SKA Science
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SKA Science: A Parameter Space Analysis

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Abstract.
This paper describes a simple parameter space analysis which we are developing to gain insight into the interplay between the science drivers and the design requirements for the Square Kilometre Array radio telescope (SKA). We base the analysis on the current SKA Science working document (Taylor et al. 1998). We have considered the requirements of 32 science drivers against the key operating parameters which will influence the design of the SKA. We have made no attempt to prioritise the individual science drivers and present the individual science requirements as a first-pass only. Even so, some minimum requirements for the SKA and areas of inter-dependencies are already identifiable. We highlight where more detailed simulations are required to refine the SKA specification. We discuss how this analysis could be developed and refined by the International Science Advisory Group and how combining this analysis with the capabilities of current and other future radio astronomy facilities, both the parameter space and science drivers unique to the SKA will be identified.

1. Background

The individual SKA science drivers are well-developed (Taylor et al. 1998). However, little attempt has been made to consider these in the light of an integrated SKA specification beyond the preliminary specification derived at the Sydney workshop in December 1997 which is reproduced in Appendix A. In this paper we discuss how the SKA specification might be determined from a large number of individual science drivers. We hope that this is a useful on-going tool for the SKA project.

2. A parameter space analysis

We have constructed an EXCEL spreadsheet on which to record the science driver requirements. The 32 science drivers are listed in Appendix B, along with the key assumptions and considerations which lie behind this analysis. For each science driver we have assessed the following parameters:

- **Frequency** Indicates the useful frequency ranges

Value 0 = useless for this science driver, 1 = marginally useful, 2 = useful or 3 = critical.

- **Sensitivity** Indicates the necessary sensitivity (5σ) at each frequency range. For most drivers this is the sensitivity assuming a 10-hour integration time.
- **Spatial resolution** The resolution required from sub-milliarcsec upwards, for each frequency range.
- **Surface brightness sensitivity** The UV coverage requirement based on the extended nature of the sources. Indicates the largest angular size at each frequency range.
- **Field of view** The imaged field size.
- **Multi-beaming** Indicates whether the science driver requires instantaneous beams and, if so, their position on the sky relative to the primary beam:

  Value N = no requirement for multi-beaming, A = multi-beaming required, adjacent to primary beam or W = multi-beaming required, widely spaced.

  For A or W the number of beams on sky is also shown.
- **Dynamic range** Clean beam dynamic range.
- **Channels** The required number of spectral channels. Indicates both the bandwidth and the frequency resolution required.
- **Freq Agility** The maximum allowable time to switch between frequencies:

  Value N = not an issue or maximum elapsed time in seconds.
- **Total Power** Indicates usefulness of total power measurement:

  Value 0 = not required for this science driver, 1 = marginally useful, 2 = useful or 3 = critical.
- **Polarization** Requirement for polarization measurements:

  Value 0 = not required for this science driver, 1 = marginally useful, 2 = useful or 3 = critical.
- **Time resolution** Whether short sampling intervals are necessary:

  Value Y = short time sampling required or N = not required.

The completed spreadsheet is attached as Appendix C.

In contrast to the preliminary SKA specification (Appendix A) we have not explicitly included the following parameters:

- Sky coverage. Assumed to be 2 sterad.
- Maximum primary beam separation. Covered in multi-beaming.

- Number of pixels.
- Instantaneous bandwidth.
- Number of instantaneous frequency bands.
- Calibratable polarisation purity.

The analysis has the following obvious weaknesses:

1. We have identified 32 'pure' astronomy science drivers from the current SKA science case. These will be refined as the SKA science case continues to develop.
2. We have ignored the synergies between the science drivers.
3. We have ignored all technical or budgetary constraints.
4. The parameter requirements ('scores') have been assigned by a single individual and should be interpreted as a first-pass only, to show the usefulness of this analysis method.

3. Initial analysis results

In this section we show how the multi-parameter analysis for the 32 science drivers gives some insight into the overall SKA requirements.

3.1. SKA frequency coverage

The distribution of scores across the frequency range 100 MHz to 10 GHz reveals that the highest-ranked range is that from 400 MHz to 4 GHz (Figure 1) where 18 or more science drivers rate this frequency range critical (score '3'). It is notable that in this range 400 MHz to 4 GHz, the scores are unequivocally '3's (critical). However, at either end of this frequency range the other frequency bands score equally highly when the scores for critical and useful ('3's + '2's) are combined. This suggests that even if the SKA covers a relatively narrow frequency range, many science drivers will be able to exploit its capabilities.

Science drivers which require low frequency coverage (< 400 MHz) are those which probe to high redshift e.g. the reionization of the IGM, supernovae etc. Science drivers which require a high frequency SKA (>10 GHz) are the Sunaev-Zeldovich effect, thermal continuum processes and molecular line studies (galactic and extragalactic).

We show the distribution of required frequency agility for the 32 science drivers in the table below. The majority of the science drivers (23/32, 72%) require no particular frequency agility for the SKA. As we have only asked the simple question whether frequency agility capability is required, we cannot say

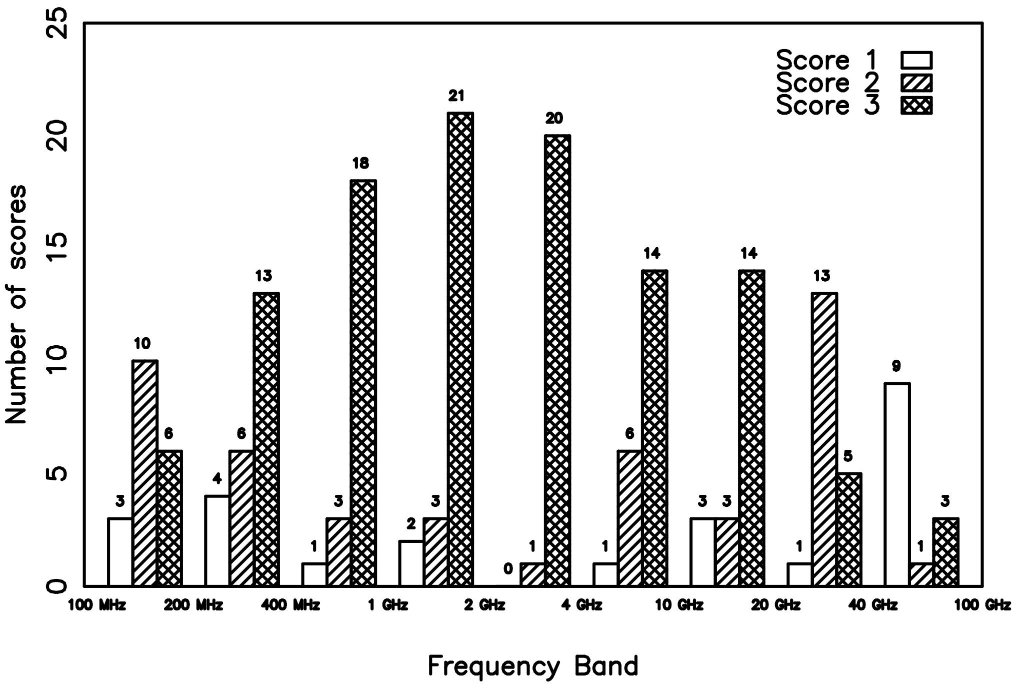

Figure 1. Distribution of scores for the 32 science drivers across the frequency bands. Scores indicate 3: Critical, 2: Useful and 1: Marginally useful. Numbers above the distributions indicate the contributing number of science drivers.

