SKA1 SCIENCE PRIORITY OUTCOMES

Document number SKA-TEL-SKO-0000122
Context .... SCI-REQ-RE
Revision 1
Author .... R. Braun, T. Bourke, J. Green, J. Wagg
Date 2014-09-25
Document Classification .... FOR PROJECT USE ONLY
Status .... Released

Name	Designation	Affiliation	Signature	
Authored by:				
R. Braun, T. Bourke, J. Green, J. Wagg				
Owned by:				
Robert Braun	Science Director	SKA Office	[signature]	
			Date:	2014-09-25
Approved by:				
Alistair McPherson	Head of Projects	SKA Office	[signature] A M McPherson	
			Date:	2014-09-25
Released by:				
Phil Diamond	SKA Director-General	SKA Office	[signature]	
			Date:	2014-09-25

DOCUMENT HISTORY

Revision	Date Of Issue	Engineering Change Number	Comments
A	2014-08-12	-	First draft
1	2014-09-25	-	Released

DOCUMENT SOFTWARE

	Package	Version	Filename
Wordprocessor	MsWord	Word 2011	SKA-TEL-SKO-0000122-SCI-REQ-RE-01-SKA1 Science Priority Outcomes

ORGANISATION DETAILS

Name	SKA Organisation
Registered Address	Jodrell Bank Observatory Lower Withington Macclesfield Cheshire SK11 9DL United Kingdom Registered in England & Wales Company Number: 07881918
Fax.	+44 (0)161 306 9600
Website	www.skatelescope.org

Table of Contents

1 Introduction 5
  1.1 Purpose of the document 5
  1.2 Scope of the document 5
2 References 5
  2.1 Applicable documents 5
  2.2 Reference documents 5
3 Method and timeline of prioritisation 5
  3.1 Input from Science Working Groups 6
  3.2 Science Goal Clarification 6
  3.3 Assessment Criteria and their Score Definitions 7
  3.4 Weighting of Criteria 9
  3.5 Scoring 9
4 Outcomes 10
5 Next Steps 11

LIST OF ABBREVIATIONS

PAF .... Phased Array Feed
SEAC .... Science and Engineering Advisory Committee
SKA............................... Square Kilometre Array
SKAO............................ Square kilometre Array Office
SPF .... Single Pixel Feed
SRP .... Science Review Panel
SWG .... Science Working Group

1 Introduction

1.1 Purpose of the document

In this document we outline the procedure that has been followed in developing and prioritising the scientific goals for the first deployment phase of the SKA.

1.2 Scope of the document

The method of tabulating a suitable set of SKA science objectives is first described. The assessment criteria and their scoring definitions are then developed, together with the relative weights with which they will be combined in forming a final score. The scoring process itself is then outlined, that results in a list of high priority science goals. More extensive documentation of the scientific objectives and the methods used to address them are provided in the Appendix. The prioritisation process and its outcome was reviewed by the *ad ho*c Science Review Panel (SRP) and subsequently by the Science and Engineering Advisory Committee (SEAC). Those reviews provided confirmation of the integrity of the process and acceptance of the general ranking outcome.

2 References

2.1 Applicable documents

The following documents are applicable to the extent stated herein. In the event of conflict between the contents of the applicable documents and this document, **the applicable documents** shall take precedence.

[1] Dewdney et al. 2013, *SKA Phase 1 System (Level 1) Specifications*, SKA-OFF.SE.ARC-SKO-SRS-001-A, Revision 1
[2] Level 1 requirements, Revision 3

2.2 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.

[3] Science Working Group Workshop summaries
[4] SKA Science Meeting Presentations

3 Method and timeline of prioritisation

At its 8 July 2014 meeting, the SKA Board approved a process for the development and testing of Science Priorities for the SKA. That process called for the development of science goals by the SKAO Science Team in conjunction with the Science Working Groups, the prioritisation of those goals by the SKAO Science Team and the review of those priorities by an *ad hoc* Science Review Panel (SRP) and subsequently by the Science and Engineering Advisory Committee (SEAC). Both the SRP and SEAC were to provide advice on those scientific priorities to the SKA Director-General. Based on those reviews there was the possibility for further refinement of the assessments by the SKAO Science Team prior to making the final science priorities available to the SKA Board. That refinement has not proven necessary. The overall process of prioritisation is described pictorially in Figure 1.

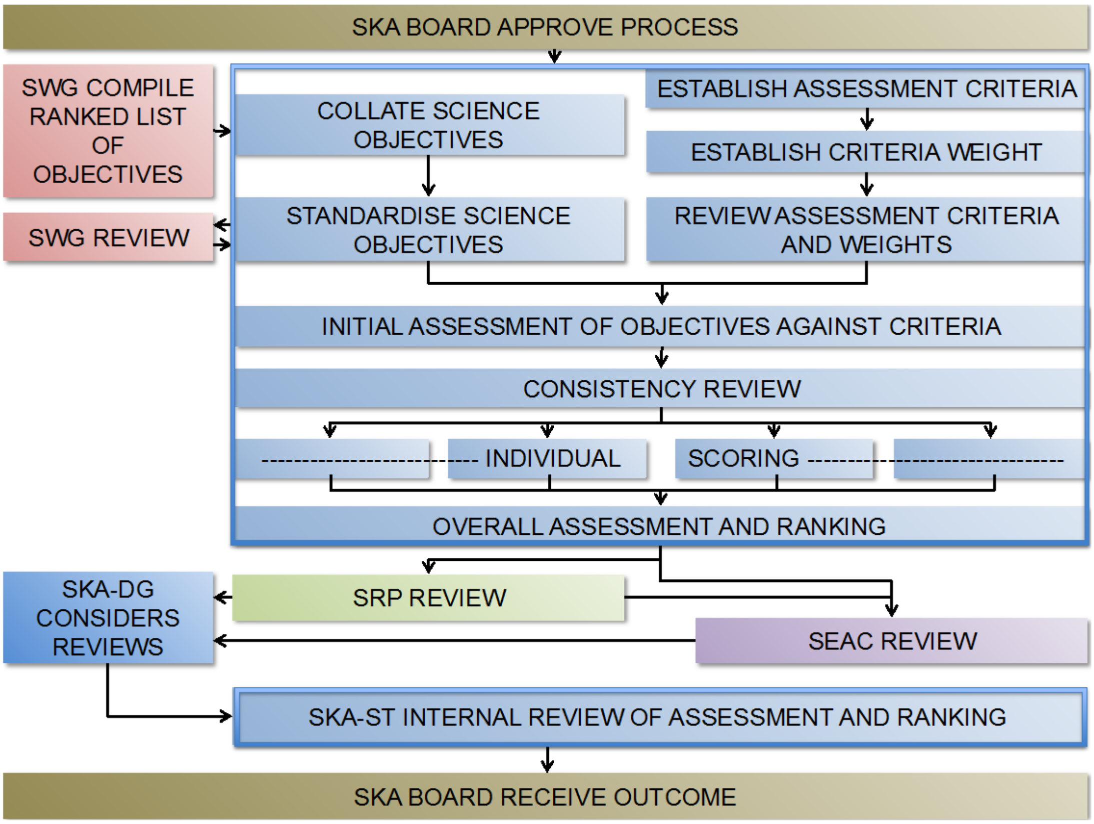


Figure 1. Pictorial representation of the science prioritisation process.

3.1 Input from Science Working Groups

This process began with a request to each of the SKA Science Working Group Chairs, in consultation with their Working Group members, to provide a list of key SKA1 scientific goals for the working group they represent. There was no hard limit on the number of such goals per SWG, but a guideline of about five and no more than ten was suggested. The SWG Chairs were asked to insure that each goal be a well-defined scientific topic, ideally using a single sentence to spell out the nature of the goal and another sentence to spell out the means of achieving it. In some cases, this information had already been compiled in the Science Assessment Workshop summaries, but each SWG was given the opportunity to reconsider and refresh those. The SWG Chairs were invited to indicate, as the means of achieving those science goals, any of the five Single Pixel Feed (SPF) bands defined for SKA1-MID, the three Phased Array Feed (PAF) bands defined for SKA1-SUR and the frequency coverage of SKA1-LOW, all as specified in the original Baseline Design [1]. In submitting the list of science goals for their working group, each Chair was asked to provide a relative ranking of those topics in terms of their overall importance as well as a numerical estimate of the factor by which the SKA1 capability for the goal exceeds the current state-of-the-art. A total of 44 distinct Science Goals was received from the eight working groups, with 3 to 9 goals coming from each group.

3.2 Science Goal Clarification

The list received from each SWG Chair was organised into a standardised spreadsheet representation by the SKAO Science Team. The content was edited for greater clarity and supplemented with any missing fields. This was refined through several iterations with each of the SWG Chairs to insure that their intent was preserved in the final representation. The most relevant text fields describing each of the science objectives are included at the end of this document as Appendix A.

3.3 Assessment Criteria and their Score Definitions

The SKAO Science Team considered what criteria might be defined in order to assess the relative priorities of the various scientific goals, together with unambiguous guidelines that could be applied to assigning a score to each. In developing such criteria, an attempt was made to consider both desirable as well as undesirable attributes. Each criterion has been phrased in such a way as to make it as "orthogonal" as possible with regard to the others. The criteria and their scoring definitions are listed below.

