SUMMARY OF THE SECOND SKA1-LOW CALIBRATION CONSULTATION WORKSHOP

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LIST OF ABBREVIATIONS

BD	SKA1 Baseline Design
EMI	Electromagnetic Interference
EoR	Epoch of Reionisation
FWHM	Full Width Half Maximum
HPSO	High Priority Science Objective
ISW	Integrated Sachs Wolfe effect
NIP	Non-image Processing
PSF	Point Spread Function
RFI	Radio Frequency Interference
RMS	Root Mean Square
SEFD	System Equivalent Flux Density
SKA	Square Kilometre Array
SKAO	SKA Organisation
SCI_REQ-	Specification number in this document

1 Introduction

1.1 Purpose of the document

On December 1, 2015 the SKAO hosted the second of the SKA1-LOW calibration consultation workshops. The consultation was attended in person by Robert Braun, Peter Dewdney, Mike Jones, Maria Grazia Labate, Benjamin Mort, Nima Razavi, Jan Geralt Bij de Vaate, Andre Van Es, Jeff Wagg, Mark Waterson, Stefan Wijnholds and Kristian Zarb Adami. External participants connecting through vidyo were Rosie Bolton, Eloy de Lera Acedo, Natasha Hurley-Walker, Vibor Jelic, Leon Koopmans, Daniel Mitchell and Catherine Trott. Richard Hills also participated as an observer on behalf of the SEAC. Prior to the calibration consultation, presentations were given by Kris Zarb Adami on the LFAA architecture and Nima Razavi on the analysis of far-sidelobe source noise (FSSN). The consultation itself consisted of presentations and discussion around the topic of a proposed SKA1-LOW configuration and the risks associated with baselining the station locations of such a configuration with respect to calibration and scientific return. This document is a summary of these presentations and the discussion surrounding them.

1.2 Scope of the document

This document is intended as a summary of the SKA1 LOW calibration consultation that took place in December, 2015.

2 References

2.1 Reference documents

The following documents are referenced in this document. In the event of conflict between the contents of the referenced documents and this document, **this document** shall take precedence.

[RD1] SKA1 LOW configuration memo v4A, 2015, SKAO science team et al.

[RD2] SKA-SCI-PRI-002-AppendixA, SKA1 Science Priority Outcomes

[RD3] SKA1 Science Book

[RD4] SKA-XXXXXXXXXXXXXXXX, SKA Phase 1 Science (Level 0) Requirements

[RD5] SKA-XXXXXXXXXXXXXXXX, SKA Baseline Design v 1

[RD6] SKA-XXXXXXXXXXXXXXXX, SKA1 Configurations

[RD7] Mellema, G. et al. 2012, European SKA EoR SWG White Paper

[RD8] Wijnholds, S. and Bregman, J. 2014, Calibratability by Design for SKA's LFAA

[RD9] Trott, C. 2015, "Impact on EoR Power Spectrum of Calibration of Ionospheric Parameters for SKA1-LOW", 25/09/2015

[RD10] SKA-TEL-INAU-0000042, Draft Cost Report

[RD11] Braun, R. 2013, A&A 551, 91, "Understanding synthesis imaging dynamic range"

[RD12] Yatawatta, S., 2013, LOFAR far sidelobe beam gain fluctuations.

[RD13] Wijnholds, S. and Bregman, J., 2015, LFAA Configuration considerations for the inner area of SKA-LOW

[RD14] SKA1 Imaging Performance memo.

[RD15] Intema, H. et al. 2011, Deep low-frequency radio observations of the NOAO Boötes field. I. Data reduction and catalog construction.

[RD16] Greig, B., Mesinger, A., Koopmans, L., 2015, Optimal core baseline design and observing strategy for probing the astrophysics of reionization with the SKA

3 SKA1-LOW calibration consultation: background

The second SKA1-LOW calibration consultation was held within the context that a layout for the SKA1-LOW array is required with high priority. This is driven by the forthcoming heritage and environmental site surveys within the Boolardy footprint and the updated cost assessments that Infra-AUS, LFAA and SaDT are expected to prepare for the system architecture review in Q1 of 2016. As such, a consultation was requested with expert members of the low frequency SKA community in order to assess the possible risks associated with moving forward with the layout of stations presented in [RD1] (hereafter referred to as configuration V4A). The participants of this workshop were then asked to consider questions related to the expected scientific performance and calibratibility of this array layout, where the latter focused on calibration of the ionosphere and EoR/CD foregrounds.
The questions were:

