SKA1 OBSERVING BANDS: SCIENTIFIC CONTEXT

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LIST OF ABBREVIATIONS

AIP .... Advanced Instrumentation Programme
BD .... SKA1 Baseline Design
DM.......................... Dispersion Measure
EMI......................... Electromagnetic Interference
EoR .... Epoch of Reionisation
FRB........................ Fast Radio Burst
FWHM.................... Full Width Half Maximum
HPSO..................... High Priority Science Objective
ISW .... Integrated Sachs Wolfe effect
NIP .... Non-image Processing
PSF .... Point Spread Function
RFI .... Radio Frequency Interference
RM.......................... Rotation Measure
RMS .... Root Mean Square
SEFD...................... System Equivalent Flux Density
SKA........................ Square Kilometre Array
SKAO .... SKA Organisation
SCI_REQ- .... Specification number in this document
VLBI .... Very Long Baseline Interferometry

1 Introduction

1.1 Purpose of the document

This document is intended to document the scientific considerations relating to the observing bands for the SKA and more specifically to the bands targeted for the initial deployment in SKA1.

1.2 Scope of the document

The document begins by outlining some of the technical boundary conditions surrounding possible frequency bands. It then places these in the context of the proposed scope for the SKA1 deployment. Each of the current Science Working Groups (SWGs) and Focus Groups (FGs) areas are then considered in turn to state the most desirable frequency coverage for example key applications. The chairpersons of the SWGs and FGs have reviewed these considerations and confirm the assessment summarised here.

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.

[AD1]

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.

[RD1] SKA-XXXXXXXXXXXXXXXX, SKA Phase 1 Science (Level 0) Requirements
[RD2] SKA-XXXXXXXXXXXXXXXX, SKA Baseline Design v 1
[RD3] SKA-SCI-PRI-002-AppendixA, SKA1 Science Priority Outcomes

3 Technical Considerations

3.1 Frequency Coverage per Band

The technologies available for high performance wide bandwidth single pixel feeds are quite well understood. The lowest noise, yet wide bandwidth performance using the SKA1 dish optics is obtained with so-called "octave bandwidth" feed systems that provide a useful fractional bandwidth, of (ν_{Max}/ν_{Min}) = 1.85. Larger fractional bandwidths require a fundamentally different, "ultra-wide-band" (UWB) design. Some UWB designs can achieve (ν_{Max}/ν_{Min}) = 10 or more, but they will generally provide a somewhat reduced sensitivity relative to octave band systems, and that sensitivity may further decline with the fractional bandwidth that is required; ie. 10:1 systems may not perform as well as 3:1 systems.

3.2 Frequency Coverage

The ultimate frequency coverage goal for the SKA Observatory, as discussed in the Level 0 Science Requirements, is about 20 MHz – 24 GHz [RD1]. A subset of this range is being targeted with the SKA1 deployment. The original Baseline Design (BDv1) [RD2] provided a first indication for how the frequency coverage might be realised and this has formed the basis for the design effort that has now progressed to the Preliminary Design Review (PDR) stage. Broad-band, log periodic antennas would provide coverage of 50 – 350 MHz in SKA1-LOW, while a set of five single pixel feed systems would provide coverage of 350 MHz – 13.8 GHz in SKA1-MID within the Gregorian focus of an off-set parabolic 15m diameter dish. The upper frequency goal of 24 GHz would be achieved through developments in the Advanced Instrumentation Programme (AIP). Since the unavoidable sky noise increases dramatically both below 1 GHz and above 10 GHz (as shown in Figure 1), it was felt appropriate [in RD2] to specify octave band feed systems for SKA1-MID at intermediate frequencies (Bands 2, 3 and 4) and wider band systems at the more extreme frequencies (Bands 1 and 5, or Band B of the AIP – effectively a 'band 5+'). With this strategy, the full frequency coverage is provided with a manageable total number of feed systems (in terms of physical, power and budgetary constraints). Current performance estimates of the BDv1 bands, based on PDR design documentation (and ongoing design effort within the AIP), are provided in Figure 1.

