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Objectives for a Proposed SKA1-Low Station-Configuration Workshop

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The purpose of the workshop is to discuss options for the antenna configuration of individual outer stations in SKA1-low as well as the detailed antenna configuration within a radius of 1700 m (see the previous outcome document 'SKA1-low Configuration Coordinates')[1]. The outcome will be a sufficiently detailed description of the configurations of the antennas in outer stations and stations within the core[2] to complete the design of the balance of the SKA1-low system.

To remain focussed only the following three main science areas will be considered:

1. EoR/CD (power spectrum and deep line imaging),
2. Pulsar search and timing,
3. Standard imaging.

Because of the urgency of settling on a station and core design, we will sharpen the decision-making by discussing a few discrete options, given the constraint of a defined overall array configuration that resulted from the consultation meeting on Dec. 1, 2015. These are broadly based on 'SKA1-low Configuration, v4A'[3]. We define three possible configuration for 'entities' that can be beamformed:

1. Station: One array of antenna elements arranged within a fixed diameter;
2. Station + superstation: Similar to item 1, except that the entire superstation (aggregation of stations) can be beamformed in addition to each station;
3. Superstation + station + substation: Similar to item 2, except that a station can also be sub-divided in smaller arrays called sub-stations.

Questions to be answered at the Workshop

In this context, it is important to frame the discussion using a few crisp questions that will lead to a well-defined result. Questions to be answered related to each of the high-priority science areas:

1. What is the ideal station diameter if only one can be chosen (option 1).
    - Single baseline signal-to-noise on calibration.
    - In the EoR white paper by Mellema et al. (2013)[4], the recommended station diameter was based on minimum FoV size, which primarily emphasises power spectrum observations.
2. What is the scientific argument for multiple station sizes?
    - One station size cannot work for all of the main science uses (see above). Why not?
3. What is the minimum acceptable ratio of collecting area in the core to outer stations?
    - Station size and core size are linked for a fixed number of available antennas. Increased outer-station size implies less area in the core.

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[1] 'SKA1-low Configuration Coordinates', P. Dewdney, 2015-12-16. Note that this provides some flexibility of in the areas occupied by the stations and by the core, but not a great deal of flexibility. This has now been adopted. Changes will require a well-justified ECP.

[2] In this document, the 'core' refers to the area within a radius of 1700 m, which was undefined in the previous document.

[3] SKAO Science Team, 2015-10-28, a discussion document.

[4] G. Mellema, et. al, "Reionization and the Cosmic Dawn with the Square Kilometre Array", arXiv:1210.0197v2 [astro-ph.CO], 24 Mar 2013.

4. Must all stations antenna configurations for a given observation be identical?
    - For imaging this would normally be considered a given.
    - Are there cases in which outer stations with smaller/larger FoV would be used to calibrate a core containing stations of a different diameter?
5. If there are three station diameters allowed (sub-stations, stations and super-stations), which of the above scientific areas will benefit and how? What are the ideal superstation, station and substation sizes?
    - Superstations will reduce the instantaneous field-of-view but provide greater control of station side-lobes.
    - If substations are allowed, it is unlikely to be possible to correlate them all (because of the large number).
6. What are the technical impediments to multiple station diameters?
    - Multiple station diameters in the spiral arms may require a more complex beam-former.
7. What are the technical impediments to building and using sub-stations or superstations?
    - If substations are allowed, it is unlikely to be possible to correlate them all (because of the large number).
8. What is the argument for/against ‘physical tapering’?
9. What is the ideal density of antennas in a station and the associated sparse-dense transition frequency?
10. What would be the cost/benefit of a ‘sea of antennas’ approach for a superstation, in which the stations and substations are formed virtually through the beamforming process?
    - Flexibility. Potentially permit multiple station sizes.
    - Probably result in a loss of collecting area, since some antennas would not be used or weighted down.

Considerations and Issues

Imaging Capability: This general capability is both the most difficult (‘pushes’ system design) and the most scientifically important.

- For EoR/CD, discovering the power spectrum will be very significant if not previously discovered by other telescopes or experiments, but the investment in SKA1-low is really justified by 3-D spectral-line imaging.
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- For Standard imaging (continuum and spectral line), imaging capability is self-evident. Figure 1 illustrates that except for very long integration times, SKA1-low continuum surveys are not seriously impacted by confusion noise down to a frequency of ~110 MHz. (Note, of course it will never be confusion limited for narrow spectral line observations).