- Ionospheric calibration
    1. To what extent and over what ranges can we trade SNR to the number of ionospheric pierce points?
    2. For a given number of pierce points, what level of complexity of 2-D phase structure can we represent across the field?
    3. How often does the ionosphere have residual phase structure greater than a 'useful amount'?
    4. What is the minimum amount of collecting area in the outer array needed to calibrate the ionosphere adequately, given that high brightness-temperature sensitivity in the core is essential?
    5. Can we reliably make measurements with the outer array, and reconstruct the phase screen over the core?
    6. To what extent can observations at frequencies higher than ~150 MHz be used to model/predict the phase-screen at frequencies down to ~50 MHz, give the λ^2 dependence?
    7. Is a single-layer model for the ionosphere sufficient for calibration?

- Foreground subtraction
    1. What is the ideal ratio of collecting area in the core to that in the outer array?
    2. How large must a super-station be to get far-sidelobe levels low enough?
    3. To what extent does the number of stations vs station size affect far-out side-lobes? (quality of synthesised beam vs sidelobes of station beam).

Following the independent assessments of the V4A configuration's ability to address these calibration issues, the participants were encouraged to identify any remaining risks that would be associated with moving forward with this layout of ~33m diameter stations.

3.1 Summary of V4A configuration

The science prioritization process carried out in 2014 by the science working groups in collaboration with the SKAO science team and an ad-hoc science review panel resulted in a list of thirteen high priority science objectives [RD2]. These are enabled by the full range of frequencies covered by the two SKA1 telescopes, while four of these would require the frequency coverage of SKA1 LOW from 50 to ~350 MHz. The primary science objectives for SKA1 LOW involve imaging and power spectrum measurements of 21cm brightness temperature fluctuations associated with the intergalactic medium in the early Universe, along with surveys and timing of pulsars at frequencies below 350 MHz. These science cases impose different yet somewhat complementary constraints on the SKA1-LOW array configuration as summarized in [RD1]. The science objectives benefit from having a compact, high filling factor within the array core to provide good surface brightness sensitivity.

Based on the scientific objectives, the main constraints that should be considered in the design of the SKA1 LOW configuration are ([RD1]):

1. A high filling factor, both in the core as well as at the station level over the primary frequency range of 100 to 200 MHz (corresponding to the frequency range of the redshifted 21cm line during the expected EoR),
2. A field of view that is larger than ~4 square degrees for EoR imaging and 16 square degrees for power spectrum measurements during the EoR and CD (between 50 and 200 MHz),
3. the ability to provide excellent direction dependent gain calibrations,
4. the ability to calibrate for the ionosphere,
5. and high sensitivity as well as good *uv* coverage for angular scales between 10 and ~1000 arcseconds.

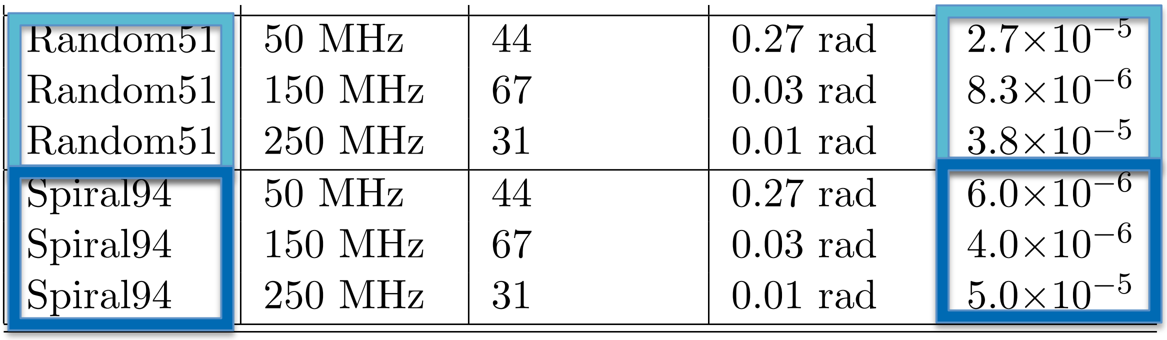
Finally, the array should also satisfy the more practical constraints related to ease of maintenance and low infrastructure costs.

