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SKA Survey Optimization

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ABSTRACT

In this study we examine the science and engineering issues involved in optimizing the SKA for survey science. Three Key Science projects require all-sky or 1000 sq deg surveys. Survey science requires low frequency, low resolution images with superb image quality, which imposes stringent requirements on the calibration and sidelobe levels at every stage of beam formation. The cost of data processing is very dependent on the antenna system, calibration, and data processing paradigm. The optimal design of the SKA must consider the overall system from the science goals to the data products. In this memo we explore performance and cost criteria which recognize the interaction of different subsystems for survey science. We use as a reference design an array of small diameter antennas with focal plane phased array feeds from 300 MHz to 3 GHz and wide band single pixel feeds at higher frequencies. The survey speed $\sim N_{beams} \times \lambda^2 \times (ND/T)^2 \times BW$, where N is the number of antennas, D is the antenna diameter and T the system temperature. The cost of the SKA is dominated by four major components: antennas, receivers, signal processing, and computing. Each has strong interdependencies, and must be optimized in the context of the overall science and engineering goals. For the highest dynamic range the calibration implicit in beamforming with FPA or station beams must be redone in the data analysis, leading to a large increase in computing costs.

1. Introduction

A major theme driving the design of the SKA has been reducing the cost of the collecting area. The reference design envisages three different antenna components: i) an array of

$\sim$ 10m diameter antennas with focal plane phased array feeds from 0.3 to 3 GHz and wide band single pixel feeds at higher frequencies up to 25 GHz, ii) aperture array tiles for all sky monitoring from 0.3 to 1 GHz, iii) an EOR array from $\sim$ 0.1 to 0.3 GHz using wideband dipoles. These three antennas share a common data transport, DSP, and computing infrastructure. The memos by Bunton and Bregman [1,2,3] discuss optimizing the antenna design and receiver systems for low frequency surveys.

A second theme driving the SKA design is the high cost of data processing [4,5,6,7]. Cornwell, taking into account the effect of non-coplanar baselines [8], derives a data processing cost equation which scales as $\sim \lambda N^2 D_{max}^3/D^4$, which for an array with a constant total collecting area, scales as D^{-8} for an array of N antennas with diameter D and maximum baseline D_{max}. These scaling relations only apply to imaging the full field of view at the highest resolution. In many cases, the SKA will image regions larger than λ/D at lower resolution. For surveys the sensitivity of an array scales as ND, rather than ND^2, so for constant survey sensitivity, the computing cost scales as D^{-6}.

The array design and data processing issues are strongly coupled. Antenna costs can be reduced by using aperture arrays and FPA receivers to provide a wide FOV for survey science. Data processing costs can be reduced by station beam forming. Each level of beam formation imprints its characteristics and error patterns on SKA images. Sidelobes of sources outside the regions of interest confuse the images, and must be subtracted to achieve high fidelity. We have to calibrate the instrumental response to each source in order to subtract its sidelobes. Calibration errors at each level of beam formation increase the coupling between beams which in turn increases the computing cost.

Computing costs can be reduced if multiple beams can be processed independently, effectively decoupling the array response across the FOV [6,7]. Cornwell [7] analyzes the computing costs with five levels of beam formation: antenna, FPA, station, correlator, and array beams. For an array with both FPA and station beam forming, he finds that focal and aperture plane beam forming are effective in limiting the computing costs only if focal plane array and station calibration can be performed independently of the full field imaging. If the coupling between beams is low, the computing cost for image formation is estimated to be $\sim$ \$100M. If the coupling between beams is high, images must be deconvolved over the full FOV and computing costs are much higher [7]. The large discrepancy between Bunton's [9] total digital processing cost $\sim$ \$30M, and Cornwell's \$100M is a direct result of attention to image fidelity.

In this memo we examine how the reference design can be optimized for survey science, without seriously compromising targeted observations. The key is to find the appropriate aggregation of collecting area which achieves the science goals and optimizes the price/performance of the total SKA from the science goals to the data products which astronomers can use.

2. Science Goals

We will take the Key Science Requirements Matrix [10] as the basis for the SKA science goals. Three of the five Key Science projects include eight experiments which require all-sky or 1000 sq deg surveys. All are below 2 GHz, with a useful range extending to 3 GHz. Four pulsar surveys are in range 1-2 GHz, the Dark Energy HI survey 0.5-1 GHz, Evolution of gas in galaxies 0.2-1.4 GHz, the all sky 1 micro Jy survey 1.4 GHz, and the EoR all sky survey of redshifted HI from z=19 to z=6 at 70-200 MHz. The instantaneous FOV required is 1-10 sq deg, except the Dark Energy HI survey which requires 50 sq deg. The maximum baselines required range from 1 to 200 km. Four surveys require only the compact core within 1-5 km (Strong Fields using binary pulsars with BH companions, pulsars in the Galactic plane and globular clusters, the Dark energy HI, and the EoR surveys). Two Key Science projects (Galaxy evolution, Probing the Dark Ages) require an image dynamic range 10^7. In summary, survey science requires low frequency, low resolution images with superb image quality. Emphasis on the dynamic range is crucial if the SKA is to achieve the science goals. HI surveys with extended HI emission in space and frequency depend on accurate subtraction of continuum emission to avoid being confusion limited. Polarization surveys require high polarization purity across the FOV and bandwidth. In some of the Key Science projects an increased FOV can offset reduced collecting area, but in others the full sensitivity of the SKA is required in a limited FOV [11].

2.1. Pulsars

The pulsar KSP requires three steps: 1) The pulsar survey 2) a follow up program to select good pulsars (either for timing or strong field gravity) 3) timing observations.

Each of these steps has quite different survey and technical requirements:

1) The pulsar survey uses relatively little observing time compared with follow up observations. While the efficiency is proportional to FOV, the total time is less than needed for the follow up, so this FOV requirement is not a critical driver.

Notes on the survey: i) The survey hardware costs are proportional to the inverse square of the filling factor and for the pulsar survey this may be the most critical factor. Only the core or incoherent summation of stations can be used. ii) Since long dwell times can't be used for acceleration searches without increased processing costs there will be a penalty to using a large FOV with too small A/T. iii) The full bandwidth is needed and it must be possible to combine signals coherently over the full band. iv) There is no requirement on polarization purity for the survey. v) There are no difficult requirements on timing accuracy for the survey. vi) Frequencies between 0.5 and 2 GHz are good for all surveys except the special case of the Galactic Centre search which need frequencies above 10 GHz but will only need to survey a small area, ~ 1 sq deg.