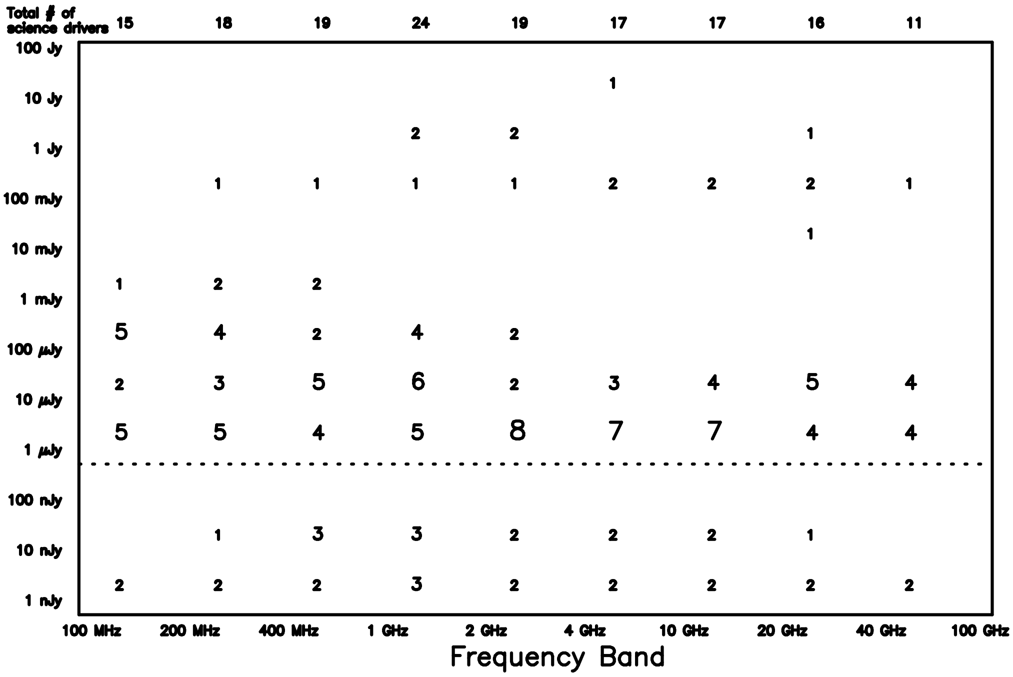

Figure 2. Distribution of required sensitivity limits (S_ν, 5σ) for the 32 science drivers across the frequency bands as shown. As not all science drivers require all frequency bands, the total per frequency band (along top of figure) is less than 32. It can be seen that a sensitivity of 1μJy across the whole frequency range would encompass all scores of 4 or more science drivers.

if it is considered necessary between all possible frequencies or is limited to a particular frequency range or pair of frequencies.

	Frequency Agility			
	None	~1 min	10 secs	~1 sec
Number of Science Drivers	23	5	1	3

The coarseness of the scoring (0 – 3) and the arbitrary division of the frequency range should both be refined in future to increase the usefulness of this key parameter. In particular the frequency ranges should be matched to those attainable by the emerging SKA technologies (e.g. Luneburg lenses, phased arrays, etc).

3.2. SKA sensitivity

The distribution of required sensitivity limits reveals that at all frequencies, the vast majority of the science drivers are attainable with a 5σ limit of 1 μJy (Figure 2).

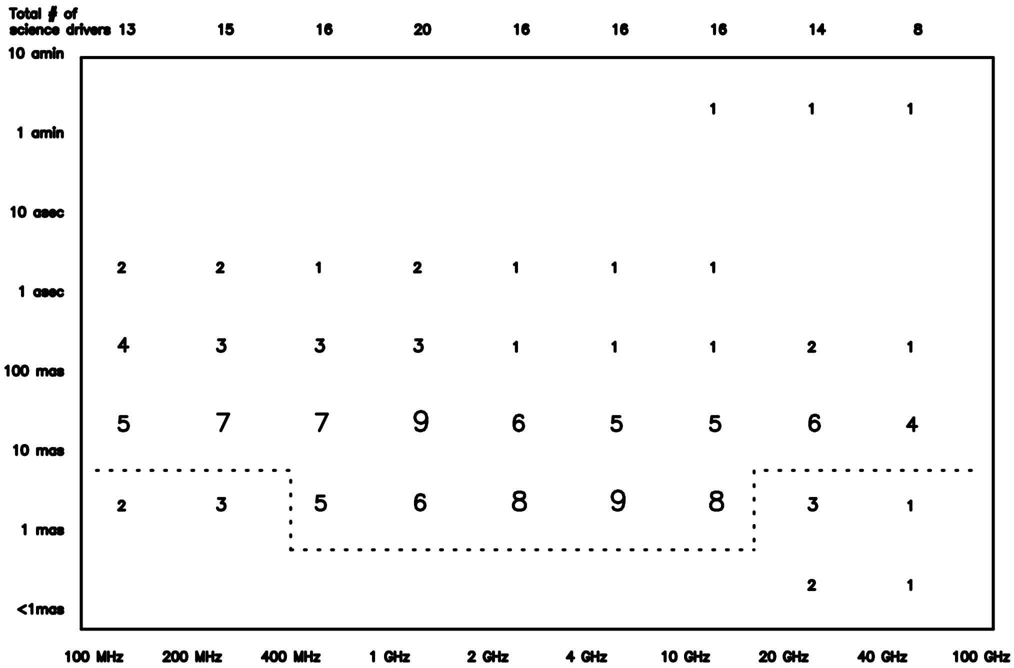

Figure 3. Distribution of required spatial resolution for the 32 science drivers across the frequency bands as shown. As not all science drivers require all frequency bands, the total per frequency band (along top of figure) is less than 32. The resolution limits required to encompass all scores of 4 or more science drivers is shown dotted.

The science drivers which require higher sensitivity are gravitional lensing, molecular lines in the local Universe and pulsar studies.

Careful consideration of the sensitivity limits must be made so that all specified values are comparable, e.g. for 10-hour integration time. Equally importantly, not all science drivers require imaging at that sensitivity, an aspect which is not discussed here.