The proposed V4A configuration has been designed with the aforementioned constraints in mind. The compact core has roughly 40% of the total collecting area, with the density of collecting area decreasing logarithmically beyond that out to the maximum radius of ~35 km. This configuration also adopts the concept of a flexible station definition, allowing for the possibility of beamforming over ~10, ~30 or ~90m diameter stations. For the purposes of the calibration consultation, participants were asked to consider the calibratibility of the 33m diameter station layout. Further work is needed to define the optimal layout and size of an individual station.

4 Assessments of the V4A configuration

4.1 Ionospheric calibration

The ionosphere is one of the primary limitations to observing at frequencies below 350 MHz, resulting in phase fluctuations across a wide range of physical scales. Early analysis by [RD9] compared the ability for V4A with other proposed configurations to make observations of the EoR power spectrum of 21cm brightness temperature fluctuations given the inherent ability of each array to estimate ionospheric phase parameters. The ionosphere is modelled using a cosine basis function and then a Fisher Information Matrix is computed to determine the Cramer-Rao Bounds (CRBs) on the parameter estimates for an optimal, unbiased estimator. These CRBs are propagated into the model visibilities for the array of stations in each of the proposed configurations. It is then possible to compute the precision with which a particular configuration is able to measure the amplitude of the ionospheric waves in the model. Figure 1 shows the parameter estimate precision for the V4A configuration ('Spiral94') compared to a configuration with a uniform distribution of stations in the outer halo. This analysis suggests that the V4A layout with the extra sensitivity of the remote 'super stations' would be very good for ionospheric calibration. It was further suggested that some of the collecting area from the remote stations might be moved into the core without a major impact on the ability to calibrate the ionosphere, and this should be analysed further.



Random51	50 MHz	44	0.27 rad	2.7×10^{-5}
Random51	150 MHz	67	0.03 rad	8.3×10^{-6}
Random51	250 MHz	31	0.01 rad	3.8×10^{-5}
Spiral94	50 MHz	44	0.27 rad	6.0×10^{-6}
Spiral94	150 MHz	67	0.03 rad	4.0×10^{-6}
Spiral94	250 MHz	31	0.01 rad	5.0×10^{-5}

Figure 1: Comparison of the ionospheric wave amplitude estimation precision using two proposed SKA1-LOW configurations (Trott 2015). Spiral94 is the V4A configuration discussed in the text.

During the configuration consultation, Stefan Wijnholds presented an analysis of the calibratibility of the V4A configuration, looking specifically at the questions of whether it would be possible to detect enough calibrators with sufficient signal-to-noise to measure pierce points from which one could characterize the ionospheric wave front. During the first calibration consultation meeting, he showed that 800 pierce points are required to characterize the ionosphere, meaning that 15 sources should be detected at each of the 55 remote station locations in the V4A configuration. For the ~33m diameter stations, assuming the 150 MHz source counts of [RD15] the field of view would enable the detection of 10 bright sources within the primary beam, and 5 more outside the field attenuated by 20dB. The analysis suggests that there would be more than enough calibrators inside the field of view to achieve the required number of pierce points.

Stefan also presented an analysis of the minimum station diameter required to adequately calibrate the ionosphere. Assuming a 15 m diameter station, the field of view extends beyond the array footprint at an assumed altitude of 400 km for the ionosphere. This would result in reduced direction diversity towards the edges of the field of view, which could in turn reduce the quality of tomographic reconstruction. The question of optimal station diameter for ionospheric calibration was left open, and should be analysed with high priority in the coming months.

Based on experience with LOFAR EoR observations, Leon Koopmans points out that the short baselines (less than ~5km) decorrelate rapidly in time (~10 seconds) and direction (~10 arcminutes). This scintillation is not expected to cause a problem for observations with the V4A configuration in the EoR window. The noise will be frequency coherent, and therefore can be removed along with the EoR foregrounds. Based on their experience, the ionosphere is sufficiently stable for EoR observations ~80% of the time. Similar studies should be conducted for the MRO site. Based on the analysis presented at the consultation, the V4A configuration was deemed to be excellent fro ionospheric calibration.

