



CALIM 2011: July 28

“More research required”:
a dialogue

Duncan Hall

Agenda:



- SKA₁ imaging requirements
- A framework to address R&D priorities
- What should we be focusing on?
- Next steps

DRM 1.3 (SKA₁) imaging rqrmts:



[1] System level specifications	Wording	Details, details, details ...
• Survey “On Sky” Time:	• 2 years	<ul style="list-style-type: none"> • Excludes calibration, maintenance, “inefficiencies” etc. • So elapsed time could be ~5 years
• Deep Field Integration Time:	• 1,000 hr ($\sim 3 \times 10^6$ seconds)	<ul style="list-style-type: none"> • Excludes calibration, maintenance, “inefficiencies” etc. • So elapsed time could be 3 times larger
• Fractional Instantaneous Bandwidth:	• ~ 1	• So as to perform “at least as well as the current systems” for continuum observations
• Spectral Baseline:	• Sufficiently flat to enable spectral line observations	• “bandpass does not show ripples or systematic fluctuations on scales smaller than a frequency corresponding to about 300 km s^{-1} that are larger than would be achieved by twice the thermal noise level after an integration of 1,000 hr”
• Correlator Integration Time:	• Sufficient to mitigate time-average smearing	• “does not result time-average smearing at the edge of the field of view exceeding 2%.”
• Spectral Resolution:	• Sufficient to mitigate bandwidth smearing	<ul style="list-style-type: none"> • “does not result in the bandwidth smearing at the edge of the field of view being larger than 2%.” • Doesn’t address RFI requirements

DRM 1.3 (SKA₁) imaging rqrmts:



[2] Probing Neutral IGM in EoR	Wording	Details, details, details ...
<ul style="list-style-type: none"> • Frequency range: 	<ul style="list-style-type: none"> • 50 ~ 240 MHz • [Table 8-2: 70 MHz ~ 240 MHz] • $v_{crit} = 100$ MHz 	<ul style="list-style-type: none"> • 100 MHz is the frequency for which the collecting area and SNR should be optimised
<ul style="list-style-type: none"> • Fractional Instantaneous Bandwidth: 	<ul style="list-style-type: none"> • $\Delta v/v$ of ~1 	<ul style="list-style-type: none"> • Desirable for increasing the sensitivity of the observations, foreground removal and constraining the ionosphere
<ul style="list-style-type: none"> • Frequency resolution 	<ul style="list-style-type: none"> • 100 kHz • 1 kHz 	<ul style="list-style-type: none"> • Radial (velocity) resolution • RFI, bandwidth smearing, and calibrate ionospheric effects
<ul style="list-style-type: none"> • Maximum baseline : 	<ul style="list-style-type: none"> • ~200 km outer baselines 	<ul style="list-style-type: none"> • “Accurate identification and removal of out-of-beam sources requires higher angular resolution” • “also required to reduce ionospheric effects on a large field of view”
<ul style="list-style-type: none"> • Antenna diameter: 	<ul style="list-style-type: none"> • 7m ~ 30m 	<ul style="list-style-type: none"> • “minimum field of view of 5° leads to maximum antenna diameter of 30m” • “Fields of view of less than 20° would have an imprint in the ionosphere <200 km, leading to the requirement that the antenna diameters are greater than 7m”

DRM 1.3 (SKA₁) imaging rqrmts:



[3] Galaxy evol'n via H I absorp'n	Wording	Details, details, details ...
<ul style="list-style-type: none"> • Frequency range: 	<ul style="list-style-type: none"> • 0.2 ~ 1.4 GHz 	<ul style="list-style-type: none"> • Follows directly from the redshift coverage requirement and rest frequency of H I = 1.4 GHz
<ul style="list-style-type: none"> • Frequency resolution 	<ul style="list-style-type: none"> • 5 kHz 	<ul style="list-style-type: none"> • Follows directly from the stated velocity resolution requirement at a nominal frequency of 200 MHz
<ul style="list-style-type: none"> • Imaging dynamic range: 	<ul style="list-style-type: none"> • 35 dB 	<ul style="list-style-type: none"> • Imaging strong sources could produce spectral artefacts ...
<ul style="list-style-type: none"> • Spectral dynamic range: 	<ul style="list-style-type: none"> • 43 dB or better 	<ul style="list-style-type: none"> • “imaging dynamic range (35 dB) and signal-to-noise ratio considerations (8 dB), for a final requirement of at least 43 dB”
<ul style="list-style-type: none"> • Field of view: 	<ul style="list-style-type: none"> • 4.5 deg² 	<ul style="list-style-type: none"> • Within a 4.5 deg² field of view, “WENSS source counts indicate that there will be, on average, a source of strength 1.5 Jy or stronger ... “

