RFI Measurement Protocol for Candidate SKA Sites

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1 Introduction

The purpose of this document is establish a protocol for the measurement and reporting of radio frequency interference (RFI) at a single site for use in the SKA site evaluation process.

Monitoring for RFI at levels which are potentially damaging to radio astronomy is a technically- and logistically-demanding activity. Specifically, to detect RFI down to the levels deemed harmful in ITU Rec RA.769 for both polarizations over the full field of view and 150 MHz - 22 GHz frequency range of SKA would certainly require many months of continuous observation. Thus, a complete and comprehensive evaluation of RFI with the sensitivity implied by the RA.769 criterion is deemed to be prohibitively difficult for the large number of geographically-dispersed sites being considered for the SKA. Instead, this document defines a protocol for RFI measurements which can be performed within a few weeks, and which should yield information sufficient to justify a subsequent ranking of different sites. *However, the authors wish to emphasize that the results obtained by following this protocol should not be interpreted as a comprehensive evaluation of the RFI at a site. Specifically, an apparent absence of RFI in the results generated by following this protocol should not be interpreted as meaning that such RFI is not present at levels damaging to radio astronomy at the time of the measurement, and certainly does not imply that such RFI will not be present in the future (when SKA will be operational).*

To further clarify the purpose and limitations of the protocol defined in this document, it is noted that:

- A quantitative assessment of the effects of RFI on SKA depends in various (and perhaps subtle) ways on the design of SKA and the relative vulnerabilities of various observing modes. The impact of the RFI identified using this protocol cannot be properly assessed without some consideration of these factors.

- It is assumed that RFI assessment activities that are not directly related to measurements – e.g., analysis of spectrum allocations, location and characteristics of known transmitters, regulatory trends, local spectrum usage trends, likely impact of population growth, and so on – are considered elsewhere. The authors wish to emphasize that these items are important aspects of the site RFI evaluation process, especially given the limitations of what can be measured. Only by taking these additional steps can one make a reasonable forecast of the RFI environment for the time SKA becomes operational.

- This protocol seeks only to identify RFI originating from terrestrial or airborne sources. Satellites and astrophysical sources of RFI are considered to to be more or less the same for all candidate sites, and thus not of interest in this evaluation. For this reason, the emphasis is on azimuthal coverage in the plane of the horizon.

Finally, the authors wish to emphasize that this protocol should be considered to be just the *beginning* of the site RFI measurement campaign, and not the complete effort. The measurements defined in this protocol are intended to be sufficient to detect and characterize the most onerous RFI, and also sufficient to permit a ranking of sites based on their observed relative "badness." However, since the sensitivity of the measurements defined here is limited (especially with respect to the RA.769 criterion), we strongly recommend a follow-up campaign aimed at a complete, comprehensive survey of the spectrum in two orthogonal polarizations to RA.769 levels at a smaller number of sites considered to be the best candidates. These follow-up measurements can be obtained using the protocol defined in this document by increasing the observation time (more "measurement cycles," in the lingo used in the following sections). The second purpose of these follow-up measurements would be to comprehensively document the RFI situation at a given site at the time of the measurement, providing a baseline so that changes in RFI over time (i.e., during the construction phase) could be noted, documented, and possibly mitigated with the earliest possible warning. This baseline should include a detailed catalog of the identified RFI sources, including station, name, power level, location, etc. Follow-up measurements would also strive to increase sensitivity specifically in the bands which are allocated by regulation for Radio Astronomy; once again to identify problems as soon as possible.

2 Instrumentation Requirements

Requirements for instrumentation for the conduct of the measurements include:

- Antennas covering the band 70 MHz – 22 GHz.* Measurements of both the vertical and horizontal linear polarizations are required.

  - **Horizontally-polarized antennas:** The directivity of these antennas should be as low as possible, as it is required to cover the entire 360° of azimuth with gain that varies by not more than 6 dB. For example, for an antenna with 90° beamwidth between −6 dB points, 4 pointings in azimuth are required. The choice of antenna type is left to the organizations performing the measurements; however, it is suggested that a convenient choice may be log-periodic antennas for low frequencies and horn antennas at high frequencies.
  - **Vertically-polarized antennas:** There are two possible options. First, one may use discone antennas. Such antennas are primarily vertically polarized with uniform azimuthal directivity. Alternatively, one may use directional antennas (perhaps the same ones used for the horizontally-polarized measurements), oriented to achieve primarily vertical polarization. In this case, the beamwidth/pointing requirements are the same as those given above for horizontally-polarized antennas.