2. The follow up timing to weed out the uninteresting pulsars.

This will be the most time consuming part of the survey so these requirements are critical. Timing requires a stable average profile and this can only be achieved after a minimum of ~ 1 min observing, so we can't freely exchange A/T for FOV. The survey expects to find ~ 12000 pulsars in 30000 sq deg of sky so there is 1 pulsar per 3 sq deg on average, although this number will be much higher at low galactic latitudes. This means any FOV large enough to simultaneously time more than one pulsar will reduce the survey follow up time linearly with the FOV as long as FOV is greater than a few square degrees. Clearly this critical number needs more study by the pulsar simulation group and is on the to do list. The current thinking is that the large FOV is CRITICAL and it's hard to see how it can be done without FOV much greater than 1 sq deg. Frequencies of 1-2GHz with large bandwidths are required. Polarization purity is not essential for this phase, so off axis observations of multiple pulsars in the FOV are not a problem. Timing hardware is only needed for a few phased array beams so more than the array core can be used. Since observing times for stronger pulsars are set by the need to achieve stable profiles rather than S/N, sub arrays will be beneficial in some cases.

3. Timing array (precision monitoring of "good" pulsars).

The density of good timing pulsars is so low that there will be only one in any realizable, contiguous FOV. With an estimate maximum of 1000 pulsars in 30000 sq deg we have 1 per 30 sq deg. The requirement for high frequencies makes such a big FOV unlikely. Sensitivity is all important for this part, and the full SKA sensitivity is likely to be required for most of the pulsars. The polarization and timing have to be free from systematic errors but all observations can all be made on axis. Frequencies will be 1.5 GHz and above up to perhaps 5 GHz. Regular observations are required. Any Galactic Centre pulsars will need frequencies greater than 10 GHz but they will likely all be in the main beam. In order to do the timing we need at least arcsec positions (otherwise we need a year of timing to sort the position from the period derivative).

2.2. HI surveys

Dark energy needs to maximize the number of HI detections over an area large enough to minimize cosmic variance. This requires the highest possible FOV at full sensitivity. The proposers argue that 100 square degrees are essential, and this is required at the survey limit - ie z=1.5, hence at 500 MHz.

Notes: i) The sensitivity requirements are reduced by distance squared for closer objects so the required FOV at higher frequencies (lower z) can be scaled by distance^4. ii) The HI surveys can freely trade A/T for FOV. iii) All the bandwidth from 0.5 to 1.4 GHz could be used simultaneously but this is not essential as the observing time is dominated by the highest redshifts. The detailed requirements should be modeled if this instantaneous bandwidth is a problem. iv) The dynamic range required is set by the continuum subtraction for galaxies with the HI emission from individual objects confined to a band of 50 MHz or less.

HI evolution has similar requirements to the dark energy experiment. Cosmic variance is no longer the limiting error so now while the large FOV is still very useful to increase efficiency, it is not essential. Detailed HI studies of samples of individual galaxies at higher angular resolution will also benefit from large FOV, but again, it is not essential.

The angular resolution requirements have been estimated by Elaine Sadler, based on the HIPASS survey, as follows:

i) Dark energy doesn't require separation of multiple cluster galaxies in the beam, provided these are not confused by continuum subtraction. 40" corresponding to 340 kpc at z = 1.5 would be sufficient resolution. Hence this KSP needs FOV but only for the core (baseline $\sim$ 2km) ii) Evolution of the HI mass function needs $\sim$ 10" at z = 1.5 (baselines to 10km) iii) HI velocity fields of individual galaxies need $\sim$ 1" resolution (100km). This would not be done in survey mode, but by looking at known galaxies which have sufficient S/N. Hence while a large FOV can improve the efficiency of such observations a small number of beams within the FOV could cover the objects of interest, reducing the bandwidth requirement for distant stations.

For spectral line surveys, confusion from continuum sources can be reduced if the spectral line signature can be identified and continuum emission can be subtracted. E.g. for narrow line emission sources. For rich clusters of galaxies with overlapping broad line emission profiles, confusion from frequency dependent sidelobe structure may limit the detection threshold. In the presence of continuum emission, bandpass calibration may limit the dynamic range. Frequency dependent polarized sidelobes are also an important source of confusion for spectral line observations.

2.3. Radio continuum

Surveys to about 1 uJy over the whole sky will use the maximum possible FOV. Dynamic range needed for these surveys will be somewhat less than 10^7 needed for the deep surveys. Surveys to the SKA flux limit for star forming galaxies and AGN structure in the early universe need the full sensitivity and dynamic range but a modest FOV would sample the areas of interest. These regions will be limited by the FOV achievable with big telescopes in other wavebands, not by the SKA FOV.

VLBI observations to the limiting flux over a wide FOV will be needed for some science, but the locations of sources in the FOV will be known in advance, so beams can be formed at the stations to reduce communication bandwidth.

Many continuum surveys depend on subtraction of background sources. CMB observations present a good use case for the SKA [33]. All baselines of the SKA are useful for detecting measuring discrete source confusion. With an $A/T \sim 2\ 10^4 m^2 K^{-1}$, high resolution continuum images are expected to have a thermal noise of about 50 nJy with 1 hr integration at 10 GHz. There are about 100 sources per *arcmin* with flux density greater than a 5 sigma detection threshold 250 nJy [33]. Accurate source subtraction depends on good calibration of the instrumental antenna positions, instrumental and atmospheric gain variation, and primary beam patterns in order to achieve the required level of background source subtraction.

2.4. Polarization surveys

Several SKA projects require high polarization purity. The polarization properties of the antennas and receivers are an important consideration. Polarization purity is required over the full FOV, and the instrumental polarization must be carefully measured for off axis beams. Frequency and polarization dependence are coupled as a source of confusion. The WENSS survey at 325 MHz shows bright polarized emission regions at arcmin resolution which extends over 10's of degrees [15,16,17]. The power spectra and structure function of Galactic polarized emission at 325 MHz [18] show that the instrumental polarization must be measured and calibrated over the whole FOV to avoid confusion with an EOR spectral line signature. Measurements of the power spectrum of polarized diffuse Galactic emission at 0.4 to 3 GHz suggest that polarized Galactic emission is unlikely to be a limitation to polarization measurements at the highest SKA frequencies [19].

For aperture arrays, or alt-azimuth mounted antennas, the beam and instrumental polarization pattern rotates on the sky. Confusion from continuum sources moving through the polarized sidelobe response of the beam pattern may be a limiting source of noise. If the instrumental polarization can be adequately calibrated over the beam, the efficiency is directly proportional to FOV and FOV can be traded for A/T. The dynamic range is set by the polarized fraction of the flux, not total flux. Frequencies 0.5 to 4GHz are required. The observing efficiency is proportional to the amount of band simultaneously covered.

