Continuum Science Assessment Workshop Summary

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Summary:

A science assessment workshop focused on the SKA1 Baseline Design and its ability to conduct science observations relevant to Continuum Survey Science was hosted by the SKA Office on 2013 September 9-11. This document summarises the discussions held and highlights the need for further analysis.

Our primary conclusion is that SKA1 can attain transformational science goals in a reasonable integration time provided that the uv distribution is carefully chosen to achieve a well-tempered synthesised beam shape, offering the required resolution and sensitivity without irregularities such as pedestals.

We recommend that detailed studies are carried out of the configuration changes which could provide such surveys on suitable timescales (e.g. from months to a few years for the largest surveys). Strongly related to this is the requirement for high dynamic range, ~60dB, for surveys with SKA1, possibly approaching, ~70dB, for SKA2.

The workshop also noted that SKA1-LOW will quickly become confusion limited at a few mJy, hence is not useful for many continuum science areas. A wider community consultation is ongoing, with the aim of identifying critical continuum science cases for SKA-LOW and finalizing recommendations. The SKA-LOW Tiger Team will report separately.

Several detailed reports (see references) went into this document (focused on SKA mid frequencies) which are recommended reading, particularly Condon (2013) from which we quote `*The largest technical risk for SKA1 continuum observations is the uncertain ability of the System Baseline Design to meet the dynamic-range requirements*.'

Simulations are ongoing to fine-tune the science cases and better assess their feasibility with the SKA1. This work, and that from the SKA-LOW Tiger Team, will be incorporated by this WG into new chapters for the updated SKA science book.

Continuum Science Cases

The Continuum Science Working Group has been convened to cover a wide range of science areas and represents a diverse cross-section of the astronomy community. At the science assessment workshop several science cases were presented and discussed, as listed below. These offered a wide, but possibly not complete, census of galactic and extra-galactic research areas which can be addressed by the SKA.

(1) Galaxy Evolution – radio luminosity can be direct tracer of star formation rate, measure star formation history to z~1 over large areas and nested surveys up to the bright end of z~5 regime. Not affected by dust extinction.

(2) AGN Evolution – evolution of high/low excitation radio galaxies, origin of the radio loudness dichotomy, AGN feedback. Not affected by gas obscuration.

(3) Diffuse/clusters – largest bound structures in the Universe, also important for Cosmology

(4) Galactic Science – detect all kinds of non-thermal sources, radio coronae across a wide range of stellar types, radio flares, coherent sources, planets etc.

(5) Cosmology – many probes: power spectrum, ISM, weak lensing which can constrain Dark Energy, non-Gaussianity

(6) Magnetism – scales larger than galaxies largely unknown: detect and characterize the cosmic web, galaxy evolution, cluster formation and galactic foreground

(7) Local Universe – local galaxies: detailed understanding of star formation outside the Milky Way, dwarf galaxies

(8) Strong Lensing – independent measure of mass, studies of magnified sources

(9) Rare/Legacy – new classes of object, serendipity, constrain the SFR of any object, legacy value and putting radio photometry on par (depth and resolution) with other wavelengths throughout astrophysics

Reference continuum surveys for the SKA1:

The scientific discussion took into account (a) the expected scientific framework in years 2020-2025; (b) the fact that SKA1 should go a major step further with respect to its precursors (e.g. JVLA, LOFAR, MWA, eMERLIN,etc.) and pathfinders (Meerkat and ASKAP); (c) other facilities coming online at the same time (i.e. the planned facilities in the other wavebands, e.g. Euclid, LSST, etc.) which tackle overlapping scientific goals, but in a different manner. Having all this in mind, three major “reference” continuum surveys were defined, that are considered to have relevant scientific impact in the SKA1 era. Such surveys are designed so as to respond to specific major scientific drivers (as indicated below), in key research areas like galaxy evolution and cosmology, but will address the majority of key science. These surveys can be used as reference to fine-tune the SKA1 design for continuum survey science:

(1) **Deep (galaxy evolution)**: A 30 deg^2 survey with 0.5" resolution (for resolved morphology of galaxies) and T~0.1K rms =~ 40nJy/beam (for galaxy evolution at z>1) – deep fields and lensing clusters. Note that a less sensitive survey can be weighted differently to provide either 0.5" resolution **or** T~0.1K depending on the science goals.