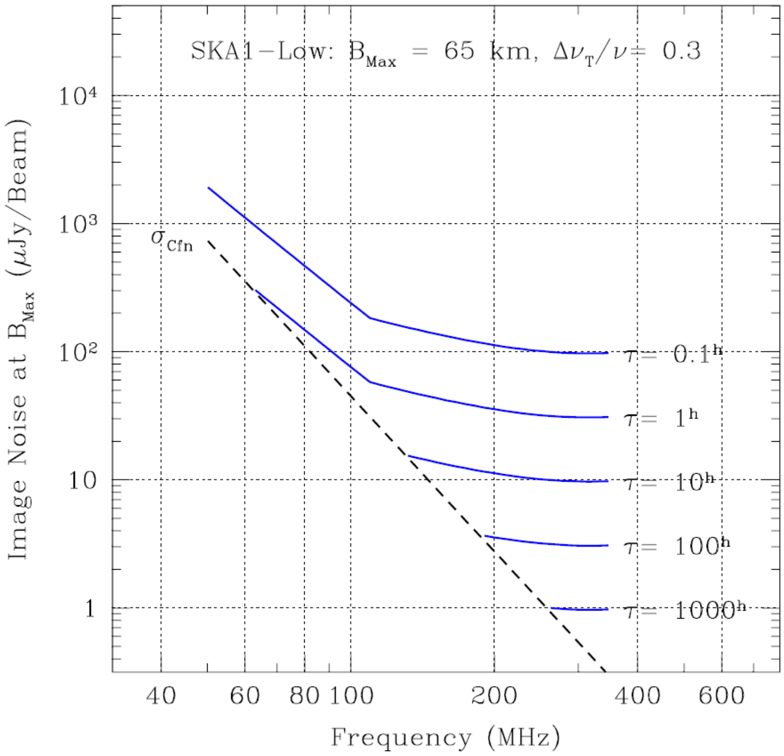

Figure 1: SKA1-low continuum confusion limits for various integration times over frequency.

The following are important factors in the station design:

- Sufficient diameter in wavelengths to reduce far-out sidelobes to an acceptable level.
- The acceptable level of near-in sidelobes.
- Sufficient collecting area for on-sky calibration (self-calibration of offset calibration).
- Smooth spatial response over the field-of-view in a single beam or in a mosaic of beams.
- Sufficient field-of-view for EoR/CD imaging.
- Polarisation response that can be accurately modelled and/or measured.
- The sparse-dense transition (see below).
- The signal-to-noise ratio for sources that aid in the characterisation of the ionospheric phase-screen.
- The fixed total number of antenna elements has an impact on station diameter: if there are too many antenna elements in each station, the number of stations will be too small.

Some of these factors interact strongly with the array configuration and others affect sensitivity, correlations and analysis. The sparse dense transition frequency has a wide-ranging impact. A complex series of trade-offs has led to a choice of the sparse-dense transition:

- Defined as the frequency at which the A_e per element is equal to the packing density.
- Antennas that are too wide will have to be spaced far apart within a station, which in turn will generate ‘grating lobes’ (or similar) at high frequencies.
- The low-frequency response will be compromised if the low-frequency ‘dipoles’ on the antenna elements are too short (in wavelengths).
- The sparse-dense transition should be at the lowest frequency possible (to extend the range where collecting area goes as λ^2).
- On the other hand, the sparse-dense transition should be as high as possible, since the entire part of the frequency range that is in the sparse regime suffers reduced brightness sensitivity.
- The sky noise spectrum is increasing rapidly at low frequencies.

Ionospheric Calibration and Foreground Source Subtraction (EoR/CD)

These were discussed in the meeting on Dec 1, 2015. The outcome for ionospheric calibration was that there is a sufficient number of ionospheric 'pierce points' with the currently adopted configuration of outer antennas.

For foreground source subtraction, it is important to provide sufficient u-v coverage to enable reliable subtraction.