2.5. Conclusions

The FOV can often be traded for sensitivity but there is a limit to this for pulsar searching. In some cases (eg dark energy) a large FOV is required at full sensitivity so there is no room to trade. Since the FOV - sensitivity trade can be done in many cases it will be valuable to explore these trade off dependencies. The dynamic range requirements for the surveys need to be specified more carefully. It is not always necessary to combine the FOV requirements with other requirements such as dynamic range, polarization parity, resolution. In many cases, the intrinsic properties of the sources can be used to reduce confusion. A more complex matrix, and closer interactions between the astronomers and the engineers is essential to optimize the survey properties of the SKA.

3. Array Optimization

We use the survey speed as a measure of the sensitivity of the SKA for surveying.

$speed = FOV \times (A/T)^2 \times BW$ ——————(1)

For the LNSD-FPA Reference Design, $FOV \sim N_{beams} \times (\lambda/D)^2$, and $A \sim ND^2$, so,

$speed = N_{beams} \times \lambda^2 \times (ND/T)^2 \times BW$ ——————(2)

where N_{beams} is the number of beams generated at each antenna, N is the number of antennas, D is the antenna diameter, T the system temperature, and BW the bandwidth. For most feeds, N_{beams} is constant. For antennas with phased-array feeds (PAF), the maximum number of beams is approximately proportional $1/\lambda^2$. The survey speed is then independent of λ, and proportional to the area of the PAF in the LNSD-PAF design. The useful bandwidth and number of beams are defined by the science targets. Note the familiar ND dependence for observations of regions which are larger than the FOV of the antenna. In practice, a combination of single feeds, multi-feed clusters, and PAFs may be needed to cover the full frequency range of the SKA. For targeted observations of sources smaller than the FOV of the primary antenna beam, the sensitivity reverts to

$(ND^2/T)^2 \times BW$ ————————————(3)

and the advantage of N_{beams} is lost. A FPA satisfies the instantaneous FOV requirement if the region observed is smaller than $N_{beams} \times (\lambda/D)^2$. For reference, a 5m antenna with a single feed gives a $\sim$ 50 sq deg instantaneous FOV at 500 MHz.

We can break the cost into categories corresponding to the major components of the SKA: antennas, receivers, signal processing, and computing.

- Antenna costs include the surface aperture, mechanical systems, antenna drives, foundations etc. The antenna cost scales as $D^{2+x}\lambda^{-y}$ with indices x and y typically in the range 0-1 up to some limiting antenna diameter.

- Receiver systems include feeds, LNA, cyrogenics, FPAs and phasing electronics. The cost is largely a function of the complexity of the receiver. Cyrogenic receivers lower the system temperature at high frequencies, but are a major operational cost.

- Signal processing includes data transport, fiber, trenches, digitizers, channelization and the DSP hardware and software to bring the data from the antennas to the array beam formers and correlators. The distribution of collecting area and the maximum baseline, are defined by the science requirements. The signal transport costs depend on the array configuration. If the antennas are clustered into compact stations the data transport costs are lower, but data processing costs increase if the uv-coverage is inadequate.

- Computing includes correlator hardware and software, calibration and image analysis. This includes the cost of calibrating phased array receivers, and calibration at every level of beam formation. The cost of computing is strongly dependent on the antenna and receiver design, and array configuration.

These cost components are strongly coupled. We need to include the cost of obtaining adequate image quality. High sidelobe levels and a high degree of coupling between beams, drive deconvolution costs higher [7]. Several studies [e.g.12,13] show that the deconvolution quality is a strong function of uv-coverage. If we make all cross correlations of N antennas, the number of correlations increases $\sim N^2/2$. However the cost of data processing required to obtain the required image fidelity depends on the sidelobe levels, so the overall computing cost may be reduced by having better uv-coverage. In the following sections we analyze this in more detail.

4. Antennas

The reference design has three different antenna components: i) an array of $\sim$ 10m diameter antennas with focal plane phased array feeds from 0.3 to 3 GHz and wide band single pixel feeds at higher frequencies up to 25 GHz, ii) aperture array tiles for all sky monitoring from 0.3 to 1 GHz, iii) an EOR array from $\sim$ 0.1 to 0.3 GHz using wideband dipoles. The antennas serve several major functions: collecting area, beam formation, sample points across the incident wavefront, and anti-aliasing filters suppressing the response to unwanted emission outside the FOV.

4.1. collecting area and aperture efficiency

A large effective collecting area is an essential attribute of the SKA. Many of the SKA Key Projects require an $A/T \sim 2\ 10^4 m^2 K^{-1}$, where A is the effective area. A high aperture efficiency can compensate for a smaller collecting area and vice-versa. Since the survey speed scales as $\sim ND$ and the cost $\sim ND^{2+x}$, a LNSD array is clearly correct for survey optimization. Using multiple apertures for low and high frequency drives down the overall cost of the telescope aperture [1,2,13]. The minimum antenna size for a prime focus system is $\sim$ 10m (10 λ at 300 MHz) for which the efficiency will still be quite limited for a traditional feed system ($\sim$ 30%). A well-designed FPA system may do significantly better although this requires real-life demonstration. Reaching better aperture efficiencies in the 300-500 MHz range may require substantially larger apertures where single horn systems can reach $\sim$ 50% and FPAs maybe $\sim$ 75%.

4.2. multiple apertures

The frequency range for each antenna type is an issue. LNSD is a good solution above $\sim$ 1 GHz, transitioning from aperture arrays to small dishes. If the cost and performance of aperture arrays can meet the requirements above $\sim$ 300 MHz, then $\sim$ 1 GHz may be a better place to break between low frequency antenna arrays, and high frequency precision antennas with cooled receivers.

Low frequency observations using an aperture array can take place simultaneously with high frequency observations using precision antennas if the data transport and DSP infrastructure are adequate. In practice, additional BW for a low frequency experiment is a small increment on the fractional BW at high frequencies, and is not limited by the fiber and DSP. However, since the two experiments require separate calibration, signal processing and analysis, computing costs may be the limiting factor.

4.3. beam formation

The primary beam pattern of the antenna aperture and feed illumination modulates the sky brightness distribution. Errors in the primary beam calibration limit the dynamic range. Although it can be argued that using expensive, high precision antennas for low frequency observations is a waste, primary beam and pointing errors dominate the image errors in mosaic observations of large sources [14]. If the antennas are engineered for observations at 25 GHz, then we will have more stable primary beam illumination patterns at lower frequencies, and fewer parameters which must be determined to calibrate the data.