Score	C1: How fundamental is the scientific impact of this result?
0	None
1	Incremental (basis for progress in field)
2	Incremental/Significant
3	Significant (significant progress in field)
4	Significant/Fundamental
5	Fundamental (broad recognition of "game-changer" status)

Score	C2: What is the importance of the radio contribution to this result?
0	None (better undertaken at other wavelengths)
1	Low (it can be undertaken with similar precision at other wavelengths)
2	Low/Medium
3	Medium (aspects of the science are addressed uniquely or with superior precision at radio wavelengths)
4	Medium/High
5	High (the science goal is addressed uniquely or with vastly superior precision at radio wavelengths)

Score	C3: Within the context of the radio data, what is the importance of the SKA1 contribution?
0	None (other existing radio facilities better suited)
1	Low (other existing radio facilities can provide similar input)
2	Low/Medium
3	Medium (aspects of the science require the capabilities of SKA1)
4	Medium/High
5	High (the science is uniquely enabled (relative to existing and planned radio facilities) by the capabilities of SKA1)

Score	C4: What portion of the SKA1 sensitivity is required to achieve a significant result within the primary science objective?
0	Beyond SKA1
1	Only possible with full SKA1
2	Requires about 75% of SKA1
3	Requires about 50% of SKA1
4	Requires about 25% of SKA1
5	Can be done with <25% of SKA1

Score	C5: To what degree does the SKA1 contribution enable enhanced outcomes when combined with other data?
0	No synergies, pure radio/SKA experiment
1	Low synergies with data from other bands/facilities
2	Low/Medium
3	Medium synergies with data from other bands/facilities that enhance the combined outcome
4	Medium/High
5	High synergies with data from other bands/facilities that greatly enhance the combined outcome.

Score	C6: Risk associated with instrumental technique (achieving performance goals)? (Receiver to data product.)
0	No-Risk
1	Low-risk (all relevant performance goals have been demonstrated to achieve necessary precision)
2	Low-/Mid-risk
3	Mid-risk (some aspects have been proven/modeled)
4	Mid-/High-risk
5	High-risk (key performance goals have not been demonstrated at the required precision)

Score	C7: Risk associated with understanding observable attributes of the target/source population?
0	No-Risk
1	Low-risk (the target/source population is well understood)
2	Low-/Mid-risk
3	Mid-risk (the target/source population is modeled with confidence)
4	Mid-/High-risk
5	High-risk (the target/source population is unknown)

Score	C8: Risk associated with scientific technique/methodology of signal extraction? (Data product to publishable result.)
0	No-Risk
1	Low-risk (all relevant analysis techniques have been demonstrated to achieve the necessary precision)
2	Low-/Mid-risk
3	Mid-risk (some aspects have been proven/modeled)
4	Mid-/High-risk
5	High-risk (key analysis methods have not been proven or demonstrated at the required precision)

3.4 Weighting of Criteria

When considering combining the scores of the individual assessment criteria, it is clear that not all of the criteria are of equal significance. Therefore in order to form a single overall score, they are first multiplied by a weight that is intended to capture the relative importance of each. The eight criteria and the relative weights that were determined for them are listed below. Suitable weights for each of the criteria were determined in an iterative fashion, beginning with an estimate based on discussion within the SKA Science Team and then calibrated by undertaking scoring of the complete set of Science Goals and comparing the relative ranking that emerged with those provided by the Science Working Groups within their own areas of expertise. This resulted in some small adjustments to the weightings, so as to better recover the SWG assessments. There was no requirement for strict recovery of every SWG ranking, but only the overall trends.

Weight	Criteria
10	C1: How fundamental is the scientific impact of this result?
6	C2: What is the importance of the radio contribution to this result?
6	C3: Within the context of the radio data, what is the importance of the SKA1 contribution?
1	C4: What portion of the SKA1 sensitivity is required to achieve a significant result within the primary science objective?
4	C5: To what degree does the SKA1 contribution enable enhanced outcomes when combined with other data?
-2	C6: Risk associated with instrumental technique (achieving performance goals)? (Receiver to data product.)
-2	C7: Risk associated with understanding observable attributes of the target/source population?
-2	C8: Risk associated with scientific technique/methodology of signal extraction? (Data product to publishable result.)

3.5 Scoring

The scoring of the 44 Science Goals was carried out independently by each of the four members of the SKA Science Team. Each score was accompanied by a brief comment that captures the reason for assignment of that particular score to that criterion. The individual team member scores and comments for each criterion were retained to track consistency. Several different methods were used in combining the scores for each criterion and quantifying their consistency. The first was the arithmetic mean of scores together with their standard deviation. A second method used the median value together with the average (absolute value of) deviation from the mean. While providing very similar outcomes, the second method was found to be more robust against occasional outliers in the scoring and so will be the one adopted here. A combined comment for each score was consolidated from the four inputs. Several methods were also considered for determining the combined weighted score. The first involved forming the weighted sum of the median scores for each criterion. The second method instead made use of the median of the individual weighted sums. It was found empirically that this second method was more robust, since there was a smaller scatter in the weighted scores given to each scientific goal, than there was for the scores given to the eight distinct assessment criteria prior to weighting. The median of weighted sums was therefore the method of combination finally adopted in producing a single ranked list. The scatter in the weighted score of each science objective was quantified with the average (absolute value of) deviation from the mean.

On completion of the independent scoring process, the Science Team members met to discuss the outcome of the scoring process in detail, paying particular attention to all instances of large dispersions in member scores, both the individual scores given to criteria as well as the weighted scores of individual science objectives. In a handful of cases, four of the forty-four, the discussion revealed new insights that were not uniformly appreciated. All Science Team members were given the opportunity to independently reconsider their scores for those four science objectives before the final combined ranking was carried out.

4 Outcomes

A spreadsheet representation of the 44 Science Goals, including an extensive description of methods, is provided in Appendix A. The list is presented as a sequence that is grouped (in arbitrary SWG order) by the submitting SWG and within each group is presented in the ranked order supplied by the SWG Chairs. A summary listing of this type is also provided in Table 1. The same summary listing is provided a second time in Table 2, but in this instance only the highest ranked objectives, resulting from the scoring process outlined here and confirmed in the reviews undertaken by the SRP and the SEAC, are shown. It should be stressed again that the ordering of the objectives in that list is completely arbitrary and does not reflect a relative ranking.

The only significant restructuring of the science objectives listed in Table 2 relative to that in Table 1 has been the bundling of objectives 37 and 38 into a single combined objective. This bundling was undertaken at the recommendation of the SRP.

From Table 2 it is apparent that the highest ranked science objectives provided by the Science Working Groups are the ones that have also received the highest scores in the prioritisation process. This is not surprising. As explained in Section 3.4, the weights given to the assessment criteria have been calibrated so as to insure a high degree of correlation between the SWG ranking and the weighted scores. The scoring process has primarily enabled a means of cross-calibration of the individual SWG listings into a combined listing of priorities on a well-documented uniform scale. It is for this reason that the set of highest priority objectives has different numbers of objectives from the various input lists.

5 Next Steps

It is clear that the SKA, even in its first phase of deployment, will provide such a substantial increase of capability that it will enable an extremely broad range of discoveries. Some of that range is captured within the list of objectives provided by our Science Working Groups in Table 1, but it also extends much further to include objectives that are not currently well-represented within our Working Group structure and perhaps not even yet imagined. It is vital to design an Observatory that is as flexible as possible so that it can enable the broadest possible range of science, including even currently unanticipated experiments. Nevertheless, some more specific guidance is required in practise, particularly when faced with the need to find substantial cost-savings relative to the SKA1 Baseline Design. The priority objectives listed in Table 2 will be used to constrain the re-baselined SKA1 design with highest weight. The full set of key scientific objectives defined by our Science Working Groups will continue to be considered to calibrate the potential for scientific return of specific re-baselined options. It will undoubtedly be the case that the adopted SKA1 design will allow an even wider range of important discoveries to be made. The principle of "maximising discovery space" is underlying all aspects of the on-going science oversight of the design. Flexibility is only abandoned when it results in a significant and necessary cost saving.