(2) **Wide (weak lensing)**: A 5,000 deg^2 survey with 0.5" resolution to detect at least 5 sources per arcminute squared (for cosmological weak lensing, galaxy evolution z<1). This approximately corresponds to 0.34 μJy/beam at ~1GHz, but there is a trade-off between frequency/depth/resolution for the source density requirement.

~~(3)~~ **All-sky (legacy/Local Universe)**: A ~1-2GHz image 31,000 deg^2/3π steradians with 2" resolution and 2μJy rms/beam (thus satisfying the confusion and temperature brightness (for power spectrum, legacy, cluster/diffuse, magnetism, galactic science, local Universe).

For these example surveys there are trade-offs in frequency, depth and resolution which are intimately related to total survey time. However the required combination of depth and resolution is the most critical issue for both *Deep* and *Wide* surveys (as discussed in more detail below). With the current configurations proposed in the`*SKA1 Science Imaging Performance'* document *Deep* and *Wide* would take of the order decades and All-sky would be possible in ~2 years. Given the extremely long observing times, the *Deep* and *Wide Surveys* are currently unfeasible with SKA1. We think however that there is ample room to improve the sensitivity of SKA1 at (sub-)arcsec resolutions with a rearrangement of the antenna configuration. The potential increase in survey speed at these resolutions could be huge (from a factor of a few up to an order of magnitude). We note that the SKAO is looking at the feasibility and trade-offs of such modifications in early 2014. While the All-sky survey is feasible with SUR, again modest reconfiguration could also greatly improve its speed.

Critical parameters

The main critical parameters for the surveys/science cases outlined above are discussed below. We anticipate the the major concern is about the inability of SKA1, as currently designed, to reach the needed survey speed and/or sensitivity at sub-arcsec resolution.

(a) ***Resolution***:

Resolution is critical for several science cases:

Cosmology: For a weak lensing survey to be competitive, we need a high number density of sources, as well as enough signal-to-noise on a galaxy in order to measure the shape. The number density should be as high as possible; around 5 galaxies per square arcminute provides competitive constraints on cosmological parameters and a survey of 5000 deg^2, although smaller areas (~1000s deg^2) could be accommodated if one considered this a pilot study for SKA2. The probable optimal resolution to be able to resolve features of typical galaxies for weak lensing is around 0.5" scales, though trade-offs exist. If the PSF is too large (>~1"), the weak lensing survey becomes impossible; we cannot use any galaxies which are approximately the same size as the PSF and therefore we are limited to ~0.5" resolution at a 10σ sensitivity per 0.5" beam, which would contain approximately 70% of the total galaxy flux. In order to achieve 5 sources/arcmin^2 we require a 10σ total flux density survey of 0.5 μJy/beam rms at around 1.4GHz. In order to obtain a 10σ measurement at 0.5μJy rms with a 0.5" beam we therefore require an rms sensitivity of 0.34μJy/beam.

Strong Lensing: The main requirement for gravitational lens surveys is resolution. For maximum efficiency, resolutions of about 0.2" are required, as was used in the CLASS survey. However, surveys of 0.5" resolution are still useful, at the expense of completeness of samples (the smaller-separation ones will be missed) and false positives (requiring more followup). Nevertheless, this problem has been investigated in the past and tricks are available to find lenses with the lower-resolution surveys. A particularly promising approach is to use two surveys - here, SKA1 together with Euclid - as this should allow much more efficient rejection of false positives. In principle, 1 in every ~600-1000 background sources is strongly lensed, the main dependency being on source redshift (approximately as $(1+z)^4$); the likely redshift distribution of SKA objects suggests that this will be continued, although detailed simulations including the various source populations have yet to be done. A survey of a few x10^8 objects, such as SKA1 should in theory yield a few hundred thousand lenses.

