Assessment of the SKA1 Baseline Design for Science in the Cradle of Life Area - Final Report

Summary:

This is the report on the suitability of the SKA1 baseline design for science in the Cradle of Life (CoL) area by the SKA SWG CoL Team. The key CoL science consists of grain growth and early-stage planet formation, searches for pre-biotic molecules, exo-planet studies and SETI. Other related work in star and planet formation will underpin this key science, but also requires many of the capabilities detailed below. This report is a result of discussions that culminated at the CoL Science Assessment Workshop on Nov 6-8 2013. A number of requests for changes and holds in the Baseline Design are put forward.

Frequency Coverage (High end): To enable SKA1-mid to carry out any significant headline science in the areas of grain growth and the initial stages of planet formation, as well as searches for pre-biotic molecules relevant to the origin of life, it will require frequencies higher than 3 GHz. The strength of the dust and line emission falls off too quickly with decreasing frequency to make detections possible with band 3. Equipping of SKA1-mid with band 5 receivers would enable users to undertake world-leading, high impact science in this area. The significantly longer baselines and higher sensitivity than the EVLA would allow studies of the location of grain growth in the inner few au of proto-planetary discs (PPDs) and the separation of confusing jet emission. Simulations show that both the emission from large grains and pre-biotic molecules can be detected with SKA1-mid at around 14 GHz. Due to the clustering of protostars multiple targets can be studied as a function of mass in a single deep pointing, whilst clusters of different ages provide the insight into the evolution of grain growth and chemical complexity. To deliver all this exciting science requires good high frequency performance of SKA1-mid.

Request for hold: The dish efficiency should be kept at 0.74 or better over the 5-14 GHz range as in Table 7 of the baseline design.

Request for hold: The dish pointing accuracy should be kept at 10 arcseconds or better as in Table 5 of the baseline design.

Request for change: That SKA1-mid be equipped with band 5 receivers. The 4.6-13.8 GHz range in Table 6 of the baseline design would satisfy the science requirements described above, although the science with SKA1 sensitivity is most feasible at the high end of this range and would preferably extend to around 15 GHz. (We note that this capability would also enable searches for Galactic centre pulsars and high redshift CO.)

Request for hold: The number of receiver slots should be kept at 5 to enable flexibility in future upgrade paths for wide-band receivers that operate at frequencies higher than 14 GHz.

Frequency Coverage (Low end): For SKA1-low to have the best chance of detecting emission from exo-planets, the lower frequency cut-off needs to be as low as possible. Planetary emission is an electron cyclotron maser, with the maximum emission frequency determined by the magnetic field strength at the planetary surface. Jupiter's maximum emission frequency is 40 MHz, and current searches have placed stringent limits on planetary emission above 100 MHz.

Request for hold: The lowest frequency of SKA1-low should remain at 50 MHz. It would also be desirable to have access to the data below 50 MHz without it being subjected to any filtering.

Baseline coverage: The 200 km baselines of SKA1-mid are needed to provide the resolution to probe the inner few au of PPDs. The 20 mas resolution at 14 GHz will give 2 au resolution for the nearest protostars (d~ 100 pc), which is sufficient to map the process of grain growth either side of the snow line in PPDs. This resolution of SKA1 at wavelengths of 2 cm is the same as that of ALMA at wavelengths of 2 mm and therefore will provide matching beam data to study the growth of grains from the mm through to the important cm regime.

Although the second generation configuration of SKA1-mid is better than the first, a distribution of baselines that extended the natural sensitivity even further down towards the highest resolution would allow the band 5 continuum imaging of PPDs into the terrestrial planet formation zone. If a high sensitivity cannot be achieved with the final configuration at 20 mas at 14 GHz then good science can still be done with 30 mas resolution and high sensitivity. The broad range of beam sizes with good monochromatic sensitivity will help with searches for pre-biotic molecules in a range of environments from pre-stellar cores at around 10" scales down to the 1" scales of the outer PPDs themselves.

Request for hold: The longest baselines of SKA1-mid remain at 200 km.

Request for change: The antenna configuration should deliver twice the naturally weighted noise level or better, for beam sizes down to within 50% of the highest angular resolution, e.g. 30 mas at 14 GHz.

Spectral capabilities: The large number of frequency channels (256,000) will enable the full 2.5 GHz bandwidth in band 5 to be sampled at 0.2-0.6 kms^{-1} resolution. This is sufficient for the pre-biotic molecular line surveys in cool pre-stellar cores and outer regions of PPDs. Follow-ups to the detection experiments to determine the kinematics and magnetic field strengths via Zeeman observations require higher spectral resolution over smaller bandwidths. The highest spectral resolution would be required by maser Zeeman observations that require a resolution of 0.05 kms^{-1}. Hence, the correlator should be able to deliver zoom modes that focus the same, or fewer, number of channels on a narrower bandwidth around lines of interest.

Request for hold: The number of spectral channels is held at 256,000 as in Table 6 of the baseline design.

Request for change: The correlator should be able to implement zoom modes where the 256,000, or fewer, channels are deployed over a narrower bandwidth anywhere in the sub-band. A zoom by up to a factor of 32 is required for the highest spectral resolution. Multiple zooms are desirable for efficient follow-up of many lines simultaneously.

Request for hold: Studies of the four important OH lines at 1612, 1665, 1667 and 1720 MHz are best carried out when they are observed simultaneously in the same band.