4.4. aliasing, sidelobes and spillover

Other issues in the antenna design are spillover and aperture blockage. The antenna primary beam pattern is our first line of defense against radiation from outside the FOV. The sidelobe structure of the primary beam pattern couples the response from sources outside the field of view and increases confusion noise. For low resolution survey science (EOR, HI), spectral and time resolution requirements do not allow much bandwidth or time averaging [22]. Spillover past the reflecting surfaces increases the system temperature, and picks up stray radiation from RFI sources and radiation from other antennas. Noise power fron one antenna bouncing off feed legs and other structures into other nearby antennas gives false, time varying correlations which are not attenuated by switching patterns designed to reduce cross talk. Careful design of scattering surfaces on the antennas can reduce this problem. An offset antenna design reduces the aperture blockage, but costs more and also increases the minimum antenna separation - an important consideration for mosaicing. An equatorial mount keeps the feed leg diffraction pattern fixed on sky for tracked observations, but also costs more to build.

5. Receivers

For some key projects, FOV can be traded for sensitivity (e.g. pulsar surveys). In other cases, (e.g. pulsar timing, dark energy) the full sensitivity is required on axis, so increasing the FOV at the cost of reduced A/T decreases the capability of the SKA. Focal plane array receivers can provide multiple beams for surveying. Focal plane array receivers might be realized using a cluster of feeds (MFC) or with phased array receivers (PAF) [34]. Horn clusters must be spaced by $> \lambda$ so that the horn is large enough for efficient illumination of the aperture. The beams do not Nyquist sample the sky and interleaved observations must be obtained to fully sample the the sky for surveying. Phased array receivers have receptors spaced by $< \lambda$ to avoid grating lobes in the beam pattern, where λ is at the shortest wavelength. Beams are formed from the amplitude and phase weighting of the phased array receptors and can fully sample the sky. The number of receivers required per beam for a phased array receiver ranges from ~ 2.4 to 3.3 as the PAF gets smaller [37]. The system temperature for a PAF receivers is likely to be higher than a cooled MFC at L-band. Attractive advantages of phased array receivers follow from the ability to control the complex weighting of the receptors to correct for off-axis aberrations, aperture blockage, and aperture surface deformations. Such corrections come at the cost of accurate calibration of the complex gains of the phased array receiver elements.

5.1. Phased Array Receivers

Focal plane arrays have obvious science and engineering appeal. They offer the advantage of re-using expensive collecting area to provide a frequency independent, wide FOV. The engineering appeal has led several groups to embrace the FPA mantra. Yet, as Cornwell reminds us in *"TheBigGulp"* [12], the beautifully engineered solution may not be the one which enables us to realize our science goals for $1B.

FPAs are clearly a good strategy if one already has large expensive antennas. A phased array receiver can also be used to correct large scale errors in the aperture surface at the cost of additional calibration parameters and computational load. The choice for the SKA is not so clear. Using larger apertures with FPA receivers transfers resources from collecting area into higher risk design and electronics, and reduces the on-axis collecting area for targeted observations. When the instantaneous FOV required is less than $Nbeams \times (\lambda/D)^2$, the advantage of $Nbeams$ is lost. If the FOV is less than $(\lambda/D)^2$, the sensitivity reverts to ND^2, and the transfer of resources from collecting area to FPA receivers compromises non-survey science.

High aperture efficiencies can be obtained using phase array receivers [34]. The Stein efficiency relates the forward gains and the cross coupling between phased array beams [35, 36]. A high efficiency implies high coupling between beams. Sidelobes of one phased array beam will appear in the direction of another phased array beam at a level $\sim 1/N_{rec}$ where N_{rec} is the number of receiver elements in the phased array receiver. This coupling between beams in different directions can be reduced by re-weighting the phased array, but this comes at the cost of reducing the forward gain, and higher sidelobes in other directions.

5.2. Risk, cost and RFI

It is often argued that Moores law drives down the cost of electronics, so we should spend less on antennas, and more on electronics. The corollary is, however, electronics become obsolete, so it is better to invest in antennas and infrastructure with longer lifetimes, and to treat the receivers as an upgrade path as the SKA is built up. RFI generated by high speed digital electronics on the antennas must be carefully shielded. As much as 100 db of isolation may be required to avoid correlated clock frequencies and switching harmonics. Alternatively, digital logic to support FPA receivers might be connected by fiber to multiple layers of RFI secure cages away from the receiver elements. This is not cheap.

6. Array Configuration

For survey research we wish to compare images of the sky at different frequencies. The quality of these comparisons is often limited by the uv-coverage which can be greatly improved by optimizing the antenna configuration. The array can be optimized for making comparisons in different frequency bands by an antenna distribution which scales with frequency, so that similar uv-coverage is obtained over a wide range of frequencies. A sharp transition from a central core into a sparse distribution of compact stations gives a frequency dependent uv-coverage which is not optimum for comparing surveys at different frequencies. The frequency dependent shortest uv-spacings are also a problem; these must be filled in with mosaicing and single dish observations.

Array control, communications logistics and data transport for 1000's of antennas distributed over $\sim$ 3000 km are quite reasonable in the context of modern wideband networks. The cost can be minimized with direct burial of fiber bundles. The antennas can be distributed in a fractal network with the fibers branching out to individual antennas from nodes. The cost of a fiber network is increased by having the antennas more widely distributed rather than clustered into stations, but not by a large factor for a logarithmic distribution of antennas. The cost of a fiber run to a cluster of antennas 100 km from the central core is not very different for a cluster of diameter 100m or a few km if existing infrastructure is minimal and land acquisition costs are low. At larger radii the antennas can be increasingly clustered since one expects to provide uv-coverage by earth rotation when needed. Cross correlations of individual antennas in the central core with antennas in a cluster at larger radii sample a broad swath of the uv-plane enabling better estimates of the visibility function and its local gradients across the uv-plane. For example, earth rotation synthesis of correlations between the central core and individual antennas spaced by the core diameter could sample the entire uv-plane with the density provided by the antennas in the core. Wideband data links are a valuable asset for nearby communities who can provide substantial public support for the SKA. The incremental cost of providing extra bandwidth for public use is small if remote antenna clusters are appropriately located near rural population centers which can benefit from the construction of the SKA and the wideband infrastructure [20].