3.3. SKA spatial resolution

The distribution of spatial resolution across the frequency range 100 MHz to 10 GHz reveals that at all frequencies, the vast majority of the science drivers require 1 milli-arcsecond (mas) resolution. However, at the low (< 400 MHz) and high (> 10 GHz) frequencies, a resolution of 10 mas would encompass the vast majority of science drivers (Figure 3). At the lower frequencies (< 400 MHz), higher resolution (i.e. 1 mas) is required by OH megamasers, extragalactic supernovae and thermal processes. At the highest frequencies (>10 GHz) higher resolution is required for AGN, megamasers, supernovae and transient studies.

Note that these required resolution limits are currently attainable with current facilities: it is the extended sensitivity at these resolutions which the SKA will explore.

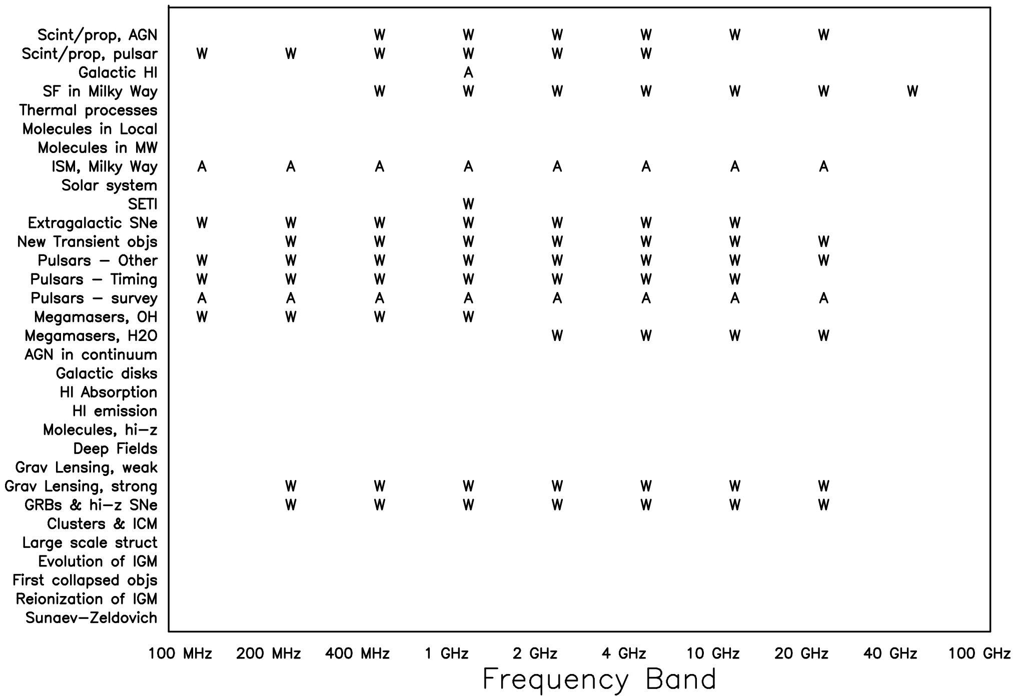

Figure 4. Distribution of science drivers requiring multi-beaming for the 32 science drivers across the frequency bands as shown: A: adjacent to primary beam, W: widely spaced, blank: no requirement.

3.4. SKA multi-beaming

Drivers which require multi-beaming divide into those requiring beams adjacent to the primary beam and those requiring widely-spaced beams, as illustrated in Figure 4.

In the table below we summarise the responses for the 32 science drivers. It can be seen that just over half (17/32, 53%) require no multi-beaming at all, whilst of the others, 12/32 (37.5%) require widely-separated beams on the sky.

	Multi-beaming Options		
	None	Adjacent to primary	Widely-separated
Number of Science Drivers	17	3	12

3.5. SKA polarimetry

The requirement for full polarisation measurements is split between those science drivers which do not require it (15/32, 47%) and those what consider it critical or useful (16/32, 50%). The full distribution by science drivers and frequency

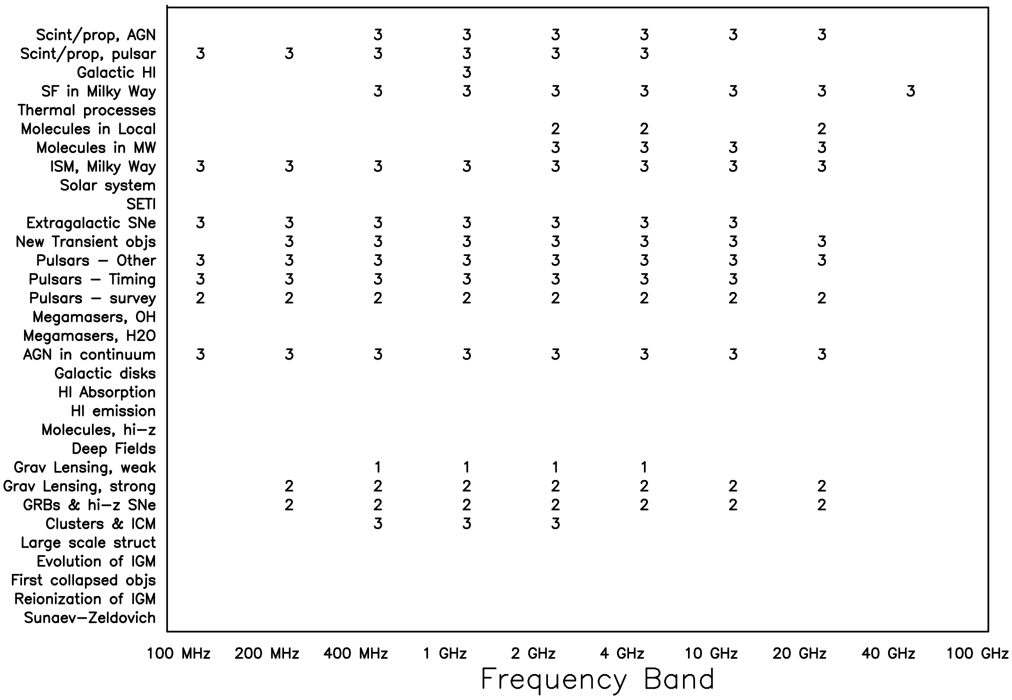

Figure 5. Distribution of science drivers requiring polarisation for the 32 science drivers across the frequency bands as shown: 3: Critical, 2: Useful and 1: Marginally useful, blank: not required.

range is shown in Figure 5. At all frequencies, there are science drivers with a critical requirement for full polarsiation measurements.