  Note that the large frequency range will probably require that multiple antennas be used. Also note that there is no specific requirement to monitor the entire frequency range, entire field of view, and both polarizations simultaneously.

- All measurements will be performed using an antenna height of 5 m ± 1 m.

*Note that the frequency range of the SKA is currently specified to begin at 150 MHz. Measurements down to 70 MHz are required to inventory RFI which is prone to be strong enough to drive receivers into compression, resulting in spurious signals; 2nd harmonics in particular.

- Receiver temperature $T_R \leq 3 \times 10^4$ K for Mode 1 measurements and $T_R \leq 300$ K for Mode 2 measurements (Note: The terms "Mode 1" and "Mode 2" are defined in Section 3.) T_R is to be measured from the antenna terminals (not from the receiver or spectrum analyzer input), and thus includes the low-noise amplifier (LNA), external filters, and cable losses. *Note:* It is common for an off-the-shelf receiver or spectrum analyzer to have noise temperature in excess of 2000 K; therefore, an appropriate LNA will be essential for Mode 2 measurements.

- Ability to achieve the time-frequency resolution and sensitivity needed to do the measurements described in Section 4. No specific receiver design is mandated for these measurements. For example, both commercial spectrum analyzers and custom coherent-sampling data acquisition systems are feasible and acceptable components of the measurement system, provided that the internal generation of aliases, harmonics. etc. are sufficiently low. However, note that if a spectrum analyzer is used, care must be taken to ensure it is configured appropriately for radiometric measurements; for example, Mode 2 measurements should utilize "sample" as opposed to "peak" detection.

- Appropriate calibration is required to establish the strengths of weak signals with reasonable accuracy and to determine the sensitivity of the measurement system. For the antenna, it will suffice to use the manufacturer's specification for the absolute gain (taking into account directivity and efficiency). However, a field measurement of gain and noise (T_R) from the antenna terminals back into the receiver is required. This measurement can be made simply by observing two noise sources – one of which could be an ambient-temperature matched load, as long as the temperature is accurately known – in lieu of the antenna. This measurement shall be performed once after the equipment is erected but before the taking of data, and this measurement will be repeated no less often than once every 24 hours while taking data. It should be noted that, even after calibrating the instrumentation as described above, the measurements will have limited accuracy due to errors including multipath interference from the ground and surrounding terrain, unknown antenna gain in the direction(s) of arrival, and changes to the antenna gain due to interactions with mounting structures.

- This protocol specifies no requirement for linearity (specifically, in response to strong RFI) of the instrumentation. However, it is in the best interest of the organizations performing the measurements to ensure that the linearity of their instrumentation is reasonable, especially at lower frequencies known to contain strong RFI. Failure to do so may result in the generation of spurious signals and non-flat noise spectral baselines that cannot (and will not) be distinguished from RFI. When linearity-threating RFI is suspected to be a factor, the use of relatively tight bandlimiting filters is strongly recommended.

3 Site Characterization

In this section we state the *minimum* requirements for characterization of a particular site by direct measurement of RFI. Assuming serial measurements (e.g., using one receiver and one antenna at a time), the required observation time is about 154 hours ($\sim$ 1 week), plus additional time required to set up, reconfigure instrumentation, and tear down.

The measurement protocol divides RFI into two broad classes:

- Strong RFI, which potentially threatens the linearity of SKA receivers, and may therefore rule out certain sites or influence the design of receivers. These are henceforth referred to as "Mode 1" measurements.

- Weak RFI, which threatens to obscure weak signals of interest. These are henceforth referred to as "Mode 2" measurements.

The methods and standards for making Mode 1 and Mode 2 measurements are the primary subjects of the remainder of this document.

3.1 Mode 1

The required Mode 1 measurements are as follows:

- 5 measurement cycles (described in Section 4, Table 1) in each of N pointings of the horizontally-polarized antenna, where N is 360° divided by the 6 dB beamwidth of the antenna. One of these pointings shall be in the direction of the nearest population center, determined using a good faith effort.