DRM 1.3 (SKA₁) imaging rqrmts:



[4] Probe EoR with 21cm Forest	Wording	Details, details, details ...
• Frequency range:	• 70–200 MHz	• Follows directly from the redshift coverage requirement and rest frequency of H I = 1.4 GHz
• Frequency resolution	• 200 Hz	• Follows directly from the stated velocity resolution requirement at a nominal frequency of 200 MHz
• Imaging dynamic range:	• 54 dB	• In order that any spectral artefacts from the strong source are below the level of the absorption line requires an imaging dynamic range of 54 dB
• Spectral dynamic range:	• 61 dB or better	<ul style="list-style-type: none"> • In order that any spectral artefacts from the strong source are below the level of the absorption line requires an imaging dynamic range of 54 dB • Plus signal-to-noise ratio considerations of 7 dB
• Field of view:	• 10 deg ²	• “consider a nominal field of view to be 10 deg ² at 150 MHz (z ~ 8)”

Just for fun – SKA₂ imaging rqrmts:



[7] SKA ₁ to SKA ₂ considerations	Wording	Details, details, details ...
<ul style="list-style-type: none"> • Frequency coverage 	<ul style="list-style-type: none"> • 70 MHz ~ 10+ GHz 	<ul style="list-style-type: none"> • Signatures of complex organic molecules around proto-planetary disks
<ul style="list-style-type: none"> • Dynamic range for continuum deep field: 	<ul style="list-style-type: none"> • 74 dB “capable” 	<ul style="list-style-type: none"> • the strongest source in the field of view [may be limited] to approximately 0.1 Jy. • Detecting luminous infrared galaxies (LIRGs) at redshift 7 will require a sensitivity of 4 nJy
<ul style="list-style-type: none"> • Spectral dynamic range for deep H I surveys: 	<ul style="list-style-type: none"> • 67 dB 	<ul style="list-style-type: none"> • Signal-to-noise ratios of at least 7 (8 dB) are probably required to identify emission line features • We expect, on average, one source with a flux density of order 1 Jy or stronger within the field of view, and want to detect a $5 \times 10^9 M_{\odot}$ galaxy at $z \sim 2$ (need 1.4 μJy rms) [\sim59 dB] • The total dynamic range requirement for HI survey is then $59 + 8 = 67$ dB
<ul style="list-style-type: none"> • Polarisation purity 	<ul style="list-style-type: none"> • 25 dB 	<ul style="list-style-type: none"> • Studies of cosmic magnetism. ... require Q, U, and V purity, after calibration, of at least 25 dB, (i.e., 0.5%)

Agenda:



- SKA₁ imaging requirements
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- What should we be focusing on?
- Next steps