	Polarisation Requirements			
	None (0)	Marginal (1)	Useful (2)	Critical (3)
Number of Science Drivers	15	1	4	12

3.6. SKA total power measurement

Whilst the majority of science drivers (24/32, 75%) do not require total power measurement, a sizeable minority (8/32, 25%) indicate that they consider it important (critical or useful). The full distribution by science drivers and frequency range is shown in Figure 6. There is a trend that total power measurement is required chiefly between 1 – 20 GHz.

	Total Power Measurement			
	None (0)	Marginal (1)	Useful (2)	Critical (3)
Number of Science Drivers	24	0	3	5

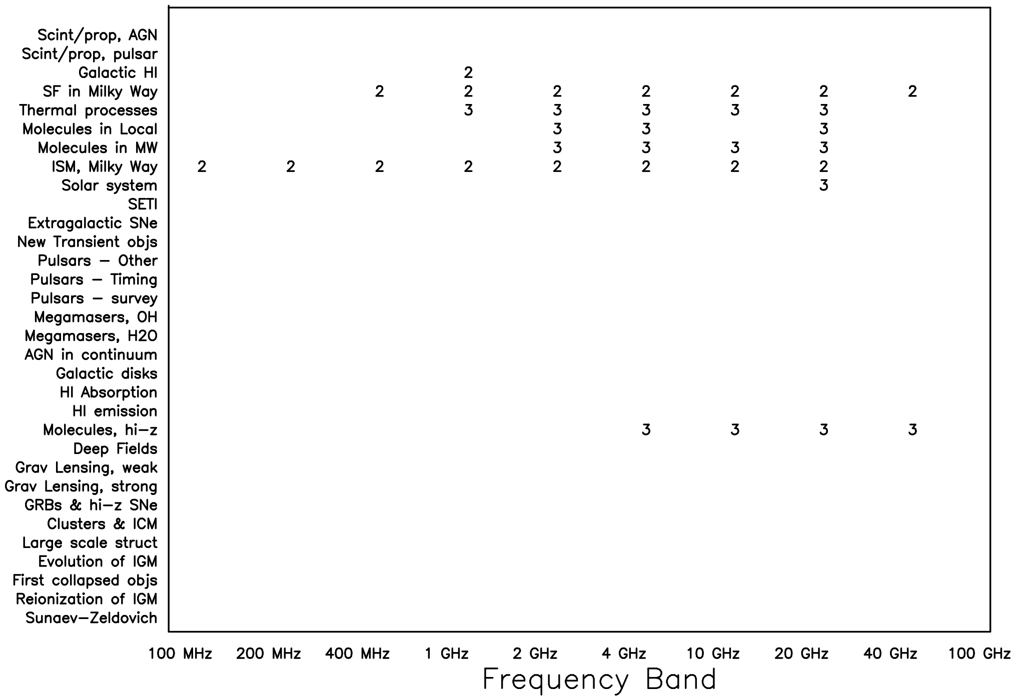

Figure 6. Distribution of science drivers requiring total power measurement for the 32 science drivers across the frequency bands as shown: 3: Critical, 2: Useful and 1: Marginally useful, blank: not required.

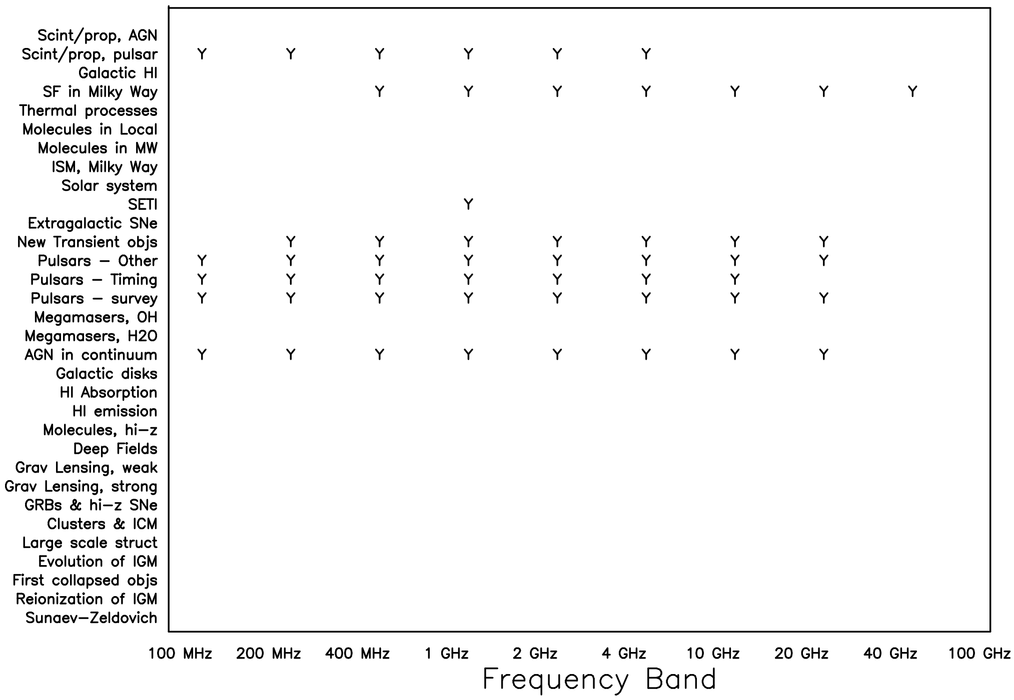

Figure 7. Distribution of science drivers requiring time resolved measurements (Y) for the 32 science drivers across the frequency bands as shown.

3.7. SKA time resolution

Whilst the majority of science drivers (24/32, 75%) do not require any particular time resolution from the SKA, a number do: these include SETI, pulsar, AGN and scintillation studies as shown in Figure 7.

	Time Resolution Requirement				
	None	1 sec	1 ms	1 μs	1 ns
Number of Science Drivers	24	2	3	1	2

3.8. SKA field of view

The required field of view ranges from around 5 – 10 degrees for the galactic science drivers to 1 degree for most extragalactic science as illustrated in Figure 8. However, it has to be clarified whether the science drivers requiring large fields of view (> 1 degree) would be achievable with mosaicing.