- 5 cycles for each pointing of the vertical polarization, otherwise the same as above. Alternatively, this measurement can be performed as 20 cycles using a discone antenna.

Assuming 4 pointings of a directional antenna are required for each polarization, this takes about 52 hours using 1 antenna and 1 receiver at a time.

Note that it is *not* required for measurement cycles to be contiguous. For example, it is not necessary to sweep from 70 MHz to 22 GHz before returning to 70 MHz to begin the next measurement cycle. For convenience in mounting antennas, it is acceptable, for example, to sweep 70 MHz to 1000 MHz multiple times before moving to frequencies above 1000 MHz. However, a good faith effort is requested to ensure that coverage of frequencies with respect to time-of-day is as uniform as possible.

The reported result shall be a plot whose horizontal axis is frequency channel, vertical axis is RFI magnitude in dB(W m^{-2} Hz^{-1}), with curves showing the median, 90%[†], and maximum (100%) levels observed as a function of frequency channel. To be clear, consider the following example: if the 90% curve goes through the point (100 MHz,-100 dB(W m^{-2} Hz^{-1})), this means that 90% of the Mode 1 measurements made in the 3 kHz-wide channel at 100 MHz were at or below -100 dB(W m^{-2} Hz^{-1})). All polarizations and pointings will be considered together and presented as a single data set, plotted on the same axes using a single curve. Multiple plots are acceptable for the purpose of dividing the frequency scale into multiple ranges only.

An attempt shall be made to correlate RFI sources revealed in the above plot(s) at or above the level considered "potentially linearity threatening" (See Section 4.1) with known sources.

[†]Note: The symbol "%" is used to denote "percentile" throughout this document.

3.2 Mode 2

The required Mode 2 measurements are as follows:

- 2 cycles in the horizontal polarization, in each of the same N pointings used for Mode 1. One cycle shall be during local business hours, whereas the second cycle shall be between 2100 and 0600 local time.
- 2 cycles in the vertical polarization, otherwise the same as above. Alternatively, 8 cycles using a discone, with a good faith effort to obtain measurements evenly distributed over time-of-day.

Assuming 4 pointings of a directional antenna are required to cover the field of view, this takes about 103 hours using 1 antenna and 1 receiver.

As in the Mode 1 measurements, it is *not* required for measurement cycles to be contiguous, although a good faith effort is requested to ensure that coverage of frequencies with respect to time-of-day and day-of-week is as uniform as possible.

The reported results shall be:

- Plots whose horizontal axis is frequency channel, vertical axis is in dB(Jy), with traces showing the maximum, 90% level, mean, median, and 10% level for each pointing of the horizontal polarization measurement (i.e., one plot per pointing), and
- The same plot for each pointing of the vertical polarization measurement.
- A bar chart whose horizontal axis is frequency band (bands as defined in Table 2), and vertical axis is occupancy, defined as the fraction of measurements for which the power measured in either polarization in any channel within the band is greater than 6 dB above the median power measured over all the channels in the same band over both polarizations. A second plot below the first, and using the same horizontal scale, shall indicate the mean value of this detection criterion as a function of band, in units of dB(Jy).[‡]

[‡]The motivation for this presentation of data is as follows: The data collected in Mode 2 is insufficient to generate meaningful spectral occupancy statistics on a channel-by-channel basis. However,

As in the Mode 1 presentation, these plots may be further subdivided only for the purpose of showing the frequency scales in greater detail.

3.3 Additional Information Required

The sensitivity of instrumentation in the same units as the presented data (see above) shall be reported in the form of a plot of sensitivity as a function of frequency, with different curves for the vertical- and horizontal-polarization measurements. For the purpose of these plots, "environmental noise" (e.g., ground temperature pickup through sidelobes) is *not* considered a limitation of the instrumentation, and thus not a factor in computing the sensitivity. This curve may be incorporated into the plots described above.

Part of the site measurement report shall be complete documentation of the instrumentation used, to include part numbers and specifications of antennas, LNAs, feedlines, and receivers. A narrative description of the calibration procedure and math used to convert the raw data into the requested units of dB(W m^{-2} Hz^{-1}) or dB(Jy) shall also be provided. Assumed characteristics of the antennas used in the calibration should be stated. Spectrum analyzer configuration and settings must be completely documented. The purpose of this request is to ensure that measurements at different sites can be fairly compared.