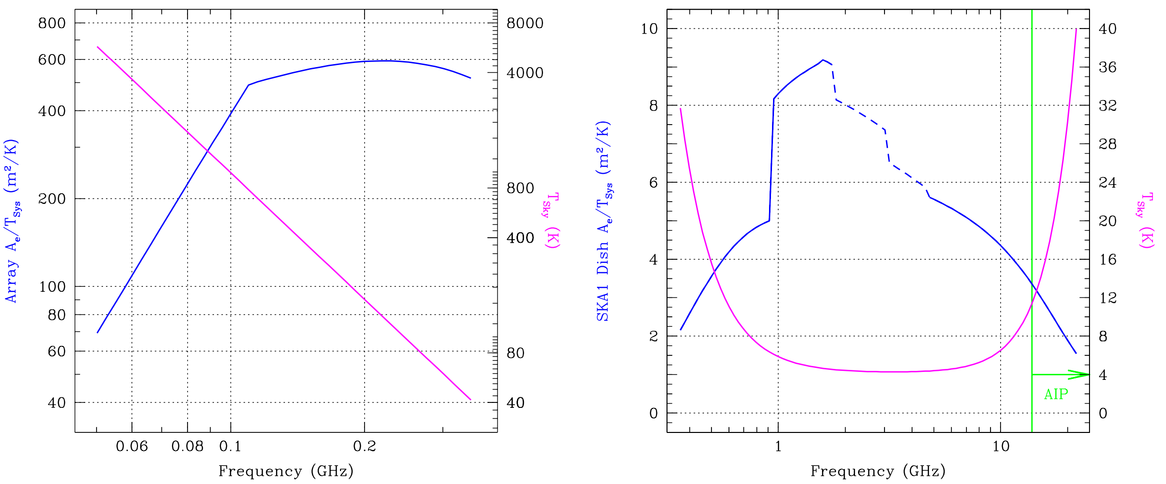

Figure 1. The full array sensitivity at zenith of SKA1-LOW (left) and the zenith sensitivity of each SKA1-MID dish (right). The blue curves show estimated sensitivity in terms of the left hand axis labels, while the magenta curve shows the typical assumed sky temperature using the right hand axis labels. The dashed blue curve depicts bands not yet scheduled for deployment (Bands 3 and 4), while the frequency interval above 13.8 GHz is under investigation in the context of the Advanced Instrumentation Program (AIP).

3.3 SKA1-MID Band Deployment

The scientific priorities for the SKA1 were assessed in RD3, based on inputs received from the Science Working Groups. This led to the recommendation, which has been adopted by the SKA Board, that in the first deployment phase SKA1-MID would be equipped with three feed systems, in the priority order Bands 2, 5 and 1.

4 Science Considerations (in alphabetical order)

4.1 Cosmic Dawn / Epoch of Reionisation

The frequency needs of this group extend from about 20 – 200 MHz to cover the λ21cm neutral hydrogen line over a relevant red-shift interval of z = 69 to z = 6. In view of the foreseen sensitivity of the SKA1 deployment it is appropriate to concentrate on the 50 – 200 MHz portion of the range in the first instance, corresponding to the red-shift interval of z = 27 to z = 6. The goal is to enable direct imaging over about 100 – 200 MHz and statistical detection in the range 50 – 100 MHz.

4.2 Cosmology

A wide range of cosmological questions will be addressed with the SKA, in particular utilising: (a) discrete galaxy detection in HI; (b) radio continuum surveys; and (c) statistical galaxy detection (so-called Intensity Mapping) in HI. Each of these approaches has an "optimum" frequency range that applies to the sensitivity and maximum baseline available in the SKA1 deployment. The highest detection rates for discrete HI galaxies in moderately wide-field surveys would be provided between about z = 0.04 – 0.7 (840 – 1365 MHz). The highest densities of continuum detections at sub-arcsecond resolution might be provided between about 800 – 1450 MHz. The most competitive cosmological constraints on large physical scales are likely provided by statistical HI detection between z = 0.5 – 3 (350 – 950 MHz).

4.3 Cradle of Life

High sensitivity to a wide range of frequencies is desired to address the range of topics in this area. These vary from 20 – 100 MHz for exo-planet emission searches, through the mid-range frequencies of 1 – 5 GHz that have traditionally been targeted for SETI searches, to the high frequencies of 5 – 25 GHz where pre-biotic molecules and proto-planetary grain growth are best studied. The highest priority overall is probably attached to the 5 – 25 GHz range.