Science Goal	SWG	Objective	SWG Rank
1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3
2	*CD/EoR*	Physics of the early universe IGM - II. Power spectrum	2/3
3	*CD/EoR*	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3
4	*Pulsars*	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5	*Pulsars*	High precision timing for testing gravity and GW detection	1/3
6	*Pulsars*	Characterising the pulsar population	2/3
7	*Pulsars*	Finding and using (Millisecond) Pulsars in Globular Clusters and External Galaxies	2/3
8	*Pulsars*	Finding pulsars in the Galactic Centre	2/3
9	*Pulsars*	Astrometric measurements of pulsars to enable improved tests of GR	2/3
10	*Pulsars*	Mapping the pulsar beam	3/3
11	*Pulsars*	Understanding pulsars and their environments through their interactions	3/3
12	*Pulsars*	Mapping the Galactic Structure	3/3
13	*HI*	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5
14	*HI*	High spatial resolution studies of the ISM in the nearby Universe.	2/5
15	*HI*	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
16	*HI*	HI absorption studies out to the highest redshifts.	4/5
17	*HI*	The gaseous interface and accretion physics between galaxies and the IGM	5/5
18	*Transients*	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
19	*Transients*	Accessing New Physics using Ultra-Luminous Cosmic Explosions	=1/4
20	*Transients*	Galaxy growth through measurements of Black Hole accretion, growth and feedback	3/4
21	*Transients*	Detect the Electromagnetic Counterparts to Gravitational Wave Events	4/4
22	*Cradle of Life*	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
23	*Cradle of Life*	Characterise exo-planet magnetic fields and rotational periods	2/5
24	*Cradle of Life*	Survey all nearby (~100 pc) stars for radio emission from technological civilizations.	3/5
25	*Cradle of Life*	The detection of pre-biotic molecules in pre-stellar cores at distance of 100 pc.	4/5
26	*Cradle of Life*	Mapping of the sub-structure and dynamics of nearby clusters using maser emission.	5/5
27	*Magnetism*	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
28	*Magnetism*	Determine origin, maintenance and amplification of magnetic fields at high redshifts - I.	2/5
29	*Magnetism*	Detection of polarised emission in Cosmic Web filaments	3/5
30	*Magnetism*	Determine origin, maintenance and amplification of magnetic fields at high redshifts - II.	4/5
31	*Magnetism*	Intrinsic properties of polarised sources	5/5
32	*Cosmology*	Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5
33	*Cosmology*	Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5
34	*Cosmology*	Map the dark Universe with a completely new kind of weak lensing survey - in the radio.	3/5
35	*Cosmology*	Dark energy & GR via power spectrum, BAO, redshift-space distortions and topology.	4/5
36	*Cosmology*	Test dark energy & general relativity with fore-runner of the 'billion galaxy' survey.	5/5
37	*Continuum*	Measure the Star formation history of the Universe (SFHU) - I. Non-thermal processes	1/8
38	*Continuum*	Measure the Star formation history of the Universe (SFHU) - II. Thermal processes	2/8
39	*Continuum*	Probe the role of black holes in galaxy evolution - I.	3/8
40	*Continuum*	Probe the role of black holes in galaxy evolution - II.	4/8
41	*Continuum*	Probe cosmic rays and magnetic fields in ICM and cosmic filaments.	5/8
42	*Continuum*	Study the detailed astrophysics of star-formation and accretion processes - I.	6/8
43	*Continuum*	Probing dark matter and the high redshift Universe with strong gravitational lensing.	7/8
44	*Continuum*	Legacy/Serendipity/Rare.	8/8

Table 1. Collated list of science goals. Within each science area, the entries are ordered in the rank provided by the SWG Chairs. The eight different groups of SWG contributions are listed in the Table in an arbitrary sequence.

Science Goal	SWG	Objective	SWG Rank
1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3
2	*CD/EoR*	Physics of the early universe IGM - II. Power spectrum	2/3
4	*Pulsars*	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5	*Pulsars*	High precision timing for testing gravity and GW detection	1/3
13	*HI*	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5
14	*HI*	High spatial resolution studies of the ISM in the nearby Universe.	2/5
15	*HI*	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
18	*Transients*	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
22	*Cradle of Life*	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
27	*Magnetism*	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
32	*Cosmology*	Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5
33	*Cosmology*	Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5
37 + 38	*Continuum*	Star formation history of the Universe (SFHU) – I+II. Non-thermal & Thermal processes	1+2/8

Table 2. List of highest priority SKA1 science objectives, grouped by SWG, but otherwise in arbitrary order.

Science Goal	SWG	Objective	Approach/Method	Improvement Factor & Criteria	Details	SWG Rank
1	CD/EoR	Physics of the early universe IGM - I. Imaging	Use SKA1-LOW (50 to 200 MHz) to detect and characterize ionized structures and HI brightness temperature fluctuations on 5 to 300 arcmin scales (varying) over the epoch of reionization /cosmic dawn (CD/EoR) redshift range z=6 to 28 to a 1-mK brightness temperature level.	This will not be feasible with any current (or funded) array with S/N>1 and is unique to SKA1-LOW. The gain is practically infinite since lowering the thermal noise ~20x over LOFAR allows direct imaging with S/N>>1. The Cosmic Dawn remains inaccessible to current/funded instruments, until SKA1-LOW.	The method would be to conduct deep 1000hr integrations on five separate 20 square degree windows covering a total of 100 square degrees on-sky area, using the 50 to 200 MHz frequency range with 0.1 MHz spectral resolution (for science). Observations of five 20 square degree fields observed for 1000 hours each with the full SKA1-LOW array over the frequency range 50-200 MHz. Multi-beaming with Nbeams=2 (if implemented) would lower the on-sky time from 5000 to 2500 hrs. Derive the state, thermal history and chemistry of the IGM, study the first stars, black holes and galaxies and constrain cosmology, the physics of dark matter and gravity	1/3
2	CD/EoR	Physics of the early universe IGM - II. Power spectrum	Use SKA1-LOW (50 to 200 MHz) to detect and characterize the 21cm power-spectrum with a peak S/N~100 measured over scales of k=0.02 to 1.00 Mpc-1 over the CD/EoR redshift range z~6 to 28.	A gain of 1 to 2 orders of magnitude over current arrays (MWA, PAPER, LOFAR) is expected (if successful) in the sample-variance limited S/N regime (k < 0.2 Mpc-1), but scales k=0.2 to 1.00 Mpc-1 are likely to remain inaccessible until SKA1-LOW is built, because of severe thermal-noise limitations. The Cosmic Dawn remains inaccessible to current/funded instruments, until SKA1-LOW.	An SKA1-LOW medium-deep pointed survey covering 1,000 square degrees and a shallower 10,000 square degree survey, both covering the 50 to 200 MHz frequency range with 0.1 MHz spectral resolution and each utilising 5000/Nbeams hours of integration. The medium-deep survey could be conducted with 50 pointings of 100 hrs integrations covering 1000 square degrees, while the shallow pointed/driftscan survey might consist of 500 fields of 10hr integrations covering 10,000 square degrees. Derive the state, thermal history and chemistry of the IGM, study the first stars, black holes and galaxies and constrain cosmology, the physics of dark matter and gravity.	2/3
3	CD/EoR	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	Use SKA1-LOW to obtain 21cm absorption line spectra from (rare) radio sources at z>6 to probe very small scales (i.e. k~1000 Mpc-1) or virialized structures (mini haloes).	No observations of this kind have ever been done and are not expected to be feasible before SKA1-LOW is built, because of the same severe thermal noise limitations that limit direct imaging. As such the gain is infinite. The Cosmic Dawn remains inaccessible to current/funded instruments, until SKA1-LOW.	Achieving this goal would require deep 1000hrs integrations on selected sources with S>1mJy (possibly in the same fields selected for deep integrations) with a spectral resolution of a few km/s (1-5 KHz at 150 MHz) over the 50 to 200 MHz frequency range (z~6 to 28). No spatial information is required meaning that the background radio sources could be unresolved. Derive the state, thermal history and chemistry of the IGM, study the first stars, black holes and galaxies and constrain cosmology, the physics of dark matter and gravity	3/3
4	Pulsars	Revealing the pulsar population and finding MSPs for gravity tests and Gravitational Wave detection	Survey the entire sky visible from the SKA sites, at high spectral and temporal resolution, using SKA1-LOW and SKA1-MID arrays. Reaching desired depths will require about 2 years of observing time.	more than order of magnitude more known pulsars in the survey area	With SKA1 we propose to discover an order of magnitude more normal and millisecond pulsars (MSPs) than are currently known to improve our understanding of the neutron star population and to reveal pulsars which can be used for: gravitational wave astronomy; perform tests of gravity in the strong field regime; and probe the equation of state of superdense matter, and reveal the details of binary and stellar evolution. Require that it be possible to efficiently and sensitively survey the entire sky visible from the SKA sites, at high spectral and temporal resolution using SKA1-LOW and SKA1-MID arrays, for pulsars, including those that might be in binary or higher-multiple systems.	1/3
5	Pulsars	High precision timing for testing gravity and GW detection	High precision timing, with instrumental contributions to the noise budget of less than 10 ns, using the SKA1-MID and SKA1-LOW arrays, of multiple pulsars simultaneously where necessary and at high cadence. SKA1-MID will provide the requisite high precision while SKA1-LOW monitors the interstellar weather.	x5-x10 sensitivity for Southern pulsars & simultaneity will allow for the essential improvement in observing cadence of about once per 2 weeks. x few increase in total number of available sources	With SKA1 we propose to undertake high precision pulsar timing of millisecond and binary pulsars to: detect and characterise the gravitational wave sky at nanohertz frequencies; start gravitational wave astronomy; and perform tests of strong field gravity. We require that it be possible to perform high precision timing, with instrumental contributions to the noise budget of less than 10 ns, using the SKA1-MID and SKA1-LOW arrays, of multiple pulsars simultaneously where necessary and at high cadence. SKA1-MID will provide the requisite high precision while SKA1-LOW monitors the interstellar weather.	1/3