Galaxy Evolution I: The optical counterparts of sub-mJy radio sources are usually quite faint, so accurate radio positions are needed to make complete and reliable optical identifications by position-coincidence alone. The completeness and reliability of identifications depend on the sky density of optical identification candidates brighter than some limiting magnitude. An extreme example is the

Hubble Ultra-Deep Field (HUDF) containing ~ 10^4 galaxies brighter than m_{AB} = +29 in 11 arcmin^2, or ≈ 10^3 galaxies per arcmin^2. The completeness and reliability also depend on the rms position error in each coordinate, and the size of the search area chosen, which should be large enough for high completeness and small enough for high reliability. A good compromise is the size that makes the completeness comparable to the reliability. The required radio resolutions for highly complete and reliable optical identifications are θ ≤ 4" and θ ≤ 2" for the LSST and HUDF, respectively. These are conservative limits because other techniques (e.g., likelihood ratios) can be used to supplement pure position coincidence.

Galaxy Evolution II: A key discriminant between radio sources powered by star formation (galaxy sized, disk or bulge like) and those powered by black holes (double lobe from core) is morphology. Hence, we need to resolve out galaxies by a certain fraction to about 0.5". A resolution of 0.5" corresponds to a physical size of about 4 kpc at redshift z>1, allowing to roughly distinguish between bulge-dominated (<few kpc) and disk dominated (>10 kpc) star formation emission. A factor 10 better resolution would be needed to resolve core star formation from embedded radio AGNs. This is beyond reach of SKA1, but envisaged for SKA2.

(b) Beam Shape:

At μJy flux density levels the source counts are such that effective beam solid angle is extremely sensitive to extended (large Ω) low-level "pedestals" and other sidelobes of the dirty beam. The naturally weighted beam of SKA1-mid, in particular, has large pedestals produced by the 1 km core array optimized for pulsars and the 8 km halo array for HI observations. Consequently it is important that the (u,v) be weighted sufficiently to remove the pedestals from the compact cores of the SKA arrays. It is also important to investigate further the effect of sidelobes to confusion noise which cannot be curtailed by weighting.

(c) Dynamic Range:

The sensitivities possible over wide areas with SKA1 naturally raise the requirement of high dynamic range for even the smallest survey tier (this is closely related to the beam shape and sidelobes discussed above). While some effort can be made to avoid the brightest sources that will not always be possible. The use of an accurate sky model can help mitigate this issue, but there will undoubtedly be regions of enhanced noise (above thermal) around bright source. For these to be minimized we require a dynamic range of ~60dB for the survey scenarios outlined above, but ultimately ~70dB will be required for SKA2.

(d) Survey Speed:

It is important to note that to achieve the resolution and accurate beam described above we currently have to weight the antennas within the core down with respect to the long baselines, but this then produces a large decrease in overall sensitivity or requires that factor squared increase in the observing time. High resolution and Gaussian beams are crucial for the main science drivers of *Wide* and *Deep Surveys*, but makes such surveys very time consuming. An increase in the number of long baselines (at the expense of shorter ones) would make a huge difference to the continuum survey time and may not have a large impact on the science requiring the compact cores. We advocate that a detailed trade-off is investigated.

(e) Systematics:

An excellent control of systematics is needed for some key science cases:

Cosmology: All-sky SKA1 surveys should be able to detect very small cosmological anisotropies in source density, from the integrated Sachs-Wolfe effect for example. Instrumental anisotropies caused by variations in the flux-density calibration or the synthesized point-spread function (PSF) with time or position on the sky should be kept smaller than the $N^{-0.5}$ Poisson fluctuations in source numbers, N. Hence, for large area surveys, a requirement of flux density calibration to ~1% over the full field-of-view of the widest tier is inferred.

