencies below 2 GHz. At 20-cm wavelength, the authors report dynamic ranges of 5,130:1 and 4,583:1, for robust and uniform imaging weighting respectively, using conventional VLA reduction practices.

At higher frequencies, $\nu > 5$ GHz, several high dynamic range results have been reported for the VLA. We report a selection of these results below, but do not analyze them in detail here as the primary focus of this memo is the frequency range $\nu < 2$ GHz.

Owen *et al.* (1989) report a dynamic range of 50,000:1 in imaging the M87 jet at 2 cm wavelength. These data require a correction for non-closing baseline-based errors at the VLA; without these closure corrections, the limiting dynamic range is ∼5,000:1. The data are deconvolved using MEM.

Jester *et al.* (2005) describe high dynamic range VLA observations of 3C273 at frequencies between 8 GHz and 43 GHz. At the lower of these frequencies, 8 GHz and 15 GHz, dynamic ranges of 75,000:1 and 110,000:1 are reported respectively. An 8 GHz observation of 3C273, obtained in spectral-line mode and with baseline-based calibration achieved a dynamic range of 330,000:1 (R. Perley, in preparation).

Zhao *et al.* (1991) report high dynamic range observations of Sgr A* at 15 GHz, achieving a dynamic range of 22,000:1. The latter authors enumerate limiting factors on dynamic range and fidelity relevant to their observations, including: i) source time variability; ii) residual self-calibration phase and amplitude errors; iii) CLEAN deconvolution limits imposed by off-grid point sources; and iv) constraints on proper use of MEM deconvolution with a point source.

3.3. ATCA

Norris *et al.* (2005) report deep observations of the HDF-S at wavelengths 20, 11, 6 and 3 cm using the Australia Telescope Compact Array (ATCA[3]). At 1.4 GHz, closest to the SKA-mid frequency range considered in this memo, the observations spanned nearly 200 hours of observing time, and achieved a central rms of 16.1μJy. The data are imaged using multifrequency synthesis, and self-calibrated at 20 cm using a full-field model (but without solving for direction-dependent gains). The authors note that their observations generally reach the thermal noise limit, approaching the classical confusion limit only at 20 cm, and report a dynamic range of 100,000:1. They note that deeper observations will likely be dynamic-range-limited without a solution or correction for direction-dependent errors such as pointing and (non-symmetric) primary beam response patterns.

Geller *et al.* (2000) report targeted high-dynamic range observations at 1.4 GHz of the $z \sim 3.15$ radio source 1935-692 in a search for Thomson-scatterd halos in the intergalactic medium. The observations achieved a Stokes I rms of 20 μJy, corresponding to a dynamic range of 77,000:1. A careful data reduction was needed to achieve this dynamic range including: i) investigation and correction for non-closing baseline-based errors (primarily of hardware origin); ii) hybrid redundant-baseline and antenna-based self-calibration; iii) multifrequency synthesis imaging; and iv) wide-field source models to remove off-axis confusing sources. The authors report residual systematic errors in the $uv-$residuals greater than the image rms noise; their origin is not unambiguous but the authors conclude that they arise most likely from systematic errors in the final source CLEAN component models. D. Whysong (private communication) reports that substantial follow-up observations achieved a dynamic range of $\sim$ 100,000:1, but were similarly affected by direction-dependent gains.

Norris *et al.* (2006) present first results from the ATLAS survey of the CDF-S/SWIRE field at 1.4 GHz with the ATCA. For the field presented, an rms of $\sim 40 - 60\mu$Jy is reported. The observations were scheduled as a 21-pointing mosaic. A limiting consideration in imaging quality and data calibration is noted as the presence of a confusing source that appears in the sidelobes of several pointings. The inability to deal easily with non-symmetric primary beams is a limitation in this regard. Companion ATLAS observations of the ELAIS-S1 field at 1.4 GHz are reported by Middelberg *et al.* (2008); these observations achieve an rms noise $< 30\mu$Jy. This field includes a 3.8 Jy confusing source, PKS 0033-44, approximately 1 degree from the field center - located on the first sidelobe of the antenna primary beam pattern - and a correspondingly large image size is needed to encompass this source. The authors were unable to remove the artifacts caused by the rotation of this source through the primary beam sidelobes as a function of parallactic angle however, despite a careful holographic measurement of the beam response using a satellite at 1.557 GHz.

[3]http://www.atnf.csiro.au

3.4. GMRT

The main limitations to high dynamic range imaging with the Giant Meterwave Radio Telescope (GMRT[4]) are believed to be ionospheric calibration, non-closing baseline-based errors (primarily believed to be of correlator origin), RFI, $uv-$coverage, and bandpass variations in spectral line observations.