Problem challenge: ranking



**Real need for
empirical results**

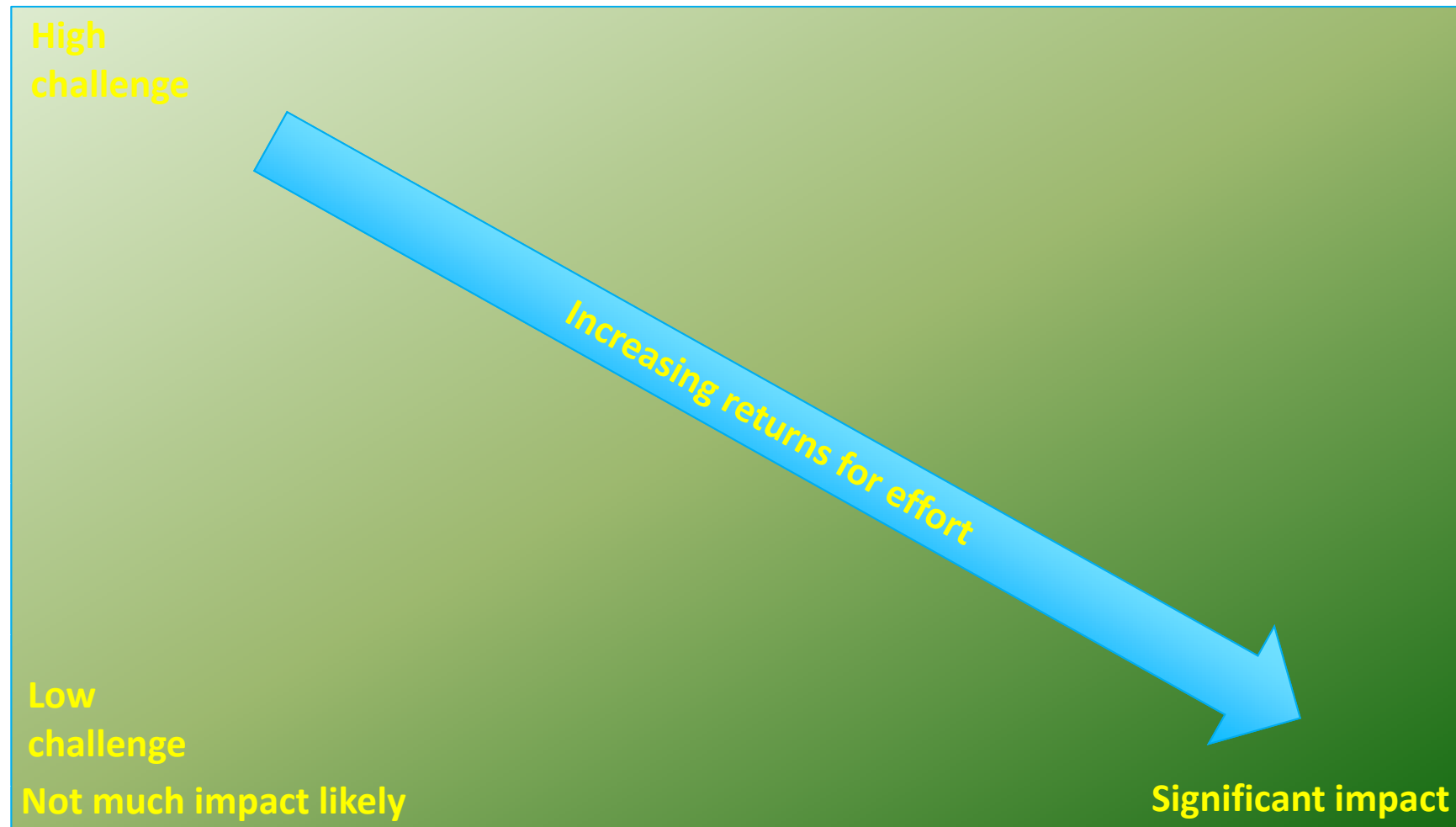
Increasing challenge

**Desk-based
simulation**

Quite a lot already known

Not a lot known

Benefits vs. effort: ranking



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[A] Required size of convolutional kernel:



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">• Baseline length and field of view: impact on <u>required size of convolutional kernel</u>	<ul style="list-style-type: none">• Standard convolutional re-sampling involves the convolution of visibility function samples (a collection of weighted Dirac delta-functions) with a constrained kernel to produce a smooth function which is sampled at the regularly spaced grid points required by an FFT algorithm• The processing scales as the number of visibility samples, and the size of the convolutional kernel• The required sizes of kernels for SKA₁ and SKA₂ have not yet been estimated, but are likely to be larger than current practice	<ul style="list-style-type: none">• The required sizes of convolutional kernels• And therefore an indication of the scale of processing required for an automated pipeline

[B] Fidelity of GSM and LSMs:



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">• Fidelity of Global Sky Model (GSM) and Local Sky Models (LSMs)	<ul style="list-style-type: none">• If the fidelities of the GSM and LSMs are such that many iterations over the observed data are required, then much greater levels of processing will be required than is currently expected	<ul style="list-style-type: none">• How much effort should be invested in GSM and LSMs?