7. System Architecture.

A hybrid system using beam formation and correlators provides a flexible development path for imaging large fields of view. Phased array beams can be formed anywhere in the sky by adding the voltages in phase from all, or any subset of antennas. The sidelobes structure of each beam depends on the array geometry, the source direction, and the amplitude and phase weighting of the signals from each antenna. Beam formation is appropriate for analyzing signals from discrete radio sources such as pulsars, SETI targets and RFI sources. Beam formation allows us to channel the collecting area of large arrays of telescopes into expensive back end analysis engines. Direct imaging using beam formation is appropriate for compact sources, but is currently too expensive for imaging large fields.

Correlators provide a familiar and versatile mechanism for integrating the data in the *uv* domain. We have the advantage of over 40 years of development for calibration and imaging using *uv* data. Large correlators are needed to correlate 1000's of antennas, and the high data rates are increased by forming correlation functions. Beam formers can be used to reduce the data rate into correlators. The time dependent calibration of beam formers may be obtained using correlators.

7.1. Beam Formers

Beam formation is a powerful construct, but has the "problem" that it phases up the signals from multiple receptors and the original information of the wavefront propagation to each receptor is lost. Not quite lost, for it is possible, but expensive, to recover some of this information in postprocessing [7]. The problem is that the beamformer phasing varies with time, frequency, and direction in the sky. We phase up the beamformer in the desired direction, but the response is to sources over the whole sky. In order to subtract a strong source in the sidelobes we need to know the calibration in that direction.

The survey science requirements for this calibration are specified by the dynamic range required to avoid being confusion limited. The dynamic range requirements are greatly reduced when the intrinsic properties of the sources, e.g. time (pulsars), frequency (narrow lines) or compact size, allow discrimination against confusing sources. For HI from rich clusters, and EOR, the statistical properties of wide line emission may help discriminate against confusion from continuum sources in time and frequency dependent sidelobes. This deserves further study.

Thompson [29] estimates the dynamic range requirement for continuum emission to be $\sim 10^{6-7}$ for confusion from a 100 mJy source within a 1 sq deg FOV at 1.4 GHz. However, 100 Jy sources in 10^{-3} sidelobes and 10 Jy sources in 1% sidelobes of the beam give a comparable confusion level. Errors in the calibration of beam formers in the direction of each source create sidelobes which will raise the noise floor. The dynamic range can be estimated from the amplitude and phase errors in the beam former calibration. For random errors, the dynamic range $\sim N/\epsilon$, where N is the number of antennas in a station beam or the number of receptors in a focal plane array receiver beam, and ϵ is the error at each antenna or receptor. Thus, we rely on the sidelobe suppression and calibration of beam formation to achieve the dynamic range required. Cornwell lists five levels of beam formation: - optical, FPA, station, array, and bandwidth/time averaging. We must calibrate each level of beam formation. Errors in these calibrations increase the coupling between beams which throws an extra burden on the data processing [7].

For RF beam formers in aperture array tiles there is no calibration at all. In a station made from a set of such tiles we need station calibration to find the electronic gains that need to be corrected with an appropriate weight in the digital beam former. Once all the tile signals are added to provide a station beam the effect of a wrong weight of a tile in a station is an error in the correlations made between stations. The same is true for the beam former in a PAF; the signals from ~ 20 receptor elements in FPA receiver can be combined to form multiple beams in different directions. The signals from these beam are correlated with the corresponding beams from other telescopes. A wrong weight in a PAF beam former is an error in the correlations made between PAF beams. The subsequent modeling in self-calibration could include some parameters to correct for the actual shape of the station and PAF beams. A complete parametrization could include all the weights for the corresponding elements of an aperture array or FPA receiver. As we go for higher degrees of difficulty such as shaping the edge illumination to minimize far out sidelobes or null steering for interferers we may need further information.

It is preferable to make calibration in close to real time to reduce cost and data handling in off-line data processing. This implies measurements with sufficient parameters and SNR to make the calibration with the accuracy, and on the time scales required. We must design systems and observing strategies to do this. Some sort of hierarchical calibration may be possible. Correlation of individual receptors with a phased up signal may be needed to obtain sufficient SNR on the time scales required. A phased up signal for some subset of the array could be routed back to each array antenna to provide a reference. A correlator or other DSP is then required at each array antenna to derive this calibration. RFI from DSP hardware at the antenna must be extremely well shielded.

Alternatively the correlation can be part of centralized real time calibration hardware, on a time and computing resource shared basis. The data bandwidth from each station is similar if N_{beams} are formed from N phased array receivers or from N antennas at the station, or in centralized (well shielded) DSP and computing nodes. E.g. see the beam former in Fig 1, ref [22]. The time resolution required for the calibration varies from slow antenna surface deformations to fast, $\sim$ 1–10 sec atmospheric phase fluctuations.

Beam formers can provide some suppression of interfering sources [32]. Complex gains are applied to the elements of the beam former (station antennas, or PAF receptors) to form nulls in the directions of interfering sources. Multiple nulls can be placed to form extended nulls or to attenuate widely separated RFI or confusing sources. Calibration errors degrade the null, and gains may need to be updated on 100 ms time scales. The SNR at the phase center is a function of the number of nulls and the number of elements in the beam former. (See fig 14 in ref [32]). The SNR $\sim$ 1 - $N_{nulls}/(2N_{ants} - N_{nulls} - 2)$.

For the highest dynamic range the calibration implicit in beamforming with FPA or station beams must be redone in the data analysis, and leads to a large increase in computing costs. Closing the calibration loop at the end of the data reduction (i.e. full selfcalibration) would probably need to be done only in continuum or for a small number of averaged channels so the load would be substantially less than that to make the images for the separate channels [30]. A key question here is whether we can find some way to quickly image using time variable primary beams. Making corrections in the gridding is one way [31].

7.2. Correlators

Cross correlation of all antennas provides the most complete sampling of the incident wavefront and allows imaging the full field of view of the individual antennas. Current technology allows construction of GHz bandwidth correlators for arrays of 1000's of antennas at a cost of a few percent of the SKA [38]. Extrapolation of existing radio astronomy correlators suggests that a 4000 antenna, 1 GHz bandwidth correlator is reasonable by 2020 [41]. The current plan is to correlate the inner ~ 2000 antennas, and to correlate phased stations at longer baselines. The large correlator needed to correlate 1000's of antennas, and the high data rates are both seen as problems.

The early fears that correlation of all antennas was not achievable are no longer a major concern. Recent developments have solved the N^2 and connectivity problems for correlators of large-N arrays [39, 40, 27]. In contrast, the strawman design which clusters the antennas into stations with correlations between the stations of phased antennas presents significant problems:

1. The Fourier plane is less well sampled leading to an increased sidelobe level in the synthesized array beams. A high sidelobe level increases the data processing required by a factor N_{sta}, the number of antennas per station [4].