All data (raw and calibrated) shall be preserved in some useful (well documented) format to facilitate additional examination later. This data need not be provided with site reports but should be available upon request.

3.4 Optional Information

It should be noted that typical RA.769 thresholds for "harmful interference" are 0–3 orders of magnitude above 1 Jy, and thus somewhat below the levels achieved by the measurements described above. It is not practical to perform comprehensive measurements to the RA.769 levels with the limited time and resources typically available for

it possible to compute a coarse estimate of spectral occupancy on a band-by-band basis, using both polarizations together.

such measurements. Therefore, additional cycles of Mode 1 or 2 measurements, or use of higher-gain antennas in either polarization, are encouraged, but not required. If such measurements are included in the site report, these extra measurements must be reported separately from the plots described above so as to preserve the ability to compare site reports prepared by different organizations.

With respect to Mode 2, note that the specified number of measurement cycles is not probably not sufficient to compute meaningful "spectral occupancy" statistics. However, we encourage the taking of additional data (i.e., many more measurement cycles) and the reduction of this data to obtain spectral occupancy, defined as the fraction of the time in which the power in a frequency channel exceeds a threshold. If included in the site report, these extra measurements must be reported separately from the plots described above.

4 Measurement Requirements

This section defines the "measurement cycles" for Modes 1 and 2. The use of these defined measurement scripts to obtain a characterization of a site was described in Section 3.

4.1 Mode 1

Table 1 defines the measurement cycle for Mode 1. "RBW" stands for "resolution bandwidth" ($\Delta\nu$), and is also the spacing between center frequencies examined. S_{0h} is the expected flux at zero-elevation (i.e., along the horizon) for a signal matched in bandwidth that generates -100 dBm at the antenna terminals (see Appendix B). This level is used as an arbitrary criterion to identify RFI events which have the *potential* to threaten receiver linearity.[§] This is the required sensitivity of the measurement. "Dwell" is the length of time that a channel (one slice of spectrum having width equal to the specified RBW) is examined. "Reps" is the number of times the experiment should be repeated per iteration of the measurement cycle. A Mode 1 measurement

[§]Although a well-designed receiver ordinarily would not have a problem with a -100 dBm input, we choose to allow a wide margin to accommodate the possibility of signal fading, polarization mismatch, etc.

Frequency Band GHz	RBW kHz	S_{0h} dB$^{(1)}$	Dwell ms	Reps	Total s	Notes
0.070–0.150	3	−166	10	5	1334	2
0.150–0.300	3	−159	10	1	500	
0.300–0.800	30	−163	10	1	167	
0.800–0.960	30	−155	10	20	1000	3
0.960–1.400	1000	−168	0.002	10^6	900	4
1.400–3.000	30	−150	10	1	534	
3.000–22.000	1000	−158	10	1	190	
TOTAL					4624	

Note 1: dB relative to 1 W m^{-2} Hz^{-1}, at lowest frequency in band.
Note 2: Needed for IP2 design information.
Note 3: Intended to optimize probability of detecting bursts from mobile radio systems.
Note 4: Intended to optimize probability of detecting pulses from radars and DME.

Table 1: Mode 1 Measurement Cycle. Total time required is 1.28 h. Sensitivity assumes antenna gain of 2 (typical of a discone) in direction of horizon. Use of directional antennas increases gain, thereby increasing sensitivity but simultaneously increasing the number of required pointings.

cycle results in a 2D grid of measurements, where the pixel dimensions are dwell × RBW, and value of the pixel is peak power observed in the natural integration time of RBW^{-1}.

4.2 Mode 2

Table 2 defines the measurement cycle for Mode 2. S_{0h} in this case is expected sensitivity along the horizon assuming T_{sys} = 300 K (See Appendix A), and is now a function of dwell as well as RBW since we are nominally observing stationary noise as opposed to time-varying RFI. This is also the required sensitivity of the measurement. A Mode 2 measurement consists of a 2D grid of measurements, where the pixel dimensions are dwell × RBW, and value of the pixel is integrated power within that pixel.