Default Proposal for Station Configuration

The discussion at the meeting will need to centre on something specific. Table 1 shows the proposed default under V4D (blue shading), which will be adopted if better proposals do not arise at or before the meeting.

Table 1: Properties of SKA1-low Station Configurations

	BD - RBS	V4A	V4D
Total number of antennas	131072	162432	131072
Antennas per station	256	288	256
Number of stations	1	6	6
Number of sub-stations	N/A	6	N/A
Number of outer superstation/stations	48 stn's	36 s-stn's	36 s-stn's
Average ant. Element spacing (m)	1.5	1.5	1.5
Antennas per superstation	N/A	1728	1536
Antennas per sub-station	N/A	48	N/A
Total antennas in outer stations	12288	62208	55296
Antennas in core (radius < 1700 m)	118784	100224	75776
Fraction in core (%)	91%	62%	58%
Diameter of Superstation 'Sea' (m)[5]	N/A	70	66
Diameter of Station 'Sea' (m)	27	29	27
Diameter of Superstation (flower) (m)	N/A	86	81
Superstations in core	464	58	49
Total Superstations	512	94	85
Correlatable entities			
Superstation	N/A	94	85
Station	512	564	512
Substation	N/A	3384	N/A
Max baselines	130816	5724036	130816

Within the 'core' (radius less than 1700 m) the default station configuration (now V4D) has been adapted from V4A as follows:

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[5] 'Sea' refers to a random arrangement of antennas filling the relevant area.

- Total number of antenna elements is the same as for baseline design after re-baselining (BD-RBS) – 131072.
- Number of antenna elements per station also same as BD-RBS.
- Retain the number of outer stations as 36, which has already been established.
- No physical substations.[6]
- Retain average spacing between antenna elements at 1.5 m.
    - However, this may have to be increased if the antenna design must be increased in size in order to improve its band-shape.
    - The impact of an increase would be to increase the sparse-dense transition frequency, unless an increase in antenna gain can also be increased to compensate.
- Features of the core station configuration retained (4 rings plus 3 spirals).
    - Number of superstations in core adjusted from 58 to 49.
    - Number in each ring (1, 5, 11, 17) – reduced by 3.[7]
    - Four superstations in each spiral arm – reduced by total of 6.[8]
    - Odd number of superstations in each ring.

Figure 2 shows the configuration of stations within a superstation. The six stations are arranged on the points of a pentagon around a central station. The pattern of antenna elements may be rotated within a station or simply arranged randomly in each one.

Figure 3 shows the array configuration within the core. Figure 4 shows the same configuration at a larger scale in which the station diameters are shown at approximately the right scale.

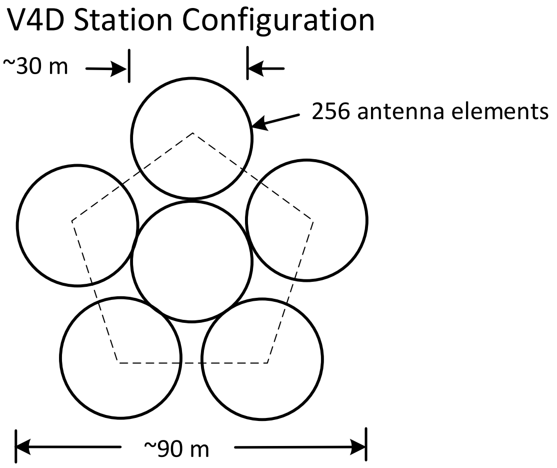

Figure 2: The configuration of a station within a superstation. The diameters shown are nominal and will vary slightly with antenna element separation.

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[6] In principle, substations can be created virtually within the station footprint. This may be possible for a subset of the total number of stations so that very short spacings can be measured.

[7] Radii: 0, 100, 190, 290 m.

[8] Generating function for each arm: $A = ae^{bk\Delta\theta}$, where a = 300 m, b = 0.513, $\Delta\theta = 37°$, k = 1, …, 4. Arms are offset by 35, 155, and 275°, respectively.