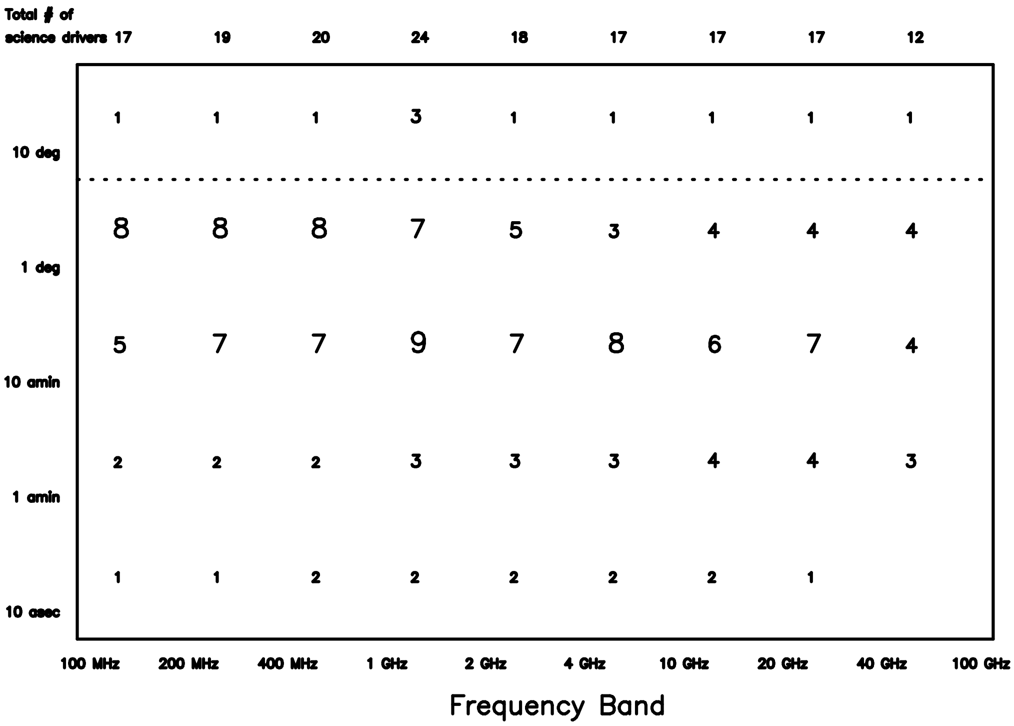

Figure 8. Distribution of required imaging field of view for the 32 science drivers across the frequency bands as shown. As not all science drivers require all frequency bands, the total per frequency band (along top of figure) is less than 32. It can be seen that a field of view of 1 degree across the whole frequency range would encompass all scores of 4 or more science drivers.

3.9. SKA summary specification

From the preceeding analysis we can 'specify' an SKA which best satisfies the science driver requirements:

	Frequency Band		
Parameter	100 – 400 MHz	400 MHz – 4 GHz	4 – 100 GHz
5σ Sensitivity	1 μJy	1 μJy*	1 μJy
Resolution	1mas	1mas	sub-mas
Multi-beaming	Y, wide	Y, wide	Y, wide
Total Power	Y(?)	Y	Y
Polarisation	Y, 3	Y, 3	Y, 3
Frequency Agility	Y, 1s	Y, 1s	Y, 1s
Field of View	1 deg	1 deg	1 deg

Note: * Would need to be extended to 1 nJy to encompass *all* science drivers (see Figure 2 and discussion in section 3.2).

Whilst we stress that this is based on a first-pass analysis of the unprioritized science drivers, we find that this methodology allows the SKA specification to be compiled as a function of frequency, whilst the interplay between the different parameters and science areas can also be explored.

4. SKA simulations

A compilation of notes for the 32 science drivers indicating the background to the scores is presented in Appendix B. Whilst these are not exhaustive, some highlight where more detailed simulations are required to fully specify the SKA parameters. These simulations should be developed and refined, particularly as the focus of the scientific drivers will change by the time the SKA technology decisions are taken.

The deep continuum fields currently being studied at very low radio flux densities (e.g. Hubble, Chandra, ATESP etc) are yielding important constraints on the nature, space distribution and angular size of faint radio sources. These results must be used in refining the confusion limits and required resolution, although large extrapolations are unavoidable due to the hugely increased sensitivity of the SKA.

5. Other SKA drivers

In this paper we have deliberately restricted the discussion to the pure astronomy science drivers and have not included activities such as NASA deep space tracking, geophysics and RFI strategies.

Neither have we considered how the parameter requirements might be implemented, e.g. how there might be a trade-off between field of view and number of instantaneous beams to achieve certain science goals and that different array configurations will favour particular science drivers.

6. What next ?

The key task for the International Science Advisory Group (ISAC) is to now identify primary science drivers for the SKA. We suggest that a similar exercise to the one described in this paper be undertaken by the ISAC sub-groups with the science drivers being scored as a result of group discussion. Moreover, the synergies between science drivers should also be identified so that the scientific return of the SKA can be maximised.

The ISAC should also what science is being done with the intermediate (SKA demonstrator) facilities and the new and upgraded radio facilities such as LOFAR and eVLA: Both of which can be viewed both as technological and scientific stepping-stones to the final SKA. Over the next few years the scientific results from these instruments will both help refine the SKA science requirements and identify the primary drivers.

In order to ensure the SKA has both identified science goals and that it exploits 'uncharted' parameter space – the latter being a form of insuring the SKA makes new serendipitous discoveries – the capabilities of radio interferometers, both in operation and planned, should also be analysed before finally specifying the SKA.

Once the science drivers are prioritized, they should then be weighted in the parameter analysis and this should then highlight the key design parameters for the SKA.

As a final note, we recommend that a similar analysis be undertaken by the SKA Technology/Engineering groups as this would then allow matching of prioritized science goals to the technological solutions. Only then can we can address the question: Can a scientifically-driven SKA be built for the available budget ?

Acknowledgements
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References

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Appendix A: Initial SKA specification

Table 1. Straw-man design for SKA: December 1997 workshop (http://www.nfra.nl/skai/science)

Operating parameter	Requirement
Aeff/Tsys	2 x 10^4 m^2/K
Sky coverage	2 sterad
Frequency range	0.03 – 20 GHz
Imaging Field of View	1 square deg. @ 1.4 GHz
Number of instantaneous pencil beams	100
Maximum primary beam separation	
low frequency	100 deg
high frequency	1 deg @ 1.4 GHz
Number of pixels	10^8
Angular resolution	0.1 arcsec @ 1.4 GHz
Surface brightness	1K @ 0.1 arcsec (continuum)
Instantaneous bandwidth	0.5 + ν/5 GHz
Number of spectral channels	10^4
Number of widely spaced, simultaneous bands	2
Clean beam dynamic range	10^6 @ 1.4 GHz
Calibratable polarisation purity	−40 dB

Table 2. Strawman SKA sensitivity.

Freq. (MHz)	Cont.Band (MHz)	Aeff/Tsys (m^2/K)	Cont.dS (/ μJy)	Line dS (/ μJy)
40	20	500	5.140	364
80	40	3000	0.606	42.9
160	80	20000	0.064	4.55
320	160	20000	0.045	3.21
640	320	20000	0.032	2.27
1280	640	20000	0.023	1.61
2560	1280	20000	0.018	1.14
5120	1500	20000	0.015	0.80
10240	2500	20000	0.011	0.57
20480	4500	10000	0.017	0.80

Table 2 gives a rough idea of the way the straw-man SKA specification of Table 1 translates into a sensitivity in a single polarization expressed in μJy per beam after an 8 hour integration using the maximum continuum bandwidth on the one hand and calculated at a spectral resolution of 10^4 (ie. 30 km/s) on the other. The dependence of Aeff/Tsys on frequency is indicated. A dual polarization observation will have square root two better sensitivity.