6	*Pulsars*	Characterising the pulsar population	High cadence (near daily) observations, including using sub-arraying to monitor a large number of pulsars, using both SKA1-MID and SKA1-LOW. Observations with parts of the array should be possible on a nearly daily basis.	x5-x10 sensitivity & ~ order of magnitude cadence, providing nearly daily observations of selected pulsars.	With SKA1 we propose to undertake high cadence pulsar timing observations of many sources to: understand the radio emitting neutron star population; revolutionise our understanding of the neutron star structure through glitches; understand the crucial relationship behind spin evolution and pulsar emission.	2/3
7	*Pulsars*	Finding and using (Millisecond) Pulsars in Globular Clusters and External Galaxies	Offline searches of (~8-12hrs) baseband data from 1-16 tied-array beams with SKA1-MID and SKA1-LOW.	x3-x4 deeper surveys -> x2-x3 increase in known population of pulsars in the Galactic globular cluster system (one- to a few-hundred new sources). For nearby galaxies this will be the first time there will be sufficient sensitivity to detect large populations of pulsars.	with SKA1 we will discover millisecond pulsars in the Galactic globular cluster system. As an ensemble, these sources will characterize the dynamical history of the clusters themselves; individually, some of the discovered pulsars can serve as probes of gravitational theories and the neutron star equation-of-state. Very similar searches of nearby galaxies will find normal and millisecond pulsars which will allow us to probe the formation of massive stars in very different stellar environments and potentially study the intergalactic medium. compared with previous deep searches with Arecibo, GBT, and Parkes, these searches will achieve on average 3-4x deeper surveys of these globular clusters. This provides the opportunity to double or perhaps triple the known population of pulsars in the Galactic globular cluster system by finding one hundred to a few hundred new sources. For nearby galaxies this will be the first time there will be sufficient sensitivity to detect large populations of pulsars.	2/3
8	*Pulsars*	Finding pulsars in the Galactic Centre	Galactic Centre observations with SKA1-MID at >5GHz, with high spectral and temporal resolution.	x5-x10 sensitvity improvement	With SKA1 we propose to discover pulsars orbiting SGR A* to: measure the mass of SGR A* to a precision of 1 solar mass; measure the spin of the central BH and test the cosmic censorship conjecture; measure the quadrupole moment of the central BH and test the no-hair theorem; place limits on the dark matter content in the GC; map the magnetized and ionized interstellar medium in the immediate vicinity of the supermassive BH, giving insight into the accretion process onto this object. To combat interstellar scattering toward the Galactic Centre, we require that it will be possible to observe at frequencies above 5 GHz, using SKA1-MID, with spectral and temporal resolution. Sensitivity improvement expected to result in detections	2/3
9	*Pulsars*	Astrometric measurements of pulsars to enable improved tests of GR	VLBI at 1.5 GHz on scales of 8000+ km with both SKA1-MID and SKA1-SUR	order of magnitude improvement in astrometric precision.	With SKA1-VLBI we propose to measure the parallax and proper motion independently of pulsar timing to enable improved tests of GR. Multiple simultaneous and independently steerable phased VLBI beams from both SKA1-MID and SKA-SUR, and scheduling and participation of these instruments in VLBI observations with other Southern Hemisphere VLBI telescopes (e.g., the Australia LBA, Hartebeestok etc) and other telescopes where possible. The best Southern Hemisphere pulsar VLBI to date has a precision of ~50 uas, and typical accuracy is several times this. SKA1-VLBI will improve upon this by an order of magnitude.	2/3

10	*Pulsars*	Mapping the pulsar beam	SKA1-MID and SKA1-LOW observations to obtain high signal to noise average pulse profiles and single pulse data from the large new population of pulsars and millisecond pulsars with wide instantaneous bandwidths	The number of pulsars observable will be greatly enhanced, including a new population of MSPs and there will be exceptional sensitivity for the known objects allowing for greatly improved single pulse observations. Sub-arrays in SKA1-MID/SKA1-LOW timing mode and/or simultaneous observations with both arrays will allow for extremely wide and contiguous frequency coverage compared to today's possibilities for the pulsars that can be observed with the reduced sub-array sensitivity.	With SKA1 we propose to map the time-variable and 3-dimensional structures of pulsar radio beams, to understand pulsar radio emission and how magnetospheric processes affect pulsar timing. require the high sensitivity of SKA1-MID and SKA1-LOW, to obtain high signal to noise average pulse profiles and single pulse data from the large new population of pulsars and millisecond pulsars; wide instantaneous bandwidths, to accurately separate intrinsic emission properties from propagation effects in the pulsar magnetosphere and the interstellar medium; high quality polarization measurements, to provide information on the beam geometry, emission heights, and propagation effects in the magnetosphere; high cadence monitoring to uncover how emission variability on a variety of time scales (from the pulse period to months and years) directly affects the pulsar rotational properties and the spin-down rate in particular.	3/3
11	*Pulsars*	Understanding pulsars and their environments through their interactions	Targeted imaging with resolution ~1 arcmin over ~0.5-1 degree with a polarised brightness temp sensitivity of ~10 mK at frequencies between ~0.1 and 1 GHz combined with time-binned imaging mode to separate pulsar emission from extended emission in small-scale PWN, and to measure the parallax distance to these pulsars.	detect considerable fraction of pulsar wind nebulae (bright at GeV and TeV energies) which have previouly remained undetected at radio. Additionally, the polarized emission from most PWNe in the southern hemisphere remains undetected due to beam depolarization and other effects along the line of sight which will be less of an issue due to the sensitivity of the SKA, allowing us to detect polarized emission from these sources over narrower bandwidths.	With SKA1 we propose to map the radio morphology, spectrum, and polarization of pulsar wind nebulae and their associated supernova remnants in the Milky Way. These measurements are required to measure the initial spin period and the energetics of the progenitor supernova for a large number of neutron stars, the multiplicity of particles in the neutron star magnetosphere, the spectrum of particles accelerated in these systems, and the diffusion of these particles into the surrounding medium. This is critical for understanding the formation of neutron stars, the physics of neutron star magnetospheres and ultrarelativistic outflows, and the origin of galactic cosmic rays - in particular the anomalous population of Gev-TeV positrons. Currently no interferometer in the Southern hemisphere can detect radio emission on these large angular scales, let alone at these sensitivites. As a result, a considerable fraction of pulsar wind nebulae bright at GeV and TeV energies remain undetected at the radio. Additionally, the polarized emission from most PWNe in the southern hemisphere remains undetected due to beam depolarization and other effects along the line of sight which will be less of an issue due to the sensitivity of the SKA, allowing us to detect polarized emission from these sources over narrower bandwidths.	3/3
12	*Pulsars*	Mapping the Galactic Structure	Polarisation observations with SKA-MID and SKA-LOW that after calibration reach a -40dB level. Wide bandwidths (>20%) are needed and absolute position angle calibration possible.	x10-x20 available sources	With SKA1 we propose to undertake wide frequency polarisation observations of pulsars to enable the mapping of the magnetoionic structure of the Galaxy and its constituent components and nearby galaxies.	3/3
13	*HI*	Galaxy evolution through resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	Targeted 100 to 1000hr observations (M* at z=0.5 - 0.8) with SKA1-Mid (0.5 deg2 at 3-4'' resolution) and (M* at z=0.4 - 0.6) with SKA1-Survey (18 deg2 at 5'' resolution). Reach column densities of 10^20 cm^-2.	x2-x5 sensitivity (depending on resolution), x2-x3 spatial resolution (making resolved studies feasible) & (dramatic) improvement in survey speed. The major step forward will be that the lookback time ~x2 (from 3-4 Gyr to 7-8 Gyr, covering most of timespan over which cosmic star formation declines by a factor ten).	this is one of the key overall science goals of the SKA, and an important phase 1 science goal according to SKA Memo 125. HI surveys with SKA1 will transform our understanding of the mass and angular momentum assembly in galaxies. While the late-stage products of galaxy evolution have been extensively studied through large-scale surveys in the optical and near-infared wavelengths, our understanding of the fundamental fuel from which galaxies are made remains rudimentary at best. Direct measurements of the HI content beyond the local universe are limited to samples of only a few hundred out to z~0.2-0.3 with current state-of the art facilities (JVLA, WSRT), compared to the >1.E+6 galaxy sample to z~1 (nearly 8 Gyr in look-back time, half the history of the Universe) that will be possible in a tiered survey approach with SKA1. Statistical studies of unresolved objects and stacked emission lines will be possible at even higher redshifts if permitted by band limits.	1/5