2. Station beams form the primary beam pattern for the array beams. The station beam has a sidelobe level $\sim 1/N_{sta}$. Moreover the station beam will be different for each station, depending on the antenna configuration and weighting, and will be time variable due to projection geometry, interference mitigation, antenna failures and calibration errors.

Thus, correlations between stations of phased antennas degrades both the primary beam, and the synthesized array beam. For an SKA with ~ 4000 antennas, a compromise would be ~ 64 stations each with ~ 64 antennas giving a sidelobe level $\sim 1.6\%$ in both station and array beams. It is not clear if a dynamic range 10^6 or an image fidelity 10^4 can be obtained from such array configurations. An alternative model where the signals from all antennas are correlated, is now possible [20].

Correlators can also be used to calibrate array receivers and station beams. We have a great deal of experience and success measuring cross correlations and using selfcalibration of array beams. As the cost of correlators has come down and the techniques of building large N correlators have been solved, this appears to provide a good solution for the SKA.

We don't have to cross correlate all of the receptors all of the time, but we do have to calibrate the wavefront into station beams and FPA's and this calibration varies with time, frequency, and direction in the sky. More correlated antennas, means more parameters from which we can better determine the calibration, and better imaging properties.

8. Calibration

Over a wide field of view the atmospheric calibration will vary due to non isoplanicity. For the shorter baselines in the SKA Key survey projects, all antennas are looking through the same ionosphere, but with a position dependent calibration [23]. Longer baselines may be larger than the scale of ionospheric fluctuations so that phase slopes vary across the array. The array can then be calibrated using a grid of known sources to measure the ionospheric phase as a function of position in the sky using sub-arrays which are smaller than the scale of ionospheric fluctuations. For a dense array of small diameter antennas, sub-arrays can be defined and adjusted to measure the phase for each isoplanatic patch across the entire array [24].

At centimeter wavelengths, atmospheric fluctuations are expected to be dominated by tropospheric water vapor. Refractive index fluctuations inferred from interferometer phase measurements have been observed with sizes from 1 m to 20 km, and times scales from 1s to several hours. The measured phase fluctuations have a median RMS path length $\sim$ 1 mm on a 1 km baseline and a baseline dependence $\sim$ 0.67 in agreement with a Kolmogorov 2D structure function. Water vapor fluctuations have large seasonal and diurnal variations [25, 26].

An a-priori model of the sky brightness distribution is used for calibration and imaging.

The model visibility is calculated as

$$V'_{j,k} = exp(2\pi i/\lambda \ r.s_0) \times \Sigma(I \times A \times B \times P \times G \times \exp(2\pi i/\lambda \ r.(s - s_o))),$$

where $I(s, \nu, p)$ is the model image, $A(s, \nu, p)$ is the illumination pattern (aka. primary beam response), $B(\nu)$ is the instrumental bandpass, $P(s, \nu, p)$ is the polarization calibration, and $G(time, s_0)$ is the gain. $r = (r_j - r_k)$ is the baseline vector between antennas (i,j), and s, ν, and p are the position, frequency and polarization. s_o is the phase center for each region of interest.

Each of the calibrations, A, B, P, and G are complex valued functions, which can be decomposed into antenna dependent components. The primary beam response is the product of the antenna voltage patterns for each correlation and will modulate the phase as well as the amplitude of sources away from the pointing center. For a phased array station beam, atmospheric fluctuations make the complex valued station beam time variable. Even for a clean voltage pattern with low level sidelobes from a single antenna, the complex sidelobe pattern will vary with time due to pointing errors, which cause a time varying illumination which can be calibrated during imaging [28].

One approach to these problems is to separately calibrate the data for multiple phase centers [22]. We can identify regions which have bright emission from a-priori images of the sky brightness, and use them to calibrate the data. The calibration can be improved by developing a global model of the calibration across the array as a function of time and frequency. Observations in multiple frequency bands can be used to separate the gains into tropospheric and ionospheric delays. The data streams must be delayed by a calibration interval so that the gains can be averaged and interpolated before being applied to the data stream.

Sidelobes of sources outside the regions of interest confuse the images, and must be subtracted to achieve high image fidelity. In order to subtract the a-priori model from the *uv* data stream we must determine the instrumental response across the sky. Deconvolution of wide field SKA observations is vastly more complex than a simple CLEAN, and is a major expense in the computation.

For high dynamic range observations, the calibration of the individual antennas within a station beam must be re-done in the deconvolution. We must take apart the station beam and recalibrate using selfcalibration to determine the propagation of the wavefront to individual antennas. Similar arguments apply to FPA beams. Each FPA beam has a different polarization, time and frequency response which can best be determined from the observations themselves.

9. Computing and Data Processing Model.

9.1. Stream Data Processing

Survey research is ideally suited to a stream data processing model, where calibration and imaging are implemented in close to real time in order to reduce the burden of expert data reduction on the end user, and to make best use of both telescope and human resources. Delayed calibration and analysis of the data limit the science which can be done. Variable sources, targets of opportunity, and RFI are more easily handled as the data are being acquired.

Data processing poses significant problems for arrays of 1000's of antennas. In the current data processing paradigm, digital signal processing is performed in on-line, custom designed correlator hardware. The correlations and calibration data are written to datasets and transferred to off-line computers where the calibrations are applied and images are made using data reduction packages. There is a severe mismatch between the data rates in the on-line correlator hardware and those supported by the off-line processing which can typically handle only a few percent of the data rates large correlators are capable of producing. This can be resolved by integrating the calibration and imaging into the data acquisition process [21,22].

At decimeter wavelengths there are problems with non coplanar array geometry and non isoplanicity of the atmosphere. The whole field of view must be imaged in order to remove the sidelobes of all the sources within primary beam pattern of the antenna, and a 2D FFT cannot be used with a large FOV. For high dynamic range we must subtract emission in the sidelobes of the primary beam pattern, which may have poorly determined and time variable calibration. Off-line data processing needed to deconvolve the sidelobes of sources in a large field using the current algorithms is very expensive.

9.2. Data Rates.

The total data bandwidth from the antennas is

$4\ 10^{12}\ (N/1000)\ (N_{pol}/2)\ (N_{beams})\ (B/GHz)\ (N_{bits}/8)$ bytes/s

The input bandwidth must be channelized, to provide spectral resolution, to facilitate interference rejection, and to reduce bandwidth smearing. The science and RFI requirements for a large number of frequency channels favor an FX architecture for the correlators. Excellent separation of frequency channels can be obtained using a polyphase filter.