4.4 Extragalactic Continuum

The highest possible sensitivity and survey speed are desired over the widest possible frequency range at sub-arcsecond resolution to provide Spectral Energy Distribution (SED) characterisation of both non-thermal and thermal source populations. An "optimum" band for non-thermal processes might be 650 – 1200 MHz, while for thermal processes it might be 8 – 15 GHz. The specific band choice would take account of the source population synchrotron spectral index, survey depth, field of view and angular resolution. Shallow surveys might be best matched to the 650 – 1200 MHz band while deeper surveys to the 950 – 1760 MHz band. High sensitivity at 100 - 300 MHz is also desired for full SED characterisation of sources such as AGN and clusters.

4.5 Extragalactic (non-HI) Spectral Line

High sensitivity at a variety of red-shifted spectral line frequencies is desired. A number of the key line transitions (rest frequencies in brackets) are those of OH (primarily 1612 – 1720 MHz, but also including excited OH lines at ≈6 GHz), H_2CO (4.8 GHz and 14.3 GHz), CH_3OH (6.7 and 12.2 GHz), NH_3 (23 – 25 GHz), H_2O (22 GHz), CS (49 GHz), HCO+ (6.3, 8.9 and 89 GHz), HCN (4.48, 6.48, 9.42 and 89 GHz), as well as CO (115 GHz). In addition to these molecular transitions a large number of Radio Recombination Lines of H, He and C, are also of extragalactic interest with rest frequencies both below 350 MHz and between 1 – 15 GHz (in particular in the range 5 – 8 and around 15 GHz). In the case of CO, red-shift coverage of z = 3.5 – 7 is provided by 14 – 25 GHz. For H_2O, the red-shift coverage extends over z = 0 – 5 with 5 – 22 GHz, while for OH there is coverage of z = 0 – 0.9 with 950 – 1720 MHz.

4.6 Galactic Science

High sensitivity at a variety of key spectral line rest frequencies is desired. The key line transitions are those of CH (near 700 MHz), HI (1420 MHz), OH (1612 – 1720 MHz), H_2CO (near 4830 MHz and 14.5 GHz), CH_3OH (6.7 and 12.2 GHz), H_2O (near 22 GHz), NH_3 (23 – 25 GHz) as well as the radio recombination lines of H, He and C, particularly those between about 1 and 15 GHz, but also the C lines below 350 MHz. In addition, a sensitive high-resolution continuum capability is desired, particularly between about 1 and 15 GHz.

4.7 HI Galaxy Science

High sensitivity is desired to the red-shifted λ21cm neutral hydrogen line from the local Universe (1450 MHz) out to the highest red-shift where discrete detections might still be viable. For SKA1 sensitivity, the upper limit for deep integrations might be about z = 1.5 (570 MHz), while for wider area surveys it might be about z = 0.9 (750 MHz). If only a single "optimum" octave band were defined for this application it might be 785 – 1450 MHz.

4.8 Magnetism

High sensitivity and survey speed are desired for non-thermal synchrotron emission in both individual sources of interest and toward source populations with the highest possible density on the sky (to enable the Rotation Measure grid, RM-grid hereafter). A large range in λ-squared space provides the highest possible precision for a RM measurement, while a sufficiently small value of λ_{Min} is needed for polarised detection of populations with a significant intrinsic Faraday depth, such as star forming galaxies. At the likely detection threshold of a wide area RM-grid survey with SKA1 sensitivity the source counts would still not be dominated by star-forming galaxies, such that an "optimum" frequency range for this application might be 785 – 1450 MHz. Studies of individual sources and deeper, small area RM-grid surveys would benefit from a somewhat higher frequency range, say 970 – 1800 MHz.

4.9 Pulsars

There are two major program types in this science area: (a) surveys for pulsar populations; and (b) precision timing of specific pulsar samples. Searching requires high sensitivity and survey speed at a frequency matched to the propagation conditions. The maximum bandwidth foreseen for the pulsar search capability is 300 MHz. At high Galactic latitudes with low Dispersion Measure (DM) the best pulsar survey speed with anticipated SKA1 specifications is achieved at about 150 – 350 MHz. For intermediate DM the best survey performance is anticipated between about 650 – 950 MHz, while for moderately high DM, the best match might be about 1250 – 1550 MHz. Special, targeted surveys would also be desired for the extreme DM conditions that apply to the Galactic centre. These would utilise higher bandwidth and frequencies, probably in the range 8 – 12 GHz. Precision timing programs rely on a large frequency range and high sensitivity to achieve an accurate DM measurement, as well as a moderately high upper frequency to minimise the complications of any residual dispersive effects. A lowest frequency as low as 150 MHz is desirable for each timing epoch. An upper frequency in the range 2 – 3.5 GHz is also desired for each epoch. An upper frequency as low as 1400 MHz is expected to severely impair timing precision.