14	*HI*	High spatial resolution studies of the ISM in the nearby Universe.	Targeted 200hrs+ observations of nearby galaxies with SKA1-MID (3-4'' spatial resolution). Reach column densities of 10^20 cm^-2.	x2.5 sensitivity (at comparable resolution)	High-spatial resolution studies of nearby galaxies to examine, in combination with data from other wavebands, the physics of the ISM and star formation on the smallest relevant scales (sub-pc scale in the Galaxy, <500 pc in nearby galaxies) where the complex inter-relations between the various constituents of the ISM have to be understood. The combination with ALMA will be particularly attractive and will give a complete picture of the dynamic, cold ISM.	2/5
15	*HI*	Multi-resolution mapping studies of the ISM in our Galaxy	high spectral resolution (~0.1 km/s, over 5 MHz) and a spatial resolution of better than 10 arcsec at 1 K sensitivity with a combination of SKA1-SUR (2 years) and SKA1-mid	x3-x5 sensitivity, x3 column density with SKA1-MID, x100 survey speed with SKA1-SUR (at 6'' resolution)	High-spatial resolution studies of the HI in the Galaxy and Magellanic Clouds to examine, in combination with data from other wavebands, the physics of the ISM and star formation on the smallest relevant scales (sub-pc scale in the Galaxy, <500 pc in nearby galaxies) where the complex inter-relations between the various constituents of the ISM have to be understood. The combination with ALMA will be particularly attractive and will give a complete picture of the dynamic, cold ISM. Observations of the Galaxy and Magellanic Clouds with SKA1-SUR will allow the mapping of detailed structure in the ISM with the greatest speed. Combined with the excellent column density sensitivity of SKA1-MID at low resolutions, a true multi-resolution picture of accretion of gas from the halo and outflow of gas from the disks of the Milky Way and Magellanic Clouds will be available.	3/5
16	*HI*	HI absorption studies out to the highest redshifts.	Sample sizes of about 1000 absorbers per redshift interval, obtained by wide-field, relatively shallow surveys for z <1 (3000 hours), very deep and wide surveys for z <= 3 (2 years covering 350 - 700 MHz) and deep targeted studies of confirmed sources for z>3 (Nx1000 hours).	x3-x5 sensitivity, x20-x80 survey speed, red-shift coverage in unique bands, z = 0.5 to 3	HI absorption studies (statistical and of individual objects) down to the highest redshifts offered by SKA1 to study the evolution of IGM (intervening absorption) as well as the changing role of AGN feedback in galaxy evolution (HI outflows, associated absorption) out to very large lookback times and in fainter source populations. For detection experiments of HI absorption, the sensitivity should be at least a factor 3-5 better than current state-of-the art in order to open up new grounds. For high-resolution follow-up of detections, JVLA sensitivity should be delivered at higher spatial resolution than the JVLA A-array (i.e. below 1.0 arcsec). Good VLBI capabilities are also required.	4/5
17	*HI*	The gaseous interface and accretion physics between galaxies and the IGM	Targeted 200-1000hr observations of nearby galaxies at 1' resolution	x5 column density sensitivity, larger field of view	Low-resolution (~1 arcmin) observations of low-column density HI around nearby galaxies to study the gaseous interface between galaxies and the IGM (the Cosmic Web), as well as the physics of gas accretion. SKA1 offers the first possibility to cross the 'HI desert' and to image at the right resolution (kpc scale) column densities well below 1.E+18 cm-2 in nearby galaxies where it is expected the galaxy-IGM interface can be detected. The requirement is to be able to detect column densities at z = 0, at arcmin resolution, below 1.E+18 cm-2 in integration times of 200-1000 hr.	5/5
18	*Transients*	Solve the missing baryon problem at z~2 and determine the Dark Energy Equation of State	The detection, localisation and spectroscopic red-shift determination of N>1000 coherent bursts at cosmological distances is required (about 2 years of commensal observing).	Of order 10 such burst are currently known, so we are considering an increase by two orders of magnitude in rates alone, which will be multiplied by the leap forward in our understanding of the astrophysics when we also have counterparts at other wavelengths	The detection and localisation of N>1000 coherent bursts at cosmological distances will directly locate the missing baryons in intergalactic space that constitute at least 50% of the present-day Universe's baryonic content and determine their association with galaxy and cluster halos; in addition as cosmological rulers, these bursts measure the curvature of the Universe with sufficient precision to determine the dark energy equation of state at redshifts > ~ 2. Requires: (i) SKA1-Mid with ~2000 coherent beams running continuously and commensally searchable for fast events, (ii) SKA1-Low with commensally-searchable beamformer, (iii) Combination of incoherent burst detection plus transient buffer boards on SKA1-Low, -Survey and -Mid. Needs implementation of beamformed commensal transient searches. Given current estimates of event rates, some two years of continuous commensal observing is implied.	=1/4

19	*Transients*	Accessing New Physics using Ultra-Luminous Cosmic Explosions	(i) SKA1-Mid and SKA1-Low in both commensal-image-search and rapid-response mode (large survey FoM plus deepest point-source sensitivity for follow up). (ii) SKA1-Survey with commensal-image-search. Needs implementation of image plane commensal transient searches and rapid response modes. (iii) Higher frequency bands -- preferably at least 5 GHz	These will be the *first* radio-selected surveys for such phenomena, sampling populations which are only partially viewed in optical- or X-ray selected samples. Predicted rates of 1 per day to 1 per week for radio TDEs, for example, dwarf the current samples of such events (less than 10)	Ultra-luminous cosmic explosions, such as tidal disruption events and gamma-ray bursts, are the sites of the most extreme astrophysics in the universe, allowing us to probe pressures, energy and matter densities, speeds and gravitational curvature far in excess of anything we will ever achieve in a laboratory; they represent the most extreme environments since the Big Bang.	=1/4
20	*Transients*	Study how galaxies grow through measurements of Black Hole accretion, growth and feedback	(i) SKA1-Mid and -Survey in both commensal-imaging-search and targetted modes. Requires support for VLBI capability. (ii) Higher frequency bands -- preferably at least 5 GHz.	For studies of stellar-mass BH, neutron stars and ultraluminous X-ray sources we estimate an increase in the number of measurements by two orders of magnitude compared to the current state of the art within ~5 years.	The often-bursty radio emission from the jets of black holes allows us to probe the kinetic feedback from black holes as a function of accretion rate, black hole mass and other observables; these are key factors in understanding how feedback affects galaxy growth. In parallel we can test theoretical paradigms such as whether or not black hole spin, or simply accretion, powers such jets.	3/4
21	*Transients*	Detect the Electromagnetic Counterparts to Gravitational Wave Events	All components of SKA1 to have rapid response and commensal search modes.	No serious previous surveys to compare to. Wide-field optical response is being planned.	Discovery of the electromagnetic counterparts of gravitational wave sources would be a major breakthrough and vital in understanding their origin (e.g. merging neutron stars, black hole merger rates), especially in the case that the gravitational wave and electromagnetic signal provided two completely independent (in the sense that only one is electromagnetic) distance measurements on cosmological scales.	4/4
22	*Cradle of Life*	Map the growth of dust grains through the important cm-sized regime in the terrestrial planet forming zone inside the snow-line in proto-planetary disks at a distance of 100 pc	Stokes-I sensitivity of 60 nJy at the top end of SKA1-MID Band 5 (ν>10 GHz; Δν/ν=0.3) at 0.04" resolution in a single pointing within 1000 hours of integration	27x faster with 4x resolution over VLA [3 (sensitivity) x 4 (resolution) x 3 (field of view – multiple targets) = 36 better than the JVLA]	A resolution of 40 mas at 100 pc provides a linear resolution of 4 AU, which is the minimum resolution need to study grain growth to cm+ sizes within the terrestrial planet-forming zone. This resolution will be possible with ALMA, but mm/submm wavelengths are insensitive to grain sizes above a cm. The sensitivity is required as the flux from thermal dust emission is dropping quickly at these frequencies. The relatively large FOV allows for observations of multiple (10's) young stars in a single pointing, greatly increasing the science return.	1/5
23	*Cradle of Life*	The detection and monitoring of bursts of auroral emission from exo-planets in order to characterise their magnetic fields in terms of strength, orientation, and their rotational periods	This requires SKA1-LOW to achieve a Stokes-V sensitivity of 150 µJy at 50 MHz (Δν/ν=0.3) over 5 deg2 within 1 minute of integration.	400x faster than LOFAR [This is a factor of 20 (sensitivity) better than LOFAR]	Low-frequency (~50 MHz) auroral bursts from Jupiter are detectable up to 10 pc. Such emission is 100% circularly polarized and provides information on rotational and orbital rates, interior structure, and star-planet interactions. They allow for comparative studies with Solar System planets. Multi-epoch observations with on-target observations of order one hour/epoch with SKA1-LOW of all nearby stars (10-30 pc) are needed. Observations can be targeted or commensal, and are enabled with a multiple beam capability (tied-array beams, trading off bandwidth).	2/5
24	*Cradle of Life*	Survey all nearby (~100 pc) stars for radio emission from technological civilizations at levels currently emitted by terrestrial transmitters	This requires SKA1 to provide data spigots across the equipped frequency range of each facility (LOW, MID, SUR) that enables commensal access to external teams to the time series voltage data for four dual polarisation beams within the primary beam while any other targeted or other commensal imaging observations are taking place.	For SKA1-MID this is a factor of 8x faster than Arecibo [1.4 (sensitivity) x 4 (number of beams)] For SKA1-LOW this is a factor of 400x faster than LOFAR [20x better sensitivity] Plus another factor of 3 from being able to search three facilities at the same time and other more difficult to quantify factors such as much better interference rejection and fast switching of targets	Commensal observations are key to maximize the number of targets observed - over 5-10 years 800x more stars can be observed than by Project Phoenix at a similar sensitivity (1000 stars, 1-3 GHz). There are always targets within the primary beam. The need to process the data with high frequency and temporal resolution requires dedicated hardware and hence the need for suitable data spigots for external teams. More beam are better, the baseline design currently only provides 4.	3/5