Recent observations with a dynamic range of 140,000:1 have been reported by Roy *et al.* (2009) of the calibrator J1609+266 at a frequency of 1280-1296 MHz with an rms of 1.5 times the thermal noise level. These observations made use of the new GMRT real-time software backend, (GSB) which mitigates earlier issues associated with the original hardware correlator. On applying the Median of Absolute Deviation (MAD) filter to eliminate broadband impulsive RFI, it is expected that the thermal noise limit will be reached in L-band using the GSB.

Broadband impulsive RFI like that produced by power lines, is hard to remove with the hardware backend at GMRT. Also, the older hardware correlator is affected by quantization issues, non-zero baseline errors, which in general produce non-closing errors. The GSB marks a significant reduction in these errors.

Roy *et al.* (2007) report an improvement in the spectral dynamic range for Galactic H 1 21 cm absorption observations of three bright, compact background sources using the technique of frequency switching. Spectral baselines obtained by switching at the fourth local oscillator (LO) has ripples limiting the dynamic range to less than 300. On the other hand, switching at the first LO produces a flatter baseline, a dynamic range ≥ 1000 for narrow sources, and $\sim 1000 \times N^{1/2}$ for features which are N channels wide. Such frequency switching techniques have and continue to be used at ATCA and WSRT.

RFI is a major limiting factor in the imaging dynamic range at GMRT particularly below 330 MHz. The standard RFI excision techniques involve high speed sampling of data which has disadvantages such as higher measured rms noise, requiring RFI-clean regions of data space and specialized hardware. Another method of RFI removal involves eigen-decomposition of correlation matrices. Athreya, (2009) presents a new, purely software technique which removes RFI using fringe patterns in the correlator output. This algorithm called RfiX can both recognise and remove RFI in this manner. It works best on correlator outputs integrated over 1-10 sec and hence is capable of removing weak RFI. It only works on spatially- and temporally-constant RFI. RfiX applied to GMRT data for 3C286 at 240 MHz produces an image which has rms noise 2 mJy / beam at the center of the field (peak / noise $\sim$ 14,000, for a peak flux density of 28 Jy) and 0.65 mJy /beam at the periphery (peak / noise $\sim$ 43,000).

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[4]http://gmrt.ncra.tifr.res.in

4. Conclusions

Although it is difficult to assemble a truly complete set of high dynamic range imaging studies obtained by current radio interferometers, the public results summarized in this memo nonetheless provide important insights into practical limitations on imaging in this regime, and the issues we are likely to encounter at even higher dynamic range with the SKA. We draw the following broad cross-cutting conclusions from the results presented here:

1. **Hardware design optimization:** Early antenna, backend, and array hardware or instrumental choices appear to define strongly the long-term imaging performance achieved by interferometers over their lifetimes. Investments in instrumental performance, such as gain and phase stability, minimization of non-closing electronic, digital signal processing, or correlator errors, and the choice of antenna mount type and primary beam sidelobe level, have lasting impacts on the long-term imaging results produced by a given array over its lifetime. These limits are imposed by hardware design choices either because they render certain instrumental properties extremely difficult (or impossible) to calibrate adequately, or impose technical costs on calibration and imaging that appear to be not cost-effective to implement in practice, even long after construction. Conversely, arrays therefore specialize in areas best suited to their instrumental limitations. This appears especially true of the antenna mount type (for the arrays considered here, either equatorial or az-el) and its impact on the rotation of the primary beam response on the sky over wide-field synthesis observations. This literature survey confirms that widely-held perception that WSRT, with equatorial antennas, out-performs arrays of az-el mounted antennas in ultra-high dynamic range imaging in the presence of strong confusing sources. The extent to which this effect can be mitigated by sidelobe minimization combined with az-el mounts is not resolved by this study however.

2. **Direction-dependent corrections:** At the limits of sensitivity and dynamic range considered here for current arrays, almost all observational studies summarized above are affected strongly or limited by un-modeled direction-dependent calibration effects, including antenna pointing errors, direction-dependent atmospheric phase and amplitude errors, or antenna primary beam response error patterns. These need to be both calibrated and removed. This has an associated requirement for wide-field, complete image sky models and the means to automatically extract and synthesize these sky models from images. Direction-dependent effects also need to be understood in terms of their polarization and frequency dependence; this is a calibration and imaging regime in which multifrequency and multiscale imaging is necessary.

3. **RFI:** RFI is a cross-cutting practical concern for almost all observational studies presented above, and robust mitigation methods that do not rely on extensive manual excision will be essential in the SKA dynamic range regime.

4. **Data rates, computational cost, and software:** Wide-field, high dynamic imaging studies in this frequency range, as summarized above, require high time- and frequency sampling,

to allow adequate RFI mitigation, minimize time- and frequency smearing, and provide sufficient sampling to allow multifrequency synthesis methods to be used over large bandwidths. The data rates inherently require larger computational efficiency, as do several of the algorithms, including joint wide-field deconvolution, and direction-dependent calibration. Current software inadequacies and inefficiencies often present significant productivity barriers in this imaging regime.

These issues will be considered further in future memos.

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