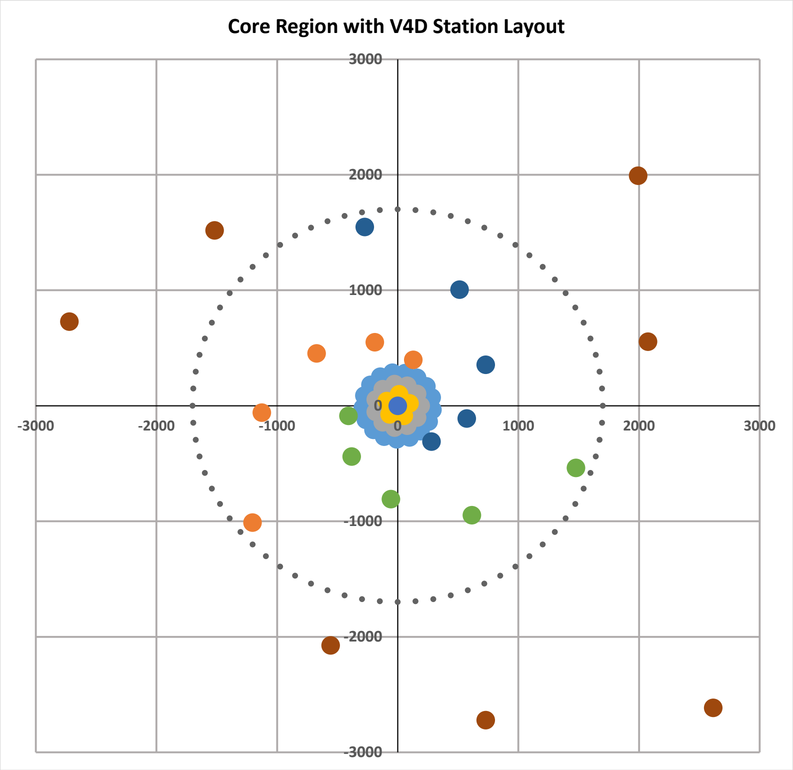

Figure 3: The default array configuration within the core, shown by the dotted circle. The dark red dots are the outer superstations.

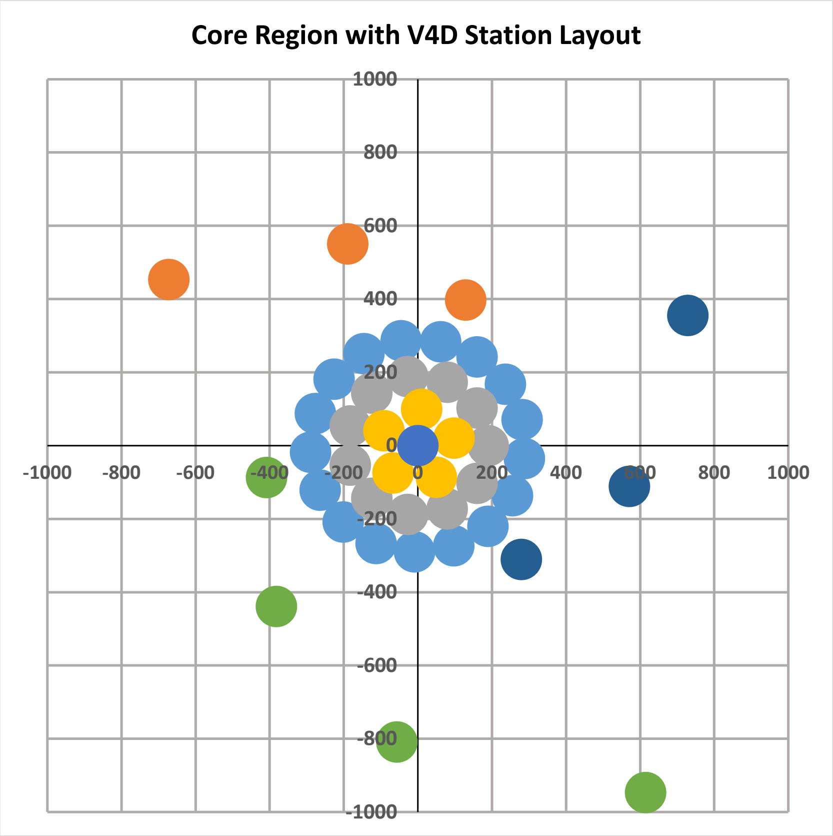

Figure 4: An exploded view of the default array configuration within the core.