4.10 Solar, Heliospheric and Ionospheric Physics

There are two basic classes of emission processes in this area: (a) plasma emission that dominates at lower frequencies of 10 – 1000 MHz; and (b) synchrotron emission that dominates at 1 – 25 GHz. Phenomena of interest occur at all frequencies in the SKA range. There is no strong preference for particular band definitions, but there is a general benefit in providing the broadest possible instantaneous frequency coverage per band since many phenomena are highly time variable.

4.11 Transients

There are many categories of transient sources spanning variability timescales of nano-seconds to years. Optimum observing frequencies are closely linked to the emission mechanism and can vary across the entire SKA range of 20 MHz to 24 GHz. Some of the highest priority source categories, such as the Fast Radio Bursts (FRBs), are best matched to about 1 GHz frequencies, where survey speeds are quite high and dispersive effects only moderate. Coherent FRB detection will likely be limited to a 300 MHz bandwidth in SKA1, as for the pulsar searches. Many explosive phenomena, such as supernova events have significant self-opacity at early times, so that they are best studied at relatively high frequencies, greater than about 5 GHz. The widest possible (and preferably instantaneous) frequency coverage and highest possible angular resolution are desired. Apart from these general considerations there are no strong preferences for more specific band definitions.

4.12 High Energy Cosmic Particles

The two main areas of interest are detection of atmospheric interactions with moderate energy particles and detection of lunar limb interactions with extremely high-energy particles. In both cases, relatively low frequencies, 100 – 350 MHz, offer the best prospects for event detection and characterisation.

4.13 Very Long Baseline Interferometry (VLBI)

VLBI offers the prospect of achieving milli-arcsecond resolution and 10 micro-arcsecond source localisation that enable a wide variety of science programs. This application relies on utilising frequency bands that overlap as much as possible amongst all of the contributing observatories in a VLBI observation. Current default central frequencies that have the widest availability are 1664, 2268, 4992, 6030/6668, 8418 and 22230 MHz. A subset of current stations also support central frequencies of 327, 610, 1416, 15362 and 43214 MHz. Typical maximum bandwidths available at this time are $512/N_P$ MHz, where N_P is the number of recorded polarisation products.

5 Summary

The primary science applications of each working group, together with their preferred frequency coverage, are summarised below in Table 1 and Figure 2.

Table 1. Preferred frequency coverage of science applications.

SWG/FG	Application	F_low (MHz)	F_high (MHz)
CD/EoR	Cosmic Dawn	50	100
CD/EoR	Epoch of Reion	100	200
Cosm	Discrete HI	840	1365
Cosm	Continuum	800	1450
Cosm	Statistical HI	350	950
CoL	Exo-planets	20	100
CoL	SETI	1000	5000
CoL	Proto-planets	5000	25000
ExG Cont	Non-thermal	100	300
ExG Cont	Non-thermal	650	1800
ExG Cont	Thermal	8000	15000
ExG Spect	OH	950	1750
ExG Spect	H2O	4800	22500
ExG Spect	CS	6000	25000
ExG Spect	HCO+	5000	25000
ExG Spect	HCN	4500	25000
ExG Spect	CO	14000	25000
Galaxy	CH	680	720
Galaxy	HI	1380	1450
Galaxy	OH	1600	1750
Galaxy	H2CO	4800	14500
Galaxy	CH3OH	6600	12500
Galaxy	H2O	21500	22500
Galaxy	NH3	22500	25500
Galaxy	RRL	1000	25000
Galaxy	Continuum	1000	15000
HI Galaxies	Wide surveys	785	1450
HI Galaxies	Deep surveys	570	1450
Magnetism	RM-grid	785	1450
Magnetism	Deep/Targeted	970	1800
Pulsar	Search low DM	150	350
Pulsar	Search mid DM	650	950
Pulsar	Search high DM	1250	1550
Pulsar	Seach GC	8000	12000
Pulsar	Timing low	150	350
Pulsar	Timing high	1350	3500
Solar	Plasma Ems	10	1000
Solar	Synchrotron Ems	1000	25000
Transients	FRBs	1000	1300
Transients	SN/GRBs	5000	25000
Particles	Atmospheric	100	350
Particles	Lunar	100	350
VLBI	18cm-band	1410	1910
VLBI	13cm-band	2010	2510
VLBI	6cm-band	4740	5240
VLBI	5cm-band	6030	6668
VLBI	4cm-band	8160	8660
VLBI	1cm-band	22000	22500