[C] Smearing:



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">• Smearing: impact on achievable image dynamic range	<ul style="list-style-type: none">• The relationship between smearing in the uv plane and the processing required to achieve a specified image dynamic range is non-deterministic• The processing required to routinely achieve image dynamic ranges in an automated pipeline of order more than 60 dB may be much greater than current expectations.	<ul style="list-style-type: none">• How much smearing can generally be tolerated• And therefore how much effort should be put into limiting smearing – which increases the data rate into the calibration and imaging process• As opposed to how much additional processing is tolerable to deconvolve smearing

[D] Receptor pointing errors:



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">• Calibration of <u>receptor pointing errors</u>	<ul style="list-style-type: none">• The relationship between calibration to correct for receptor pointing error and achieving high dynamic range is instrument specific• Systematic errors in source or beam models prevent pointing calibration accuracy at the level required by the SKA	<ul style="list-style-type: none">• How much pointing error is tolerable for SKA₁ and SKA₂

[E] Modelling bright sources outside the primary beam:



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">• <u>Modelling</u> the effects of <u>bright sources outside the primary beam</u>	<ul style="list-style-type: none">• Side lobes well outside the primary beam need to be accurately modelled to take into account artifacts from bright sources that happen to lie within the side lobes• We need to know how well modelling artifacts from bright sources works for arrays under construction	<ul style="list-style-type: none">• How much effort should be put into modelling side lobes and implementing those models in calibration and imaging algorithms

[F] Characterisation of primary beam:



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">• <u>Parameterisation of primary beam responses for calibration purposes</u>	<ul style="list-style-type: none">• Smirnov: “Know Thy Beams”	<ul style="list-style-type: none">• How much effort should be put into characterising primary beam response

[G] Stability of side lobe responses:



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">• <u>Stability of side lobe responses</u>	<ul style="list-style-type: none">• The array uv coverage has to be very complete and side lobes very stable• The point spread function level of side lobes must be <0.01% (derived from the square root of the maximum noise to achieve the required dynamic range of order 60 dB)• If the point spread function level of side lobes is variable, then much greater levels of processing will be required than is currently expected	<ul style="list-style-type: none">• How much effort should be put into modelling the variability of side lobe responses and implementing those models in calibration and imaging algorithms

[H] Relativistic effects:



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">• Consideration of <u>relativistic effects</u> in high dynamic range imaging	<ul style="list-style-type: none">• To achieve high dynamic range – i.e. greater than 60 dB – we will have to consider relativistic effects, as well as tectonic movement within 8 hour periods over long baselines.• If relativistic effects must be considered, then greater levels of processing will be required than is currently expected	<ul style="list-style-type: none">• How much effort should be put into modelling the relativistic effects and implementing those models in calibration and imaging algorithms

[I] Non-uniqueness of solutions:



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">• <u>Non-uniqueness of solutions</u> found to automated model fitting	<ul style="list-style-type: none">• The Jones matrix solutions are not unique: there is unavoidable ambiguity in their solution set• Automated software solvers will simply pick one of the possible solutions – and there may be other more reasonable solutions	<ul style="list-style-type: none">• How much we should worry about this

[J] Sparse array configuration:



Short Description	Why is research required?	What might research resolve?
• <u>Sparse array configuration</u>	• The sparse array configuration specification is not sufficiently mature to guarantee that the number of stations, their diameter and the number of beams may change	• How much we should worry about this

[K] Packing density of the core:



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">• Compromise on the <u>packing density of the telescope core</u>	<ul style="list-style-type: none">• The requirements for imaging oppose requirements for non-imaging processing• This means that the close packing requirement specified in the DRM is a compromise with a comparatively large core diameter of 5km• Beamforming across this diameter results in very small diameter pencil beams with implications on the data rates and required processing power for a given survey speed	<ul style="list-style-type: none">• How much we should worry about this

[L] Full-field gain self-calibration:



Short Description	Why is research required?	What might research resolve?
• <u>Full-field gain self-calibration</u>	• Full-field gain self-calibration may prove to be infeasible at mid to high frequencies with weaker sources and smaller fields-of-view	• How much we should worry about this

[M] General parameterised models:



Short Description	Why is research required?	What might research resolve?
• General , position-dependent <u>parameterised models</u>	• Development of more general, parameterised models may be needed to address non-isoplanatism at the level of SKA calibration and imaging goals	• How much we should worry about this

[N] Non-closing errors:



Short Description	Why is research required?	What might research resolve?
• <u>Non-closing errors</u>	• Non-closing errors may provide a ceiling to achievable SKA imaging dynamic range, and this is beneath the target SKA requirements	• How much we should worry about this

[O] 'Estimation noise':