4.2 EoR/CD foreground characterization

Along with the ionosphere, one of the major calibration challenges faced by all present and future EoR/CD experiments is dealing with the diffuse galactic and extragalactic foregrounds. The continuum foreground emission can be three to four orders of magnitude brighter than the intrinsic 21cm fluctuation signal from the early Universe. Excision of this signal can accomplished by modelling the smooth spectral signature of the foregrounds, but also requires sufficiently long baselines to resolve the extragalactic sources which have source structure on scales of ~200 arcseconds down to below 10 arcseconds. This constraint motivates the maximum baseline length of ~70 km adopted for configuration V4A, while the ability to model these sources requires good sampling of the *uv* plane.

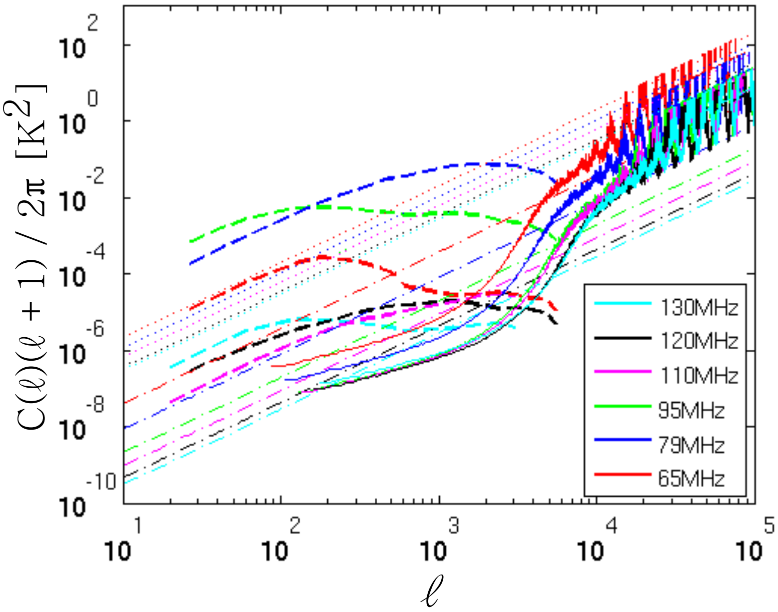


Figure 2 - Predicted power spectrum of EoR/CD 21cm brightness temperature fluctuations measured at different redshifts (long-dashed lines). The solid lines show the expected thermal sensitivity of a nominal (pre-rebaselining) SKA1-LOW configuration. The dotted lines show the residual contribution to the noise from sources outside the field of view if significant antenna level gain errors are present (David Sinclair, PhD thesis 2015).

During the calibration consultation, presentations were given by Mike Jones and Stefan Wijnholds on the impact of the distribution of SKA1-LOW remote stations on the ability to characterize and remove EoR/CD foregrounds. Mike Jones presented an analysis of pre-rebaselining SKA1-LOW configurations, and the impact of un-calibrated antenna level gain errors on ones ability to model and subtract sources outside the field of view. The predicted power spectrum of 21cm EoR fluctuations at different frequencies is plotted in Figure 2, compared to the signal produced by residual source noise due to poorly subtracted sources outside the field of view when 10% gain errors on each antenna are included. This noise can be brought down through further foreground modelling and subtraction in the spectral domain. It was recommended that future work be done to determine how much residual power can be present following the initial source subtraction, and also to check the dependence of this noise on the assumed source counts. The models adopted for this analysis extrapolate the deep 150 MHz source counts of [RD15]. Leon Koopmans indicated that even with the sparse *uv* sampling of the LOFAR array, which is far less complete than that of the V4A configuration, the EoR team is already able to remove the noise contribution from sources outside the field of view to levels lower than those predicted by this analysis. One interpretation of this is that the LOFAR station beam gain errors are actually much lower than what has been assumed for the analysis.