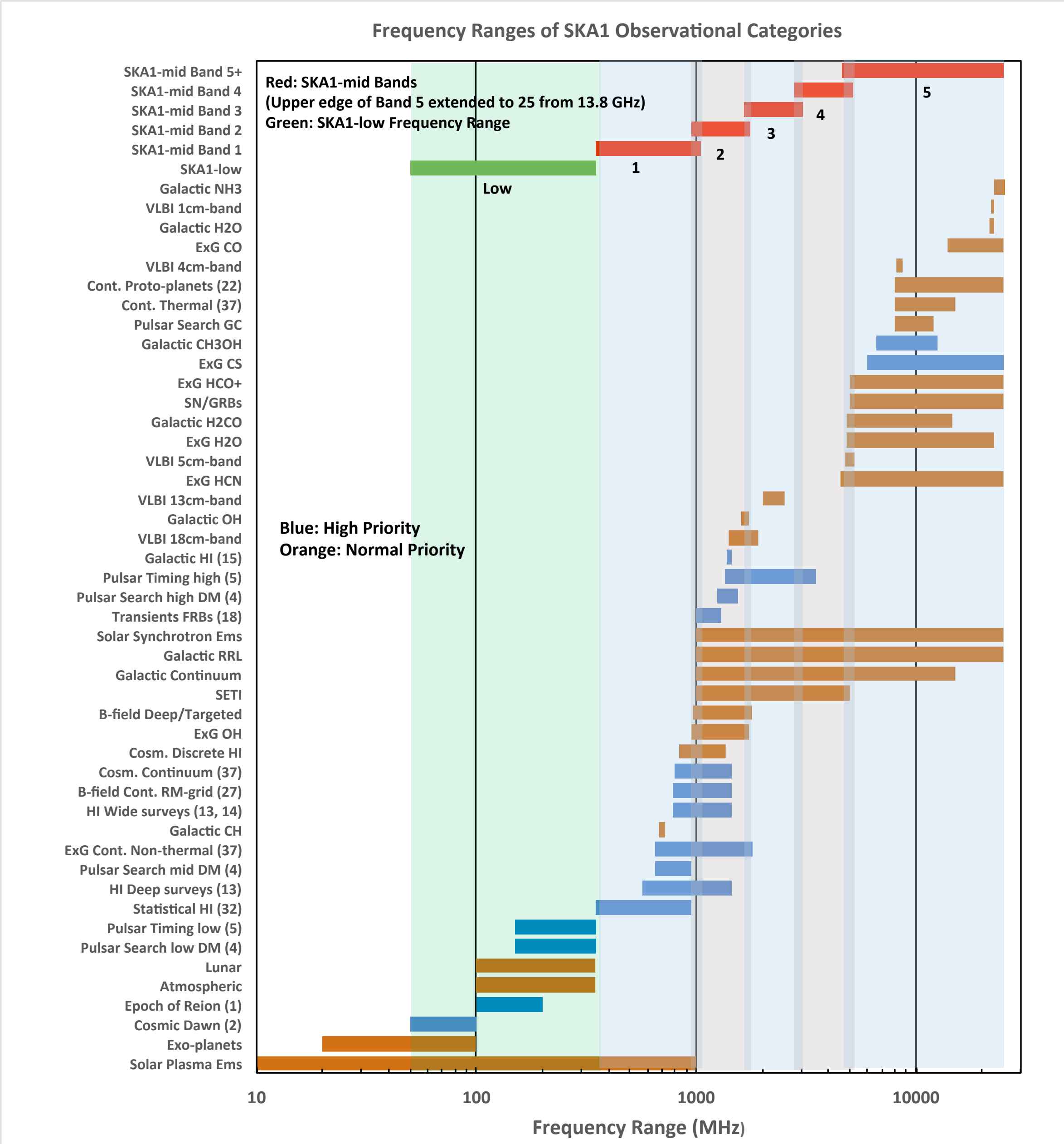

Figure 2. Preferred frequency coverage of science applications.