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">• 'Estimation noise' restricts achievable dynamic range	<ul style="list-style-type: none">• Estimation noise is the contribution to the noise floor caused by the fact that estimation of calibration parameters extracts information from the data that can no longer be used to reconstruct the source image• At some point, too much information is lost to calibration to achieve the desired dynamic range• May provide a ceiling to achievable SKA imaging dynamic range, and this is beneath the target SKA requirements	<ul style="list-style-type: none">• How much we should worry about this

[P] Time-varying Direction Dependent Effects:



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">• Inability to deal with <u>Time-varying Direction Dependent Effects</u> (TDDEs)	<ul style="list-style-type: none">• Current imaging software may not be able to address TDDEs• May provide a ceiling to achievable SKA imaging dynamic range, and this is beneath the target SKA requirements	<ul style="list-style-type: none">• How much we should worry about this

[Q] Fundamental limits:



Short Description	Why is research required?	What might research resolve?
<ul style="list-style-type: none">•Some things can never be “calibrated away”	<ul style="list-style-type: none">•Carozzi’s Intrinsic Cross Polarisation (IXR) ratio characterizes polarimetric calibratability•Analogous IXR for full RIME under development<ul style="list-style-type: none">•“Bad telescope design can never be replaced by clever software”•“Computational muscle is not the end all of Callm: it's applying it where/when it makes a difference”•May provide a ceiling to achievable SKA imaging dynamic range, and this is beneath the target SKA requirements	<ul style="list-style-type: none">•How much we should worry about this

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Workshop suggestions:



Short Description	Why is research required?
<ul style="list-style-type: none"> • Deconvolution algorithms and errors [can be done “soon”] 	<ul style="list-style-type: none"> • Represents a significant proportion of processing load which may limit scalability to SKA • Limits imaging fidelity
<ul style="list-style-type: none"> • Imaging quality for extended sources [can be done “soon”] 	<ul style="list-style-type: none"> • Currently a difficult question to answer, for example what is required to observe Epoch of Reionisation • Need some experiences from precursors and pathfinders
<ul style="list-style-type: none"> • Mitigating antenna sidelobes [can be done “soon”] 	<ul style="list-style-type: none"> • In addition, “how well do we know the primary beam” – required to achieve the dynamic ranges SKA aspires to • ASKAP will experiment with switching sky de-rotation on and off
<ul style="list-style-type: none"> • Focus on system performance 	<ul style="list-style-type: none"> • We don’t really know “how to get from A to B” in terms of modelling integrated system performance
<ul style="list-style-type: none"> • Hardware-software tradeoffs 	<ul style="list-style-type: none"> • We already know that high frequencies put tighter constraints on antenna design (e.g. ALMA) • An antenna designed for high frequencies should work better at lower frequencies
<ul style="list-style-type: none"> • Error budget 	<ul style="list-style-type: none"> • For example system level error budget engineering typically done for optical systems, e.g. for LSST • ALMA project carried out an error budget analysis – but it wasn’t integrated end to end, and it should have been done earlier
<ul style="list-style-type: none"> • Fundamental limits 	<ul style="list-style-type: none"> • Fundamental limits are intrinsically “hard limits”; as opposed to ... • Computational challenges – potentially can be overcome with time, technology and algorithm development
<ul style="list-style-type: none"> • Precise definitions of metrics 	<ul style="list-style-type: none"> • For example image fidelity, various measures of polarisation purity – needs to be done earlier rather than later • DRM really needs a lot more work to define exactly what the criteria for engineering design should be • Verification criteria should be incorporated in the definitions
<ul style="list-style-type: none"> • IXR (Intrinsic Cross Polarization) metric and extensions 	<ul style="list-style-type: none"> • Polarisation requirements could easily be got wrong – SKA₁ polarisation purity metric was “plucked out of the air” • An example of both precise definition of a metric and highlighting fundamental limits to imaging fidelity
<ul style="list-style-type: none"> • ALMA definition of image fidelity 	<ul style="list-style-type: none"> • Various confusing definitions currently in use; rather than “Dynamic Range” perhaps better to use “Effective Noise” • ALMA struggling with how to make its “image fidelity” metric testable – ALMA’s work could be shared
<ul style="list-style-type: none"> • More spectral line cases 	<ul style="list-style-type: none"> • Realisation that SKA₁ as currently defined in DRM 1.3 is not an HI telescope – an original motivator for the SKA