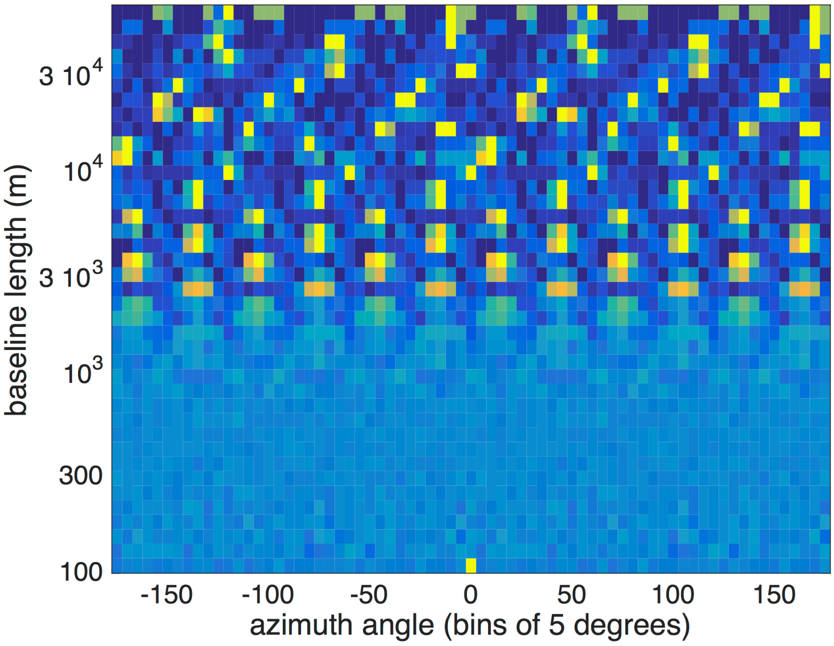


Figure 3 - Azimuthal dependence of the instantaneous uv sample density as a function of baseline length for configuration V4A.

It was pointed out by Stefan that the spectral approach adopted for the LOFAR EoR data analysis requires that the PSF be identical between frequency bins or channels. This is possible only if the *uv* coverage is complete. An open question is the baseline length range over which this must be true. It was shown that after a six hour track, the *uv* coverage of V4A is complete on baselines ranging from 35 to 500, and close to complete out to nearly 10 km radius. Figure 3 shows the azimuthal dependence of the instantaneous uv sampling. Further analysis by Rosie Bolton of the *uv* coverage within the core reveals the very azimuthally smooth nature of the sampling enabled by the V4A configuration (Figure 4). In general it was felt that the azimuthal smoothness of the uv coverage provided by the V4A configuration is very good given the spiral layout, which has been chosen to minimize the costs of infrastructure and SaDT.

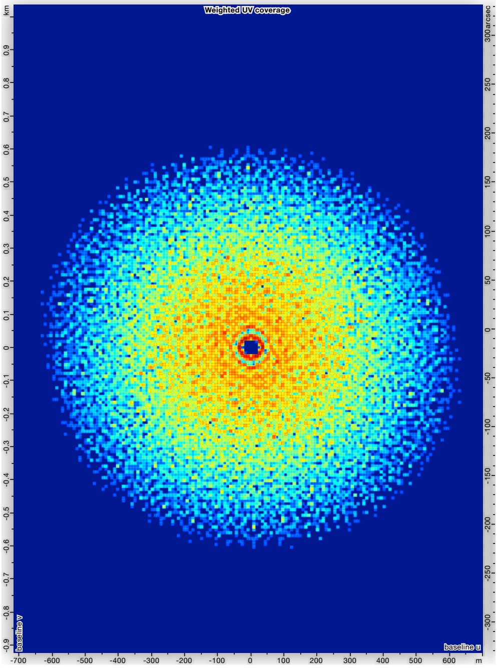


Figure 4 – Density of u versus v sampling of the 4VA configuration, zoomed in to focus on the core region.

4.3 Sensitivity to 21cm brightness temperature fluctuations

After dealing with calibration of the ionosphere and EoR/CD foregrounds, the SKA1-LOW array should be optimized for sensitivity on the scales relevant for the EoR/CD signal. As discussed in [RD1] and [RD7], the configuration constraints imposed by EoR/CD power spectrum measurements (50 to 200 MHz) are slightly different than those of the EoR imaging (100 to 200 MHz) science objective. For EoR imaging, simulations predict that the peak 21 cm brightness temperature signal could be 10 mK on scales of 1 to 10 arcminutes in frequency channels of 1 MHz. The power spectrum of 21 cm brightness temperature fluctuations is expected to be measurable over much larger degree angular scales. Both science objectives require a high filling factor of stations within the central ~1km diameter core.