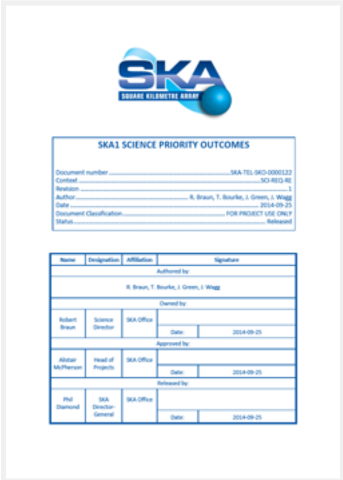
25	*Cradle of Life*	The detection of pre-biotic molecules with the best current estimate of their abundances of 10-11 relative to H in pre-stellar cores at distance of 100 pc.	This requires SKA1-MID to achieve a thermal noise-limited Stokes-I sensitivity of 35 µJy at a velocity resolution of 0.4 kms-1 at the top end of band 5 (12 GHz) with 3 arcsec resolution, in a single pointing within 500 hours of integration.	430x faster than VLA [3(sensitivity) x 16 (number of spectral channels) x 3 (field of view – multiple/extended targets) better than the JVLA]	The detection of pre-biotic molecules, in particular amino acids and molecules with peptide bonds, is a key focus of astro-chemistry/biology. The observations require a spectral resolution matched to the expected line-width for maximum sensitivity, and require the full 2.5 GHz (with 256k channels) at the high-end of the band to cover a number of transitions from a single molecule, to confirm any detection. While ALMA can also observe many similar molecules with multiple transitions, those observations suffer greatly from line confusion, with many lines blended with lines of other molecules (line forests), so unique line identification is almost impossible.	4/5
26	*Cradle of Life*	The accurate mapping of the sub-structure and dynamics of nearby clusters of forming stars via their continuum emission and the kinematics of their accretion flows and outflows using maser emission.	This requires SKA1-MID to support VLBI with four tied-array beams distributed over one or more sub-arrays.	400x faster than VLBA [10(sensitivity) x 4 (beams) better than the VLBA] 100x faster than EVN [5 (sensitivity) x 4 (beams) better than the EVN]	Requires multi-epoch observations to observe the proper-motions of radio-detected protostars, proper motions of their jets, and orbital motions of protostellar-binaries. VLBI needed to provide µas resolution, SKA1 needed to provide sensitivity - current observations are very sensitivity limited (<5 stars per cloud). Observations < 10 GHz to avoid confusion from dust emission. Order magnitude improvement over GAIA, which is also restricted to optical - many YSOs are not detected at optical wavelengths.	5/5
27	*Magnetism*	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	All-Sky polarization survey between 1 and 1.5 GHz to a sensitivity of 2 microJy, resolution of 2'' and polarisation purity of 0.1% (1.5 years).	x300-x1000 current RM measurements.	An All-Sky Polarisation Survey to be performed with SKA1 at ~1-1.5 GHz will provide a densely-spaced Grid of Rotation Measure (RM) measurements, essential to investigate magnetic fields in a variety of astrophysical contexts. This will permit detailed knowledge of the magnetic field strength and structure in the interstellar medium, external galaxies, AGNs, in the intra-cluster medium, at the boundary of galaxy clusters, in the bridges which join clusters, and possibly in the larger filamen tary Cosmic Web.	1/5
28	*Magnetism*	Determine origin, maintenance and amplification of magnetic fields at high redshifts - I.	10 square degree field between 1 and 2 GHz to a sensitivity of 0.1 microJy, resolution of 0.5-1.0'' and polarisation purity of 0.1% (1 year).	Sensitivity over an order magnitude compared to the present state-of-the-art instruments (e.g. JVLA).	We would exploit the sensitivity of SKA1 to investigate magnetic fields at high redshift. Studying the evolution of magnetic fields might lead to the origin of magnetism and constrain the mechanism of their maintenance and amplification. Deep surveys at 1-2 GHz will offer, for the first time, the opportunity to systematically explore the polarisation properties in faint and distant objects, exploring the emergence and evolution of magnetic fields across cosmic time in a large number of galaxies, AGNs, galaxy clusters and intergalactic filaments.	2/5
29	*Magnetism*	Detection of polarised emission in Cosmic Web filaments	Targeted regions between clusters at ~ 600MHz to a sensitivity of 0.2 microJy, resolution of 3 to 30'' and a polarisation purity of 0.1% (1000 hours).	Sensitivity improved by a factor of~ 200-1000 compared to current attempts to detect Cosmic Web filaments with the GMRT at 610 MHz.	SKA1 has the potential to discover the polarised synchrotron emission of the Cosmic-Web, illuminating large-scale magnetic fields in the Universe. The detection of the Cosmic-Web is among the most exciting challenges in modern astrophysics and would have a high scientific impact. Since galaxy clusters are believed to be formed at the intersection of cosmological filaments, the observations should be centered on distant (z ~ 0.4–0.5) and massive galaxy clusters.	3/5
30	*Magnetism*	Determine origin, maintenance and amplification of magnetic fields at high redshifts - II.	3 square degree field between 2 and 3 GHz to a sensitivity of 0.1 microJy, resolution of 0.5-1.0'' and polarisation purity of 0.1% (1 year).	Sensitivity over an order magnitude compared to the present state-of-the-art instruments (e.g. JVLA).	We would exploit the sensitivity of SKA1 to investigate magnetic fields at high redshift. Studying the evolution of magnetic fields might lead to the origin of magnetism and constrain the mechanism of their maintenance and amplification. Deep surveys at 2-3 GHz will offer, for the first time, the opportunity to systematically explore the polarisation properties in faint and distant objects, exploring the emergence and evolution of magnetic fields across cosmic time in a large number of galaxies, AGNs, galaxy clusters and intergalactic filaments.	4/5

31	*Magnetism*	Intrinsic properties of polarised sources	Targeted observations of nearby star-forming galaxies and AGNs between ~3 and 5 GHz For star-foming galaxies a sensitivity of 0.2 microJy, and resolution of 5'' is required. AGNs studies requires ultra-high angular resolutions, feasible through the addition of VLBI observations. SKA1-MID in Band4 (and possibly in Band5) is the most appropriate instrument (100 hours/target).	Spatial resolution of 1–100 pc (in nearby star-forming galaxies), not reachable with the sensitivity of present-day radio telescopes.	High frequency and high resolution pointed observations of polarised sources like star-forming galaxies and AGNs are extremely important since moderate Faraday rotation and internal depolarisation are expected to have a weak effect on the observed polarisation thus reflecting the intrinsic linear polarisation properties of the sources. The study the intrinsic polarisation properties of particularly compact sources such as relativistic jets from supermassive black holes in AGNs, requires ultra-high angular resolutions up to a few milliarcseconds or lower, which is feasible through very long baseline interferometry (VLBI) involving phased SKA1-MID and other external radio stations/arrays all around the globe. Optimum VLBI observations are from ~1 GHz to as high as possible, ideally reaching SKA1-MID Band5.	5/5
32	*Cosmology*	Map the 3D matter distribution on the largest scales and deepest redshifts ever - in order to obtain transformational constraints on primordial non-Gaussianity and to perform the first tests of gravity on super-horizon scales.	HI Intensity Mapping survey of 30,000 square degrees covering redshift z=0.2 to 3 (nu=350 - 1200 MHz).	(a) Transformational precision on non-Gaussianity, up to 10 x better than Planck, allowing for a test of the simplest inflation models (and out-performing Euclid). (b) The first ever tests of gravity on scales near and above the horizon; forecasting still in progress, but precision is likely up to 10x better than current state of the art.	Ultra-large volume, bigger than any other cosmological spectroscopic survey, with very accurate redshifts. This allows us to map for the first time the large-scale HI distribution in 3/4 of the universe, from today all the way back to the start of dark energy domination and then well before that. Requires calibrated auto-correlation data. Completely different systematics than optical/IR surveys allow SKA1 to deliver significant improvements on the precision of future optical/IR competitors via cross-correlation. Estimated survey time is ~10,000 hours with each of bands 1 and 2 as defined on either SKA1-MID or SKA1-SUR	1/5
33	*Cosmology*	Probe the initial conditions and the global features of the Universe - through non-Gaussianity and the dipole in the matter distribution - using high precision measurements of the angular correlation functions.	Continuum survey of 30,000 square degrees, at few microJy sensitivity and few arcsecond resolution.	(a) SKA1 will give the first answer to the key question – does the matter dipole agree with the CMB dipole? – with precision ~100x better than NVSS. (b) Precision on non-Gaussuanity ~3x better than Planck - and independent of HI IM approach.	Achieve precision constraints on two key indicators that could rule out standard models of Inflation, using the ultra-large volumes of a Continuum survey. Redshift information from HI and optical/IR surveys is used to strengthen the constraints. Separation of radio galaxy populations improves the constraining power via the multi-tracer technique. Completely different systematics than optical/IR surveys allow SKA1 to deliver significant improvements on the precision of future optical/IR competitors via cross-correlation. Estimated survey time is ~10,000 hours with band 2 of SKA1-MID or SKA1-SUR.	2/5
34	*Cosmology*	Map the dark Universe with a completely new kind of weak lensing survey - in the radio.	Measuring galaxy shapes in a Continuum survey of 5000 deg2; achieving 0.6 arcsec resolution or better, and 5 galaxies per square arcmin or more.	(a) Competitive with DES (but probing higher redshifts) – and SKA1-DES cross-correlation could be a game-changer in overcoming the systematic floor that either survey reaches on its own. (b) Commensal measurement of lensing of the HI intensity is a completely new probe with no competitors.	The first ever weak lensing survey in the radio that can deliver cosmological precision, mapping the dark matter and dark energy/ modified gravity in an entirely new and independent way. Full SKA will be transformational in combination with Euclid – provided that the groundwork has been done with an SKA1 weak lensing survey. New techniques (radio polarisation and 21cm rotational velocity measurements) to reduce contamination due to intrinsic alignments, the key limiting astrophysical systematic in weak lensing – these techniques are not available in the optical. Estimated survey time is ~10,000 hours with band 2 of SKA1-MID (Requirement is Bmax >=120km.)	3/5
35	*Cosmology*	Test dark energy & general relativity through high-precision measurements over a wide redshift range of the power spectrum, BAO, redshift-space distortions and topology.	HI Intensity Mapping survey of 30,000 square degrees covering redshift z=0.2 to 3 (nu=350 - 1200 MHz).	Dark Energy FoM~10 x better than BOSS. Similar precision to (and earlier than) Euclid, but probes higher redshift.	Tackle the most fundamental question in cosmology – is the acceleration of the Universe driven by vacuum energy (cosmological constant) or by dynamical dark energy or by a breakdown in General Relativity? – by constraining the equation of state and the growth rate. Survey details: the same survey as in objective 1.	4/5
36	*Cosmology*	Test dark energy & general relativity by conducting the fore-runner of the 'billion galaxy' survey.	HI Galaxy Redshift survey detecting 10^7 galaxies over 5000 square degrees at median redshift z = 0.25.	The highest precision measurements ever of standard dark energy probes, but only at low redshifts, so that there is insufficient volume to match the BOSS FoM – but it can enhance the power of an Intensity Mapping survey.	This survey is essential to build the foundations for the 'billion galaxy' survey of the full SKA, which will be the real state of the art in cosmology, out-performing all optical/IR competitors. Estimated survey time is ~10,000 hours with band 2 of SKA1-SUR or SKA1-MID.	5/5