After the frequency transform, the data bandwidth may be reduced by sampling the narrow band channels with fewer bits and by selecting appropriate bits in each frequency channel. RFI can be characterized using post correlation techniques. After the frequency transform, the data can be processed in parallel, reducing the data rate in each frequency channel by a factor N_{chan} [22].

The choice of bit width is heavily influenced by the RFI environment, local expertize, and available hardware. 16-bits may be the best choice with a high RFI environment and an IBM super computor, but may not be the best choice for the SKA in a low RFI with custom designed hardware. A polyphase filter provides an excellent way to isolate RFI into well defined narrow frequency channels. The cost of a polyphase filter scales as N_{taps} (which defines how sharp the filter edges are), and $log(N_{chan})$, the number of frequency channels. The X-correlation cost scales as $(N_{bits} \times N_{ants})^2$, so we can trade the number of correlated antennas with the number of bits if we reduce the dynamic range by using well defined narrow channels.

Sampling the correlator at the fringe rate allows us to make images over a wide field of view, including targets of interest, calibration sources, and sources whose sidelobes confuse the regions of interest. In order to correlate the signals from a siderial source anywhere in the entire sky, the data bandwidth from the correlator is:

$$N(N+1)/2 \times N_{pol} \times N_{beams} \times N_{chan} \times N_{bits} \times 2\ sdot \times D_{max}/\lambda$$

where $sdot$ is the earth rotation rate, 7.27 10^{-5} radian/s.

e.g. for $N = 1000$, $N_{chan} = 10^5$, $N_{pol} = 4$, $N_{beams} = 1$, $D_{max} = 100\ km$, $\lambda = 10\ cm$, and $N_{bits} = 2 \times 16$ (complex data), the total data bandwidth $\sim 10^{14}$ bytes/s. The data rate can be greatly reduced with more appropriate integration and sampling.

9.3. Integration at Multiple Phase Centers

For the SKA, with 12 m diameter antennas at $\lambda = 10$ cm, the primary beam $FWHM$ is only ~ 0.5 deg, and mosaics at multiple pointings, array receivers, or on-the fly mapping are required to image larger regions. We can form simultaneous images in multiple regions within the field of view by integrating the output from the correlators at multiple phase centers. The data stream from each correlator is multiplied by phase factors, $\exp(2\pi i/\lambda\ r.s_o)$, where $r = (r_j - r_k)$ is the baseline vector, and s_o is the phase center in each region of interest. Within a restricted field of view, the required sample rate is reduced to the range of fringe rates within the FOV. The data bandwidth for imaging the full primary beam $FWHM$ is:

$$N(N-1)/2 \times N_{pol} \times N_{beams} \times N_{chan} \times N_{bits} \times 2\ sdot \times D_{max}/D_{ant}$$

e.g. for $N = 1000$, $N_{chan} = 10^5$, $N_{pol} = 4$, $N_{beams} = 1$, $D_{ant} = 12\ m$, and $N_{bits} = 2 \times 16$ (complex data), the total data bandwidth $\sim\ 10^{12}$ bytes/s for 100 km baselines. The data rate per frequency channel $\sim$ 10 Mbytes/s, is within the capabilities of a modern PC for calibration and imaging [22].

10. Imaging

The imaging process is a forwards derivation of the sky brightness distribution, followed by a backwards deconvolution using the best model of the sky. This is an iterative process so the image formation does not have to image the whole region of interest, and indeed can not do so when the calibration varies across the sky. The larger computational burden is in the deconvolution process. Imaging quality is optimized by maximizing the sampling and quality of the data, and minimizing the instrumental parameters which must be determined.

Images can be made simultaneously for multiple regions within the field of view by integrating the output from the correlators at multiple phase centers centered on targets of interest, calibration sources, and sources whose sidelobes confuse the regions of interest. The regions imaged are used to update and improve the a-priori model, which becomes the final calibrated image by the time the observations are complete.

Images in different frequency channels can be processed in parallel in a distributed architecture. The images are formed from the calibrated *uv* data streams from which an a-priori source model has been subtracted, and are therefore difference images from the model image. These difference images can be used to update the model. As the observations proceed, both the model image and the calibration are improved. The process converges when the difference images approach the noise level and the model image is consistent with the *uv* data streams. Indeed, this criteria could be used to define when the observations are complete. Variable sources are detected as intermittent sources which are inconsistent with the current model. We should also accumulate a χ^2 image to help identify pixels where there are time variable sources or RFI.

We view imaging as a dynamic process which can be guided in real time by observers inspecting the convergence of the model image and the χ^2 image. As the observations proceed, the phase centers can be moved to image regions where more data are needed to define the science goals, either regions of interest, sources of confusing sidelobes, or new sources which are discovered in the imaging process. Isoplanatic patches may vary during the observations requiring different phase centers to adequately determine the calibration across the FOV. The SKA will be capable of producing data at an astonishing rate. We must include data processing for handling the data and making images in close to real time in order to keep up with the data rate. Full image processing may not be needed for all the data, but it will be important to produce images which can be easily compared (overlayed, cross-correlated) with images at other wavelengths. These images must be readily available to the investigators. Fast inspection of SKA images will enable better scheduling of future observations.

11. Operational Model for SKA surveys

Operational expenses, $\sim 10\%$ of the capital cost, are the same as annual construction costs if the SKA is built over 10 years. The long term viability of the SKA will depend on low operational costs, including maintenance and energy. Complex electronics, and cyrogenic receivers on telescopes are to be avoided where possible.

11.1. Data Transport and Distribution

The data for each antenna can be digitized and packetized, and sent to the array processing centers. The data in each packet are uniquely identified so that they can be routed to distributed, asynchronous data processing engines without ancillary information. The data packets should contain the metadata needed to calibrate and make images for multiple regions. Commercial routers can be used to distribute the data to beam formers and correlators. There may be multiple routers in the system to allocate and reuse the hardware for IF processors, beam formers, correlators, and integrators in different projects. Flexible routing also allows the data processing hardware to be upgraded, repaired, and reprogrammed with minimum interruption to array operations.

There should be a large archive to allow interpolation of calibration data, and re-analysis of stored data, e.g. when a transient event is detected.

11.2. Observing Modes

Calibration and imaging are interdependent. Our observations determine both the sky brightness distribution and the calibration. The image quality is optimized by minimizing the number of calibration parameters which must be determined from the observations.