Appendix B: Notes for Individual Science Drivers

The reader is also directed to the papers in van Haarlem (1999) for more background on the individual science drivers.

Science Driver #1
The Sunaev-Zeldovich Effect

Detect high-redshift clusters via imaging of the Sunaev-Zeldovich decrement in the CMB background.

Key assumptions

The SKA will have huge number of long baselines so will be able to subtract confusing sources with high accuracy. The combination of (low) T_{sys}, (high) antenna efficiency and favourable atmospheric conditions mitigates that SZ detection will be best done around 10 GHz with the SKA.

Science Driver #2
Reionization of the IGM

Detect the epoch of reionization.

Key assumptions

A global spectral feature from the reionization epoch may be present over the whole sky. The measurement of the signal between 70 and 240 MHz if reionization occurs between z=5 and 20 will be a easily detectable by the SKA.

More challenging is the measurement of fluctuations and features prior to the reionization which is the science driver 'First Collapsed Objects'.

Science Driver #3
The First Collapsed Objects

Detect the fluctuations in the 'sea' of HI and individual HI features caused by the most luminous sources at the reionization epoch, e.g. the first quasars.

Science Driver #4
Evolution of the IGM

Determine the thermal history of the IGM: Map the features and temperature of the filamentary structure.

Science Driver #5
Large Scale Structure

Trace the development of structure in the Universe and detect dark matter concentrations.

Key assumptions

That this driver sets out to trace low column density intergalactic HI emission to map the structure of filaments and sheets throughout the evolving universe.

These filaments and sheets are suggested by the detection of the complex Lyman-alpha forest. The connection between these structures, the density fluctuations in the early universe and evolved structures is yet to be resolved. But the SKA is the only instrument capable of detecting these structures out to high redshift.

It is assumed that both a) a wide-angle shallow HI survey which would allow the direct determination of the evolution of large-scale structure from about z=1.3 to the present and b) a deep pencil beam HI survey survey on a single field to detect galaxies and HI concentrations to $z > 4$, are covered under the HI emission in galaxies section.

Science Driver #6
Clusters & the ICM

Determine the relationship between the magnetic, non-thermal and thermal components of the inter-cluster medium over a wide range of redshift, including detecting Faraday rotation between ~500 MHz and 3 GHz.

Science Driver #7
Gamma-Ray Bursts & High-z Supernovae

Search for, and monitor, gamma-ray bursts and high-redshift supernovae.

Key assumptions

Goal is sensitivity-limited: required sensitivities give significant improvement over current facilities and would reach high redshift.

Sources are unresolved. Multi-beaming would be useful for monitoring programs, but not initial searches.

Science Driver # 8
Gravitational Lensing: Strong

Investigate the geometry of the Universe through measurement of time delay between multiple images of a compact source seen though a gravitational lens.

Key assumptions

Compact source implies a flat-spectrum core. Need to monitor the source flux, for each object in the sample, at intervals of a few days. A relatively small number of sources ($\sim$10) in the sample should suffice. High dynamic range and good uv coverage is needed in order to measure the faint (de-magnified) central image. The frequency range reflects the fact that the compact core is likely to be most variable (and therefore most useful for delay measurements) at high frequencies (10 – 20 GHz); the low frequencies are relevant to the extended structure which provides input to the lens models. Imaging the source at a variety of frequencies is important in providing as many independent constraints on the lens model as is possible; monitoring at several frequencies is important in that it allows for a redundant determination. High angular resolution is important if the core is highly magnified (i.e. it is located near a caustic). Because this program involves regular monitoring it benefits enormously from the availability of wide-angle multi-beaming. Flux monitoring to the necessary level of sensitivity can be achieved quite quickly (minutes), and the array needs to be frequency agile to take advantage of this.

Other considerations

The largest errors in existing determinations are now attributable to systematic uncertainties in the lens model; to minimise the influence of these uncertainties we need to find systems in which the data provide a large number of constraints on viable lens models (radio rings). Finding suitable examples will require imaging a very large number of candidate sources (which will therefore be quite faint relative to currently known examples).

The radio band is well-suited to studies of gravitational lensing because one avoids any problems associated with obscuration introduced by the lens.

Science Driver # 9
Gravitational Lensing: Weak

Measure the power-spectrum of mass fluctuations in the Universe 'directly', from statistical estimates of the gravitational image distortion of background sources.

Key assumptions

The sources are predominantly disks of 'normal' galaxies, exhibiting synchrotron emission from cosmic-ray electrons (associated with recent or ongoing star formation). This suggests that the optimum frequencies are in the range 0.4 – 4 GHz, as a compromise between angular resolution and sensitivity. It is necessary to average the signal over a number of targets, in order to average-out the contribution from intrinsic source shape. Consequently, making a map of the distortions requires measurements over a very large field, and thus drives a requirement for large FOV. It is highly likely that a program of this nature would also mosaic fields in order to yield measurements at smaller wavenumbers. Excellent imaging is required for this project.

Other considerations

Other avenues (notably deep optical imaging) lead to the same scientific product, but the need for wide FOV means that these avenues are unlikely to develop significantly from their current status — the 8m-class facilities are of little relevance. The need for high resolution images over a wide field is well matched to anticipated SKA specifications; this coupled with the fact that the SKA point-spread-function will be accurately known means that SKA will be able to tackle this scientific program much more effectively than any other facility.

It should be possible to significantly improve the link between theory and observation of the 3D power-spectrum of density fluctuations, by measuring the redshift of the target galaxies from their 21cm line emission. Furthermore, if it is possible to measure the 21cm velocity field of target galaxies, then one can presumably determine the intrinsic orientation and axis ratio of *each* galaxy (under the cold disk assumption). In turn this would lead to a much lower noise level on the power-spectrum estimate for any given angular scale, and it would thus allow the power-spectrum measurement to be extended to correspondingly smaller spatial scales.

Science Driver #10
Deep Fields in Continuum

Deep continuum imaging to probe extremely faint and distant radio source populations.

Key assumptions

Sensitivity-limited: require 1 μJy to achieve significant improvement over current facilities and to probe whole range of redshifts. However, specified parameter values may hit the confusion limit.

Other considerations

Simulations: need to update continuum confusion limits (e.g. Hopkins contribution to the SKA Science case) across a wide range of frequencies.

Also need to consider future capabilities at all wavelengths: require similar resolution with SKA to allow unambiguously identification of sources.