37	*Continuum*	Measure the Star formation history of the Universe (SFHU) - I. Non-thermal processes	Tiered Survey Approach: (T1) 1000-5000 square degrees at ~1 GHz with a sensitivity of 1 microJy/beam rms and ~0.5" resolution (1 year). // (T2) 10 to 30 square degrees with a sensitivity of 0.2 microJy/beam rms at ~1 GHz with ~0.5'' resolution (2000 h) // (T3) one square degree at ~1 GHz with a sensitivity of 50 nJy/beam rms at 0.5'' resolution (2000 h)	(T1) same sensitivity as the MeerKAT MIGHTEE-2 survey but cover 30 to 100 times more area // (T2) 10x deeper than VLASS-3 (JVLA) over the same area. // (T3) 40x deeper than VLASS-3 over a 10x smaller area.	The radio luminosity provides a much more reliable tracer of star formation rate than optical/UV luminosities, especially at high redshift where the latter are strongly affected by dust extinction. This survey will provide an unbiased measurement of the Star Formation Rate Density (SFRD) as a function of cosmic time, stellar mass, galaxy morphology and environment. The choice of ~0.5'' resolution at ~1 GHz has been chosen to be similar to that of next generation optical/near-infrared survey telescopes (ie. Euclid (0.2")and LSST (0.7")). In addition it guarantees that T2 and T3 can reach thermal noise (not confusion limited). (T1) will probe the bulk of the SFG population (down to SFR~0.5 M☉/yr at z~0.1; and to SFR~5 M☉/yr at z~0.5) over a wide range of environments, and will allow to perform resolved SF studies (bulge vs disk emission) in the redshift range where the evolution function presents its strongest derivative (0<z<1). Cosmic variance effects <5%. (T2) will detect SFR>10 M☉/yr galaxies at z~1-2, ie at the epoch of maximum star formation activity. Cosmic variance effects <5-10% at the redshifts of interest, for <1010 11 M☉ galaxies. (T3) will detect SFR>10 M☉/yr galaxies up to z~3-4, and SFR>50 M☉/yr galaxies up to z~6, to probe star formation in the very early phases of galaxy evolution.	1/8
38	*Continuum*	Measure the Star formation history of the Universe (SFHU) - II. Thermal processes	Tiered Survey Approach: (T1) image 0.5 square degrees at 10 GHz with a sensivity of 300 nJy/beam rms at 0.05'' resolution (1000 h) // (T2) 30 square arcmin field imaged at 10 GHz with a sensitivity of 30 nJy/beam rms at 0.1'' resolution (1000 h)	(T1) 3x deeper than a current JVLA 10 GHz pointing of GOODS-North (0.2'' resolution) over a 80x larger area. It would also be a factor ~2x deeper than the 5 GHz tier of the eMERGE legacy survey (GOODS-N, 0.05" resolution) over a 20x larger area. // (T2) 30x deeper than the JVLA 10 GHz single pointing of the GOODS-N deep field (0.2'' resolution) over a similar area. It would also be a factor ~20x deeper than the 5 GHz tier of the eMERGE legacy survey (GOODS-N, 0.05" resolution) but over a 3x smaller area.	Observations at 10 GHz provide insights on the ISM properties at high redshift, where they probe rest-frame wavelengths where thermal (free-free) dominates over synchrotron emission. In addition, resolutions of the order of 0.05-0.1" allows to map the distribution of active SF within galaxies, and morphologically separate out AGN contributions for unbiased measurements of SFRs. (T1) will detect SFR ~100 M☉/yr galaxies out to z≲3 (rest-frame 40 GHz for robust SFR estimates); will resolve SFR>100 M☉/yr galaxies on sub-kpc (≲0.1") scales out to z~0.5 // (T2) will detect SFR ~50 M☉/yr galaxies out to z~6 (same as Ultra Deep Tier at 1 GHz in their rest-frame 70 GHz emission, providing a robust SFR indicator; will resolve SFR>100 M☉/yr galaxies on sub-kpc (~0.1") scales out to z~1; will resolve SFR>100 M☉/yr galaxies on kpc (≲0.2") scales out to the peak of the cosmic star formation rate density (z≲2; rest-frame 30 GHz, also typically dominated by free-free emission);	2/8