In his calibration consultation presentation, Leon Koopmans points out that one would also like to maximize the field of view per station in order to minimize sample variance. He gave an overview of the benefits for EoR/CD power spectrum measurements that could be achieved by decreasing the station size within the compact core ([RD16]), however this is likely to make calibration more challenging and would increase the SDP processing load. [RD16] compare the V4A configuration sensitivity on the angular scales of interest for EoR/CD power spectrum measurements to that of the proposed configurations with smaller stations (Figure 5). The power spectrum sensitivity of V4A is less than that of an array of smaller stations for values of k [Mpc^{-1}] larger than ~0.5, unless the concept of 10m diameter 'sub-stations' as described in [RD1] is adopted. On larger angular scales, the difference between these configurations is insignificant with respect to the expected 21cm EoR signal strength.

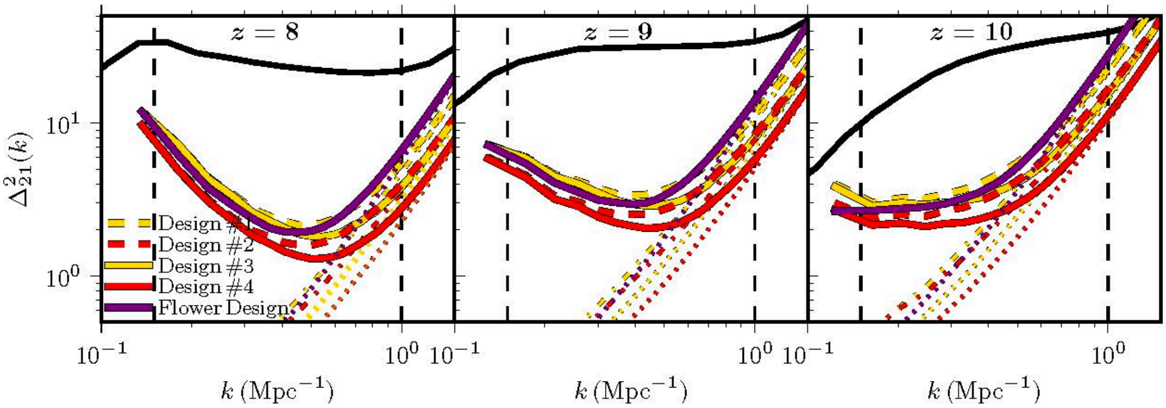


Figure 5 - The 21cm brightness temperature sensitivity as a function of inverse physical scale of the V4A configuration ('Flower design') compared to that of the predicted EoR signal strength (Greig et al. 2015).

Given the comparisons presented in [RD16], the V4A configuration with ~33m diameter stations is deemed to provide excellent sensitivity on the angular scales required for EoR/CD power spectrum and imaging studies. An open question that came up during the consultation was whether we could afford to move collecting area from remote stations back into the core to improve the EoR/CD sensitivity. Leon Koopmans indicates that the ideal ratio of halo-to-core collecting area is one that would allow >5-sigma detections of 0.5 to 1 Jy sources over the full 50 to 200 MHz range in less than 10 seconds of integration. The V4A configuration already has sufficient sensitivity outside of the core to achieve this.

5 Summary and recommendations

Following the calibration consultation, the members of the LOW-TT met to discuss whether the workshop had revealed any major risks associated with moving forward with adopting the SKA1-LOW station positions proposed in V4A. There was general agreement that any changes to the proposed station locations outside of the core would be unlikely to improve the imaging capabilities of the array. A re-emerging theme of the workshop was the possibility of bringing collecting area into the core from the outer halo (i.e. moving one station in from each of the remote locations). Such a change would increase the sensitivity for EoR/CD studies and the survey speed for the pulsar science objectives.

Although the LOW TT members did agree that the level of risk associated with adopting the V4A locations was low enough to proceed, it was acknowledged that more work by a resolution team is needed to address the question of the optimal station diameter for SKA1-LOW, in particular with respect to trade offs between scientific return and the reduction of far-sidelobe source noise. Furthermore, it was decided that another resolution team should conduct an in-depth analysis of the halo-to-core collecting area ratio, taking into consideration the implication of bringing some stations into the core region from the remote locations. As stated above, such a change would involve bringing collecting area in from each of the remote locations, rather than eliminating entire groups of stations. This work should incorporate simulations that include EoR and foreground input models and realistic station beam models for the V4A layout. In spite of these open issues, it was deemed that very little risk is associated with baselining of the V4A configuration of ~33m diameter stations and moving ahead with the planned survey work.