Polarization: A high degree of polarization purity is required for key SKA1 observational investigations in cosmic magnetism. Large-scale diffuse emission associated with optically-thin AGN jets and with clusters is often highly polarized at levels of a few 10's of percent. However AGN cores are more typically polarized at a few percent and the integrated emission of most galaxies is less than 1% at 1.4 GHz. Such sources will be the dominant population of the microJy radio sky. Aside from the issue of direct detection of polarized emission from sources with linear polarized intensity of order 1%, instrumental polarization creates artifacts in RM Synthesis around zero Faraday depth. Instrumental polarization thus affects experiments that rely on small variations in Faraday depth near zero, for example investigations of Faraday rotation by large-scale structure in the universe. Instrumental polarization is also a limiting factor in measurement of depolarization fraction as a function of wavelength, a unique source of information about in situ magnetized plasmas. To enable the basic cosmic magnetism goals with large area continuum surveys, post-calibration polarization purity of 0.1% is required over the field of view. Note valuable science may be obtained from circular polarization of AGN, but that requires 0.025% purity which would be challenging even on axis so we leave it for SKA2.

(f) Minimum Baselines:

A minimum baseline of the order of 10 m would be more suited for the study of diffuse radio emission in low-z clusters and for possible detection of radio emission associated to the cosmic web. Of course all spacings from 10 up to 15 m could be well sampled by a single dish whose diameter is at least twice 15 m. SKA1 observations could therefore be complemented by single dish data (Ferrari et al., 2013).

(g) Frequency Coverage:

The highest priority continuum science goals can only be realized with unprecedented high dynamic range imaging. This in turn requires high-performance dishes that may be able to work at frequencies up to 30 GHz (i.e., where ALMA Band-1 begins), which would open up a critical new part of frequency space for continuum science goals.

Computational Costs and Data Products:

Some comments came up in discussions addressing data processing and included the suggestions to remove the shortest baselines in the processing (to reduce data volume), or, depending on the science, reprocessing at lower resolution after removing point sources (to detect diffuse structure), and the optimization of cleaning algorithm (e.g. compressed sensing – for speed and accuracy).

Recommendations for SKA1:

The key outcome of the meeting was that *the currently proposed configurations for the mid frequency elements do not provide the sensitivity at high resolution required to conduct the Deep and Wide surveys in a reasonable time*. The down-weighting of the short baselines leads to survey times of decades, rather than months/years as would be expected of a general user facility. The All-sky survey, on the other hand, could be feasible with SUR in 2 years timescale.

This WG therefore requests that the SKAO carry out detailed configuration studies examining the trade-offs (in cost and capabilities) which would provide an array with minimal down-weighting to observe at the highest possible resolution. This change is essential for the science described above and should be part of SKA1 if it is to have the impact in over the diverse continuum science goals as expected. For example, any weighted and tapered (u,v) coverage should simultaneously yields dirty beams with < 1% sidelobes and low image noise over the resolution range 0.5" < θ < 4" FWHM.

A critical and poorly understood requirement is dynamic range as high as 60 dB, which should be addressed before the antenna design is frozen. We recommend an investigation into how much survey area is lost around sources this bright and what precision of beam shape and sidelobes is required. We note also that sky areas lost due to poor dynamic range increase the total exposure time by requiring a larger area to be surveyed.

The Path to SKA2:

The WG acknowledged that there were some capabilities not supported by the baseline design and that look beyond reach of SKA1. However, for the long term goals of the science above it is essential that these capabilities are achieved for SKA2 at mid frequencies:

- 0.1" resolution at ~1 GHz (thermal noise limited), for resolved star-formation studies

- dynamic range of >~70dB, for deep surveys, e.g. the Milky Way at z~7

- imaging up to 30GHz either for Galactic or high-z star-formation studies. We note that dishes capable of extreme dynamic range, >60dB), at 1-2GHz should be good enough for observing at this frequency.

- 0.025% polarization purity over the full field of view for polarization surveys

Participants:

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