Science Driver #11
Molecules at High-z

Trace redshifted CO in galaxies (z $\sim 5-10$).

Key assumptions

Sensitivity of 10 μJy with FWHM 300 km s^{-1} should be sufficient to distinguish between different galaxy formation/evolution models.

Science Driver #12
HI Emission in Galaxies

Evolution of the HI mass function from the galaxy formation epoch to z=0: the 'radio Madau' plot, from a very deep survey.

Key assumptions

Sensitivity-limited: require sensitivities shown to achieve significant improvement over current facilities and to reach z $\sim$ 2–3.

That a typical normal galaxy at z $\sim$3 (distance $\sim$ 6000 Mpc) has angular diameter $\sim$ 0.5 arcsecs. Obviously dwarfs are smaller. Determination of the rotation curve requires 10 data points, implying 50 mas resolution is necessary.

Typical bright spiral galaxy has $\sim$ 2.5 x 10^{10} $M_\odot$ HI, Δv = 200 km s^{-1}.

Strategy: target area of a few square degrees for about one month's observing time.

Science Driver #13
HI Absorption in Galaxies

Detection of galaxies, proto-galaxies and Lyman-alpha clouds via HI absorption against bright continuum sources over a wide redshift range.

Key assumptions

Sensitivity-limited: require sensitivities shown to achieve significant improvement over current facilities and to reach z $\sim$ 2–3.

Need 2 – 3 arcsec resolution to decompose HI groups at z $\sim$ 3.

Strategy: targeted fields around quasars, probably from multi-beam capability.

Other considerations

Need to simulate HI masses as a function of redshift and flux density for plausible formation scenarios to determine sensitivity requirements better.

HI absorption distribution will 'come for free' from HI emission studies.

Science Driver #14
Galactic Disks in Continuum

Continuum imaging of individual galactic disks. Follow-up IRAS/ULIRAS galaxies, study merging and interactions.

Key assumptions

Sensitivity-limited: require 1 μJy to achieve significant improvement over current facilities and to reach z $\sim$ 2–3. However, specified parameter values may hit the confusion limit.

Other considerations

Simulations: need to update confusion limits (e.g. Hopkins contribution to the SKA Science case) across a wide range of frequencies.

Science Driver #15
Continuum imaging of AGN

Imaging of AGNs: core emission, jet propagation studies, etc.

Science Driver #16 – 17
Circumnuclear Megamasers

H_2O megamasers probe the parsec-scale structure of individual galactic nuclei, whilst OH and H_2CO megamasers probe structure on the few-hundred-parsec scale. Methanol megamasers are associated with star-forming regions and molecular clouds.

Key assumptions

H_2O megamasers (ν_{rest} = 22 GHz) are VLBI sources as they are confined to a thin molecular disk of order of <1 parsec in diameter. These masers are the best probe of the inner workings of an active nucleus, giving the 3D velocity field of the gas in the AGN. Potentially, H_2O megamasers could be used to determine the relationship between MBHs and the host galaxy.

OH and H_2CO megamasers (ν_{rest} = 1.6 GHz and 4.83 GHz) probe scales of a few hundred parsecs in galaxies.

Methanol megamasers are associated with giant molecular clouds and HII regions. To date they are only detected in our galaxy and the Magellanic clouds, although they may be detectable in nearby galaxies (ν_{rest} = 6.7 - 146 GHz).

Other considerations

As a stand-alone instrument an SKA with GHz-frequency coverage will be able to detect megamasers that are too weak for existing instruments. Multi-beaming and high sensitivity allowing routine phase referencing.

Science working document suggests that a stand-alone SKA should detect:

- Moderate-luminosity OH megamasers (like Arp 220) will be detected at 20μJy at z=2 at 10 km s^{-1}: This assumes a frequency range of 530 MHz to 1.6 GHz.
- Moderate-luminosity H_2O megamasers (like NGC 4258) will be detected at 5μJy at z=0.15 at 1 km s^{-1}: This assumes a frequency range of 19 GHz to 22 GHz.

However, significant results from this science driver will only be realised if the SKA is used as an element in a VLBI array where phased-referenced observations are vital.

Science Drivers #18 – 20
Pulsars

Pulsar surveys - finding new pulsars both within our own Galaxy and other galaxies. This science case is well covered in the current SKA science document. The SKA will find many thousand new pulsars. It should discover sub-millisecond pulsars if they exist.

Pulsar timing - timing of (mostly) millisecond pulsars for use as 'clocks' long-term. There's a huge amount of physics in pulsar timing (general relativity tests, solid state physics etc) and it's a project which has had enormous success over the last 20 years.

Other pulsar science - all other science you can do with pulsars and a high sensitivity instrument including polarization, scintillation, single pulses, HI studies, emission physics, coherency, statistical analysis, multi-frequency analysis, pulsar glitches etc etc. This topic is barely scratched in the science case which exists to date. It ties in with topics like ISM and galactic structure, also poorly addressed in current documents.

Key assumptions

Pulsar astronomy has special requirements. The most obvious of these is high time resolution. At least 1 μs is needed for surveys and 'baseband' recording (i.e. at the ns level) is needed for the other aspects of pulsar astronomy.

Simultaneously, there is a need for a large number of frequency channels to combat effects of interstellar dispersion. At frequencies below 2 GHz, at least kHz resolution is needed.

Finally, the correlator needs to be multi-bit (i.e. high dynamic range) to combat interference and to deal with the pulsed flux being extremely high compared to the off-pulsar flux.

These 3 things together result in a highly specialised back-end and vast data rates. Both these problems need to be tackled in the context of the SKA.

Polarization purity is vital in pulsar timing and highly desirable for other pulsar experiments (but not surveys).

Frequency space: Traditionally pulsar astronomy has been done at frequencies below about 2 GHz. However, high frequency observations (up to 20 GHz) have given insights into emission physics.

Field of view: For pulsar surveys a large FOV is useful so that the sky can be covered in a reasonable time. Even for extra-galactic surveys, fitting a whole galaxy into the beam would be highly desirable. For pulsar timing and pulsar 'other' a small beam is best.

Multi-beam: For pulsar timing where sensitivity is not the key issue, multi-beaming is critical so that as many objects can be done in as short a time as possible. 100 beams or so would be great with the ability to point at random over a large fraction of the sky. For other pulsar science this is also the case.

Frequency agility: having a large instantaneous bandwidth is ideal. Failing this, frequency switching a short time scales (minutes) is desirable.

Other considerations

The main advantage of the SKA over other instruments (for pulsars) is its instantaneous sensitivity. A pulsar survey will undoubtedly find many thousands of pulsars. Pulsar timing is a topic likely to excite the rest of the astrophysical community, it has a proven track record in key physics areas.

Science Driver #21
New Transient Populations

Detect new classes of transient radio sources.