For all-sky surveys, in many cases we can obtain the data by allowing the sky to rotate through beam patterns which are fixed w.r.t. ground radiation and ground-based RFI. Antenna pointing errors, and sidelobe patterns require fewer parameters, and are more easily deconvolved from the data.

A single dish observing mode is also required for observations of extended emission. The minimum uv-spacing sampled by the array is limited by the dish diameter. Smaller spatial frequencies must be obtained from mosaic and single dish observations.

11.3. Data Processing

Off-line data processing is time consuming and requires a level of expertize which many astronomers do not want to learn in order to do their science using radio telescopes. Delayed calibration and analysis of the data also limit the science which can be done. Variable sources, targets of opportunity, and RFI are more easily handled as the data are being acquired. The large-N design for the SKA does not fit well with of the current paradigm using custom designed correlator hardware and off-line data reduction.

The mismatch between the data rates in the on-line correlator hardware and those supported by off-line processing is resolved by integrating the calibration and imaging with the data acquisition process. Calibration and imaging can be handled with the real time feedback of the antenna gains needed for beam formers and RFI suppression [22].

12. Image Fidelity, Dynamic range, Mosaicing and FPA receivers.

Image quality is specified in the requirements matrix as a dynamic range; the noise level away from strong sources. The dynamic range is relevant in specifying the residual sidelobes level after calibration and deconvolution. Note inclusion of calibration in this definition; calibration errors and inadequate uv-coverage limit the dynamic range. On-source noise is usually specified by an image fidelity, which is particularly relevant to survey science which relies on accurate images of extended emission. The dynamic range is a function of distance from strong sources, with image fidelity as a limiting case of noise within an image of bright emission and/or absorption.

The case for mosaicing with a homogeneous array well is studied [14]. Image fidelity is severely limited by antenna pointing (illumination pattern errors), focus and aperture errors (phasing and atmospheric errors for phased array antennas). Stringent pointing and surface accuracy specifications for ALMA antennas are required to obtain an image fidelity ~ 1000. These consideration are also relevant for imaging extended structures with the SKA. The SKA dynamic range specification should reflect the dependence on angular scale and distance from bright sources.

The image fidelity is strongly dependent on the quality of the single dish observations, and it is perhaps here that FPA receivers will play their best role, enabling accurate calibration of the pointing and illumination patterns for single dish observations with multiple telescopes to decouple atmospheric variations from the radio brightness distribution.

An FPA allows simultaneous mosaicing with multiple beams, but these must be calibrated and combined, and time multiplexed for more extended areas if the FPA does not Nyquist sample the instantaneous FOV. An FPA speeds up mosaicing but a large FOV still requires stitching together multiple beams. We need to cross calibrate the different beams. This is an additional level of calibration and imaging complexity compared with observations with the same beam.

Image quality is effected by every level of beam formation. If the on-line beam formation cannot be adequately calibrated, then the beam formation must effectively be redone using expensive post processing. (Cornwell's coupled case [7]). For example, a phased array of dipole antennas with 50% grating sidelobes must be calibrated 50 times as well as a single dish with 1% sidelobes. A well designed SD and mechanical system has much to recommend it for high fidelity observations. It is a good anti-aliasing filter which suppresses sidelobes and decouples images for each pointing center.

13. Conclusions

In this study we examine the science and engineering issues involved in optimizing the SKA for survey science.

• Survey science requires low frequency, low resolution images with superb image quality, which imposes stringent requirements on the calibration and sidelobe levels at every stage of beam formation.

• The cost of data processing is very dependent on the antenna system, calibration, and science requirements. The optimal design of the SKA must consider the overall system from the science goals to the data products.

• The cost of the SKA is dominated by four major components: antennas, receivers, signal processing, and computing. Each has strong interdependencies, and must be optimized in the context of the overall science and engineering goals.

• Closer interactions between the astronomers and the engineers is essential to optimize the survey properties of the SKA. In some cases FOV can be traded for sensitivity but in many cases a large FOV is required at full sensitivity so there is no room to trade.

• SKA surveys are all-sky imaging, and for the highest dynamic range will require all-sky calibration from a global model of the sky brightness and instrumental transfer function.

• The large frequency range, from 0.1 to 25 GHz requires multiple telescope apertures to provide cost effective large apertures at low frequencies, and precision antennas at high frequencies. LNSD is a good solution above $\sim$ 1 GHz transitioning from aperture arrays to small dishes with cooled receivers. Whilst a single dish provides good attenuation of emission outside its FOV, an aperture or dipole array has large, frequency and polarization dependent, sidelobes which couple beams across the sky.

• FPA receivers provide multiple beams to reuse the telescope aperture aperture and give a wider field of view, but transfer resources from collecting area to electronics which have short lifetime and higher replacement/maintenance costs.

• Array antennas, station beam formers and FPAs require careful calibration for high dynamic range observations. For the highest dynamic range the calibration implicit in beamforming with FPA or station beams must be redone in the data analysis, which leads to a large increase in computing costs.

• The LNSD design maximizes ND for survey science. A LNSD array with single pixel receivers also maximizes the collecting area ND^2 for targeted observations. The instantaneous FOV requirement can be efficiently met above ~ 1 GHz by using a large number of small, ~ 5m, diameter antennas. Building a smaller number of larger antennas is not such a good solution since sources larger than the primary beamwidth must be mosaiced; the image fidelity is degraded by pointing errors and by the sparse *uv* coverage.

• Sources of non thermal noise may limit the capabilities of the SKA. For high dynamic range, sidelobes of sources outside the regions of interest must be subtracted or the SKA will be confusion limited. In order to achieve the sensitivity and image fidelity goals, the calibration must match the thermal noise.

• Calibration and imaging are intimately related. We use a model of the sky brightness distribution to determine the instrumental and atmospheric calibrations. A model is used to subtract sidelobes from sources outside the regions of interest. The calibration varies across the sky due to uncertainties and time variations in the primary beam, instrumental polarization and non-isoplanicity. We must measure the gain variations in the directions of sources whose sidelobes corrupt the regions of interest. The calibration can be improved by using a global model of the sky brightness and gains.

• RFI is a serious problem. Self generated RFI from high speed digital electronics on the antennas must be carefully shielded. RFI and time variable sources must be identified and measured so they can be correctly separated and subtracted from the *uv* data.

• Extrapolating the existing deconvolution algorithms for off-line data processing of large fields of view is very expensive for a large N array. There is a severe mismatch between the data rates in the on-line correlator hardware and those supported by the off-line processing. These problems can be resolved by integrating the calibration and imaging into the data acquisition process

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