39	*Continuum*	Probe the role of black holes in galaxy evolution - I.	Tiered Survey Approach: (T1) 1000 5000 square degrees at ~1 GHz with a sensitivity of 1 microJy/beam rms and ~0.5" resolution (1 year). // (T2) 10 to 30 square degrees with an rms a sensitivity of 0.2 microJy/beam rms at ~1 GHz with ~0.5'' resolution (2000 h) // (T3) one square degree at ~1 GHz with a sensitivity of 50 nJy/beam rms at 0.5'' resolution (2000 h)	(T1) same sensitivity as the MeerKAT MIGHTEE-2 survey but cover 30 to 100 times more area. // (T2) 10x deeper than VLASS-3 (JVLA) over the same area. // (T3) 40x deeper than VLASS-3 over a 10x smaller area.	This survey will probe galaxy/AGN co-evolution and AGN feedback as a function of cosmic time, stellar/BH mass, galaxy morphology and environment. Current evidences show that deep radio surveys can probe the entire AGN population (both Radio-Loud (RL) and Radio Quiet (RQ) AGN), and therefore both radio (slow) and quasar (fast) accretion/feedback modes. Radio emission is not affected by dust/gas obscuration and therefore free from AGN type /orientation selection effects. The choice of 0.5'' resolution at 1 GHz has been chosen to be similar to that of next generation optical/near-infrared survey telescopes (ie. Euclid (0.2") and LSST (0.7")). In addition it guarantees that T2 and T3 can reach thermal noise (not confusion limited). T1) will be sensitive to the bulk of the AGN population (RQ and low-power RL AGNs down to L~1.E+21 W/Hz at z~0.1 and to L~1.E+22 W/Hz at z~0.5) over a wide range of environments, for detailed studies of the radio-quiet/radio-loud (RQ/RL) dichotomy; AGN-galaxy coevolution and feedback. T2) will detect RQ and low-power RL AGNs down to L~1.E+22 W/Hz at z~1-2, thus probing galaxy/AGN co-evolution and AGN feedback at the epoch of maximum activity for detailed studies of AGN-galaxy co-evolution and AGN feedback as a function of stellar/BH mass, environment and galaxy morphology. T3) will detect RQ and low-power RL AGNs down to L~1.E+22 W/Hz at z~3-4, to probe galaxy/AGN co-evolution and AGN feedback in the early phases of galaxy evolution for detailed studies of AGN-galaxy co-evolution and AGN feedback as a function of stellar/BH mass, environment and galaxy morphology.	3/8
40	*Continuum*	Probe the role of black holes in galaxy evolution - II.	Tiered Survey Approach: (T1) image 0.5 square degrees at 10 GHz with a sensitivity of 300 nJy/beam rms at 0.05'' resolution (1000 h) // (T2) 30 square arcmin field imaged at 10 GHz with a sensitivity of 30 nJy/beam rms at 0.1'' resolution (1000 h)	(T1) 3x deeper than a current JVLA 10 GHz pointing of GOODS-North (0.2'' resolution) but 80x larger area. It would also be a factor ~2x deeper than the 5 GHz tier of the eMERGE legacy survey (GOODS-N, 0.05" resolution) over a 20x larger area. // (T2) 30x deeper than the JVLA 10 GHz single pointing of the GOODS-N deep field (0.2'' resolution) but with a similar area. It would also be a factor ~20x deeper than the 5 GHz tier of the eMERGE legacy survey (GOODS-N, 0.05" resolution) but over a 3x smaller area.	This survey is complementary to the survey proposed for science objective Continuum - 3. Resolutions of the order of 0.05-0.1" allows to morphologically separate out AGN contributions to total energetics for detailed studies of AGN/SF co-evolution and AGN feedback. T1) will resolve sub-kpc (≲0.1") scales out to z~0.5 allowing to spectro-morphologically separate out flat spectrum AGN radio cores for detailed studies of AGN-galaxy co-evolution/feedback. T2) will resolve sub-kpc (~0.1") scales up to z~1 allowing to spectro-morphologically separate out fllat spectrum AGN radio cores for detailed studies of AGN-galaxy co-evolution/feedback.	4/8
41	*Continuum*	Probe the non-thermal components (cosmic rays and magnetic fields) in the intra-cluster medium (ICM) and cosmic filaments.	All-sky survey with SKA1-LOW (2-years): Image an area of 31,000 square degrees at 120 MHz with a sensitivity of 20 microJy/beam rms at 10'' resolution.	Factor of 3x better surface brightness sensitivity than current LOFAR all-sky surveys which corresponds to detection of a factor of 10x fainter radio haloes/relics.	Radio observations of galaxy clusters are a unique probe for diffuse (Mpc scale) synchrotron radio emission in galaxy clusters and filaments. This emission is thought to be produced by mechanisms of particle acceleration (via shock and turbulence) active during the hierarchical formation of the large scale structure of the Universe. a) will detect ~2600 radio haloes (RHs) up to z~0.6, including ~1000 ultra steep spectra radio haloes (USSRH), a factor ~7x increase over LOFAR All Sky Survey; b) will probe for the very first time the existence of hadronic 'off-state' radio halos, predicted for virialized cluster. c) will be able to detect RHs in clusters up to z~1 and with masses down to M500 ~ 1.E+14 M⊙, thus competing with eROSITA and Sunyaev-Zel'dovich (SZ) surveys in blind cluster searches; d) will detect >1-10% fraction of the diffuse non-thermal emission in massive B~0.1-0.3 μG cosmic filaments, or will provide an upper limit in case of lower magnetic fields.	5/8

42	*Continuum*	Study the detailed astrophysics of star-formation and accretion processes - I.	All-sky high-resolution survey at Band 2 (2 years) - : Image an area of 31,000 square degrees at 1.4 GHz with a sensitivity of 3 microJy/beam rms at 0.5" resolution.	Factor of more than three deeper than ASKAP EMU survey with 20x higher resolution	Fundamental understanding of the physics of the Inter Stellar Medium (ISM) in the Local Universe. Resolved studies of star-formation processes within local galaxies as a function of galaxy type, environment and evolutionary stage provide an essential anchor point to using thermal or non-thermal radio continuum (RC) emission as a star-formation tracer at all redshifts and is key requirement for the interpretation of deep radio continuum surveys. An angular resolution of the order of 0.5 arcsec will allow to resolve 100 pc scales at distances of D~40 Mpc.	6/8
43	*Continuum*	Probing dark matter and the high redshift Universe with strong gravitational lensing.	All-sky high-resolution survey (2 years) -: Image an area of 31,000 square degrees at 1.4 GHz to an rms of 3 microJy/beam at ≤0.5" resolution.	This survey will be about a factor 5 more sensitive than the ASKAP all-sky survey (EMU) with a factor ~20 better angular resolution. This survey could detect up to 30000 new strong gravitational lenses, an improvement of a factor 1000 from the number known now, with about 7000 within this sample having sufficient brightness and large enough lensed image separations for straight-forward identification in the first instance.	Gravitational lenses are intrinsically rare events (~1:1000 for galaxy- and ~1:50000 for cluster-lenses) and thus require sensitive wide-field surveys to be carried out at sub-arcsecond angular resolution. For maximal efficiency, resolutions of 0.2'' are required. However, resolutions of 0.5'' are also useful, at the expense of sample completeness (lenses producing smaller image separations will be missed) and an increase in the number of false positives (requiring a higher level of follow-up). A particularly promising approach is to combine two surveys at different wavelengths — here, SKA1 together with Euclid/LSST — as this will allow a more efficient rejection of false positives. This survey will: a) test models for galaxy formation and dark matter that predict well defined mass-density profiles for individual haloes (as a function of mass, epoch and environment) and the form of the dark matter halo mass function. b) will allow detailed studies of the source population that will be routinely detected with the full SKA because of the improved sensitivity and angular resolution provided by the lensing magnifications (typically factors of ~5-10).	7/8
44	*Continuum*	Legacy/Serendipity/Rare.	All-sky low-resolution survey (2 years): Image an area 31,000 square degrees at 1.4 GHz with a sensitivity of 2 microJy/beam rms at ≤1'' resolution.	The proposed survey is expected to be a factor of 5 more sensitive than the ASKAP all-sky survey (EMU) with a factor of 10 higher angular resolution	a) Legacy: Previous radioastronomical surveys have typically had about one-tenth the publications and citations of optical surveys, because radio surveys previously were dominated by the rare radio-loud AGN. Next-generation surveys break through a a barrier where they will be dominated by mainstream galaxies, providing radio photometry (and spectral index) for most galaxies brighter than R=23, bringing radio-astronomy into the mainstreeam. Post-SKA SEDs and photometric redshifts will routinely use radio data, which is currently absent from such studies. b) Serendipity: History shows that the major discoveries made with major new telescopes (such as HST) are rarely those listed as specific science goals. Instead, the majority of major astronomical discoveries are unexpected. So to maximise major discoveries with SKA means that the instrument should be designed to maximise versatility and parameter space, and should include software to mine the data for unexpected discoveries. c) Rare: all-sky surveys can provide sizeable samples of rare classes of objects. This survey, for instance, will provide crucial high-n (spectral index) information for galaxy cluster radio halos, by detecting ~750 new halos up to z~0.6;	8/8


SKA1 SCIENCE PRIORITY OUTCOMES

SKA-SCI-PRI-002-AppendixA

EchoSign Document History September 26, 2014

Created:	September 25, 2014
By:	Susan Nel (s.nel@skatelescope.org)
Status:	SIGNED
Transaction ID:	XEIIXQR63XXR242

"SKA-SCI-PRI-002-AppendixA" History

Document created by Susan Nel (s.nel@skatelescope.org)
September 25, 2014 - 10:16 AM GMT - IP address: 194.81.218.60

Document emailed to Robert Braun (r.braun@skatelescope.org) for signature
September 25, 2014 - 10:17 AM GMT

Document viewed by Robert Braun (r.braun@skatelescope.org)
September 25, 2014 - 10:36 AM GMT - IP address: 130.88.0.208

Document e-signed by Robert Braun (r.braun@skatelescope.org)
Signature Date: September 25, 2014 - 10:40 AM GMT - Time Source: server - IP address: 130.88.0.208

Document emailed to Alistair McPherson (a.mcpherson@skatelescope.org) for signature
September 25, 2014 - 10:40 AM GMT

Document viewed by Alistair McPherson (a.mcpherson@skatelescope.org)
September 26, 2014 - 12:47 PM GMT - IP address: 58.7.187.124

Document e-signed by Alistair McPherson (a.mcpherson@skatelescope.org)
Signature Date: September 26, 2014 - 12:48 PM GMT - Time Source: server - IP address: 58.7.187.124

Document emailed to Philip Diamond (p.diamond@skatelescope.org) for signature
September 26, 2014 - 12:48 PM GMT

Document viewed by Philip Diamond (p.diamond@skatelescope.org)
September 26, 2014 - 12:53 PM GMT - IP address: 193.205.246.219

Document e-signed by Philip Diamond (p.diamond@skatelescope.org)
Signature Date: September 26, 2014 - 12:53 PM GMT - Time Source: server - IP address: 193.205.246.219

Signed document emailed to Susan Nel (s.nel@skatelescope.org), Philip Diamond (p.diamond@skatelescope.org), Alistair McPherson (a.mcpherson@skatelescope.org) and Robert Braun (r.braun@skatelescope.org)
September 26, 2014 - 12:53 PM GMT