Bandwidth: Ideally the 2 x 2.5 GHz bandwidth in Table 6 of the baseline design would allow both the sensitive continuum and line studies of PPDs to be very efficient as the large simultaneous bandwidth would probe the continuum spectral slope and cover many potential molecular line transitions at once. If only 1 x 2.5 GHz bandwidth the science could still be done, but at a slower rate.

FoV: The >5' FoV in band 5 is well matched to the size of young stellar clusters and so allows a large multiplexing of objects during a single long integration.

Required A/T, sensitivity: Simulations show that both the PPD continuum studies and pre-biotic molecular line searches will need the full sensitivity of SKA1-mid. For exo-planet signals, theoretical work and scaling laws give estimates of several mJy to several μJy at 100 pc range for exo-planet radio emission in the 10's MHz-10's GHz range. As an illustration, at a distance of 10 pc, Jupiter has a flux density of only about 50 μJy; planets closer to their host star will likely have higher flux densities, scaling with the planet-host star distance as $\sim 1/d^2$. Analogs of the brightest radio emission produced by human technology, the Arecibo Planetary Radar, would be detectable at 100-1000 pc in single 0.1 Hz resolution integrations. Similarly, only SETI signals at least as powerful as terrestrial airport radars will be detectable over distances of order 10 pc.

Request for hold: The A/T of the combined SKA1-mid array should be held at 1200 m^2/K for band 5 as in Table 9 of the baseline design, and at 144 m^2/K SKA1-Low at 50 MHz as in Table 3 of the baseline design.

Multiple beams on SKA1-low: There are likely to be many tens of confirmed exo-planets per field of view when SKA1-low is operating due to new surveys such as NGTS, TESS and ESPRESSO. Efficient searches will require multiple beams with high duty cycle monitoring on timescales of minutes over periods of many hours. This would allow targeted observations of known habitable exo-planets and could be carried out commensally with other observations.

Request for change: SKA1-low should be able to observe with about 10 independent beams.

Data spigots: To conduct the sensitive SETI searches requires access to complex time domain voltage data from about 10 tied array beams via a data spigot. These data would be transferred to externally provided compute resources that will perform very high spectral resolution channelization searches for narrow-band signals, with a characteristic frequency resolution of about 1 Hz. Searches for wideband SETI signals can also be carried out. Ideally these data spigots should be provided on SKA1-low as well as on SKA1-mid to search as much of frequency space as possible. The ability to observe multiple locations on the sky simultaneously using beamformed data is extremely beneficial for SETI observations to remove false alarms due to terrestrial interference. The 10 tied array beams should be capable of being independently and commensally steered within the primary beam to search both known nearby exo-planetary systems and serendipitous lines of sight. Tied array beams should be formed over the widest bandwidth possible, and coarse (~MHz) channelization by upstream filterbanks is acceptable and even preferable. Further beams would make the searches more efficient.

Request for change: SKA1-low and SKA1-mid should have data spigots that allow access to the complex time domain voltage data from at least 10 tied array beams. The observatory should provide sufficient calibration procedures for these beams.

Commensal observing: Many data spigots in an open DSP architecture will enable efficient use of SKA1 by multiple observers simultaneously. For example, such an architecture will allow transient and SETI searches to be carried out at the same time as deep imaging experiments and pulsar timing observations. To facilitate commensal observing SKA1 needs to make real-time array status and sensitivity information available.

Request for change: SKA1 should enable and encourage commensal observing to increase the efficiency of science carried out on the telescope. Procedures and protocols for commensal observing should be developed and agreed. Sufficient real-time status and sensitivity information should be made available for SKA1-low and SKA1-mid to enable commensal observers to make the best use of the arrays.

VLBI observing: The high sensitivity of the phased up SKA1 means that it can form a very sensitive VLBI system even when combined with existing VLBI dishes. The astrometric accuracy provided by this capability can be used to measure accurate distances, 3D structure and kinematics of the stellar clusters in which the PPD targets are located. VLBI observations can study the non-thermal continuum emission that is likely to originate from magnetic flaring activity in the protostar-disk system. Sub-au resolution and temporal studies of this activity will aid the understanding of the phenomena that are thought to be responsible for the isotope ratios and chondrule formation in the meteoritic record of the early solar system. Any masing regions would allow high resolution astrometry, dynamical studies and Zeeman measurements of the magnetic field. The small field of view resulting from the full phased SKA1 means that to carry out the simultaneous observations of several calibrators and targets requires data from several phased sub-arrays.

Request for change: SKA1 should provide a VLBI-format output for correlation with other telescopes. This requires each SKA1 instrument to have the capability to produce at least a few, but preferably many phased array beams at full bandwidth.

Computational Costs and Data Products: We anticipate that SETI observers will largely use custom algorithms operating on time domain voltage data delivered to circular memory buffers on commodity compute elements. Identical digital hardware to that used for coherent de-dispersion in pulsar timing applications will likely be suitable for a wide range of SETI observations. Fast network access between these resources and to science center compute resources will be helpful in ensuring that large datasets produced by SETI experiments can be moved efficiently.

Path to SKA2: The equipping of SKA1-mid with band 5 receivers will provide valuable pointers to the high frequency science that can be done with SKA2. It will also open up SKA1 to the much wider community involved in the formation and evolution of stars in the Galaxy and nearby galaxies. Similarly, the ability to use SKA1 in VLBI will involve a larger high resolution and astrometric community in preparation for longer baselines in SKA2. The origin of life questions that can only be addressed at high frequencies are of great interest to the general public and hence likely to help attract the funding necessary to build SKA2.

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