Key assumptions

There are transient radio sources which we remain ignorant of because we rely on data from other wave-bands to tell us that there is an interesting source to look at.

Other considerations

Monitor the whole sky at all times, looking for transient radio sources. SKA may have useful sensitivity even in the far sidelobes of the primary beam, particularly at low frequencies. Exploiting this sensitivity will require that visibilities be computed at very large lags.

Science Driver #22
Supernovae

Study galactic and extragalactic supernovae: detect star formation regions and history in individual galaxies.

Science Driver #23
SETI

Search for extraterrestrial radio signals. Assuming search range is 1 – 10 GHz.

Science Driver #24
Solar System Science

Studies of solar system objects.

Key assumptions

SKA science case requires more clarification. 20 GHz will be good for mapping asteroids and moons, and for picking up Kuiper belt objects – want 10 mas resolution (hence the high frequency).

Other science (not considered here) includes OH emission from comets, radar studies of planets (2 – 20 GHz) and solar radar studies (for coronal mass ejection) at around $\sim$100 MHz.

Science Driver #25
Milky Way & Local Group (ISM)

Study the ISM in the galaxy and local group.

Science Driver #26
Molecular Lines in the Milky Way

Detect molecules in the galaxy. This includes:

- Imaging cloud cores in NH_3 and CCS (dicarbon sulphide) at 22 and 23 GHz.
- Determining the magnetic field in nearby (1 kpc) cores using Zeeman in CCS line at 11 GHz.
- Map diffuse molecular gas (e.g. at the edges of clouds) via weak CH line at 3.335 GHz. This component of the ISM has been little observed, except towards some high-latitude clouds. This presents an interesting intermediary between molecular clouds and the other phases of the ISM.
- Map clouds in H_2CO at 4.8 GHz and the four OH lines at 1612, 1665, 1667 and 1720 MHz in absorption against the CMB. These transitions have an optical depth of order unity for an H2 column density of 10^{22} cm^{-2}. The OH line may be more compromised by non-thermal continuum as it is at a lower frequency.

Key assumptions

- A molecular cloud complex has scale of 10 – 30 pc.
- Individual cores are about 0.1 pc in size.
- 22/23 and 11 GHz lines have $T_b = 0.1$ K and $\Delta v = 0.2$ km s^{-1}, so require 0.1 K sensitivity in 0.05 km s^{-1} channels.
- 11 GHz Zeeman detection requires 0.01 K sensitivity in 0.01 km s^{-1} channels and polarisation information.
- 3.3 GHz CH line has T_b=0.01 K and Δv = 3 km s^{-1}.
- CMB absorption requires sensitivity 0.01 K in 0.05 km s^{-1} channels.

Science Driver #27
Molecular Lines in the Local Universe

Detect masers in the galaxies (see also science drivers 16 & 17). Also included here is the absorption of the CMB by OH and H_2CO and CH emission for the ISM of other galaxies, assuming a sensitivity of 0.1 K in a 5 km s^{-1} channel.

Key assumptions

Masers essentially point sources. Milky Way masers are typically 10 kpc distant and have flux densities in the ranges 10 – 100 Jy (H_20 at 22 GHz), 1 – 10 Jy (CH_3OH at 6.6 GHz) and 0.1 – 1 Jy (OH at 1665/7 MHz). So we require require 0.1 mJy sensitivity in a 0.5 km/s channel to detect these masers out to several Mpc.

Science Driver #28
Thermal Processes

Detect extragalactic compact HII regions and recombination lines.

Key assumptions

Simultaneous multi-frequency capability will be particularly useful for this driver. Lower frequencies are contaminated by non-thermal emission so are probably less useful.

Compact/generic HII regions have T_b ~1000 and ~30 K at 1 GHz respectively.

Recombination lines have ΔT_b / T_b about 1% and FWHM of 10 km s^{-1}.

Science Driver #29
SF in the Galaxy, Galactic HI

Trace galactic star formation history, galactic HI and giant molecular clouds.

Science Driver #30
Galactic HI (structure & dynamics)

Study galactic structure and dynamics through HI.

Science Drivers # 31 & 32
Radio-wave Propagation & Scintillation

Study the small-scale density structure in ionised Galactic gas. Specific goals include: understanding the physical processes and cascade phenomena associated with the very broad spectrum of density fluctuations in the ISM; understanding the nature of discrete propagation phenomena, namely Extreme Scattering and Multiple Imaging Events; understanding the Intra-Day Variations of AGN and quasars; and nano-/micro-arcsecond 'imaging' studies of gamma-ray burst afterglows, quasars and pulsars.

Key assumptions

Only compact sources are useful for these goals: principally pulsars and flat/inverted-spectrum AGN (although studies of H_2O Megamasers are also of interest). Studies using PSRs place very different requirements on the telescope to those using AGN.

Studies of interstellar scattering using PSRs would be undertaken principally through the monitoring of dynamic spectra, this requires millisecond time resolution, and simultaneously fine frequency resolution (of order 3 kHz) over a broad band (of order 300 MHz). Mostly dynamic spectra will be monitored at low frequencies (0.2 – 2 GHz), but it is noteworthy that SKA will open up the possibility of studying pulsars at higher frequencies – where the scattering changes character from 'strong' to 'weak' – for the first time.

Studies of AGN will generally take place at higher frequencies (1 – 20 GHz), with only modest spectral resolution, and no requirement for rapid sampling. Understanding the Extreme Scattering Events, which are rare, will require a very large number of sources (of order 10,000) to be monitored on a regular basis ($\sim$ a few days between successive samples), over a very broad spectral baseline, and this will require both frequency agility and rapid slewing, albeit over small angular separations.

The phenomenon of Intra-Day Variability is best studied with a sample of sources similar in nature, but smaller in number, to that just described in connection with ESEs. Studies of IDV might therefore be most effectively pursued by conducting more intensive monitoring of a small sub-sample of sources, namely those which are discovered to have significantly different fluxes at adjacent time samples.

Wide-angle multi-beaming is required for all three types of investigation, because they involve intensive monitoring, and in the case of the AGN studies this is also required at high frequencies. High angular resolution is also required, in order to measure refractive wander and to determine the locations of multiple images, where present (though this feature need not necessarily be available simultaneously with the other requirements).

Constraints on source structure at the micro-arcsecond level and below will follow from the above programs.

Other considerations

This science is unique to the SKA: it cannot be pursued at other wavelengths because the refractive index of ionised gas is a strong function of frequency; existing radio telescopes do not have sufficient sensitivity to allow either high resolution dynamic spectra to be acquired, in the case of pulsars, or to make even low resolution measurements of the very large number of AGN which will be required to properly characterise the ESE phenomenon.

Appendix C: SKA Analysis: Attached EXCEL spreadsheet