Freq. Band GHz	RBW kHz	Dwell ms	S_{0h} dB(Jy)	Subtotal s	% of Total	Common Uses
0.150–0.153	1	100	52	300	1.31	Continuum
0.153–0.322	3	10	54	564	2.46	
0.322–0.329	3	1000	51	2334	10.21	DI
0.329–0.406	30	10	56	26	0.11	
0.406–0.410	30	10000	43	1334	5.83	Continuum
0.410–0.608	30	10	57	66	0.29	
0.608–0.614	30	10000	46	2000	8.76	Continuum
0.614–1.000	30	10	61	129	0.56	
1.000–1.370	30	300	58	3700	16.20	Continuum (not protected)
1.370–1.427	30	1000	58	1900	8.32	HI, SETI
1.427–1.606	30	100	64	597	2.61	SETI (not protected)
1.606–1.723	30	1000	60	3900	17.08	OH, SETI
1.723–2.655	30	10	70	311	1.36	
2.655–2.700	100	1000	62	450	1.97	Continuum
2.700–3.300	100	10	72	60	0.26	
3.300–3.400	100	1000	63	1000	4.60	CH
3.400–4.800	100	10	74	140	0.61	
4.800–5.000	100	1000	67	2000	8.72	H_2CO
5.000–6.600	300	10	75	54	0.23	
6.600–6.700	300	1000	67	334	1.45	CH_3OH
6.700–8.600	300	10	77	64	0.28	
8.600–8.700	300	1000	69	334	1.45	$^3He^+$
8.700–12.100	300	10	79	114	0.49	
12.100–12.200	300	1000	72	334	1.45	CH_3OH
12.200–14.400	300	10	82	74	0.32	
14.400–14.500	300	1000	74	334	1.45	H_2CO
14.500–18.300	300	10	84	127	0.55	
18.300–18.400	300	1000	76	334	1.45	C_3H_2
18.400–22.000	300	10	86	120	0.52	
TOTAL				23025	100.00	

Table 2: Mode 2 Measurement Cycle. Total time required is 6.4 h. Sensitivity assumes antenna gain of 2 (typical of a discone) in direction of horizon. Use of directional antennas increases gain, thereby increasing sensitivity but simultaneously increasing the number of required pointings.

5 Miscellaneous Comments

- The RBW specified in Tables 1 and 2 may vary by a factor of up to 2 (more or less) in order to accommodate equipment constraints. In this case, the number of frequency channels must be adjusted accordingly. Similarly, dwell may vary by a factor of up to 2 (more or less) with the appropriate adjustment in number of iterations. In no case may RBW and dwell be adjusted in such a way that sensitivity requirements are not achieved.

- Note that the per-pointing sensitivity requirements expressed in Tables 1 and 2 can be reached with shorter observation time by increasing the directivity of the antenna. Even when this is the case, however, it is not allowed to shorten the total duration of the Mode 1 and Mode 2 measurement cycles. This is to ensure that all observations have approximately uniform coverage in the time domain (as well as in the frequency and angle-of-arrival domains) regardless of the specific designs of the antennas used.

- Questions, comments, notice of errors, and suggestions for improvements pertaining to this document should be directed to the chair of the International Working Group on RFI Measurements, S. Ellingson, ellingson.1@osu.edu.

A The Sensitivity of a Single-Antenna Horizon-Monitoring RFI Measurement System

Here, we consider the sensitivity to a single noise-like signal occupying bandwidth B incident on the antenna with spectral flux density S (W m^{-2} Hz^{-1}). The power generated at the antenna terminals is

$$P_s = \frac{1}{2} SAB \tag{1}$$

where A is the effective aperture of the antenna. The factor of $\frac{1}{2}$ arises because we only measure one of two orthogonal polarizations, and we assume that the incident power is equally divided between them. Noise power referenced to the antenna terminals is

$$P_n = kT_{sys}B_m \tag{2}$$

where $k = 1.38 \times 10^{-23}$ J/K, T_{sys} is the system temperature, and we assume B_m is measurement bandwidth. Because (for the purpose of RFI measurements) we wish to have the best possible sensitivity to narrowband signals, we shall assume that $B_m \sim B$. For a signal-to-noise ratio of 1, $P_s = P_n$; solving for S and calling this value S_0:

$$S_0 = \frac{2kT_{sys}}{A} \tag{3}$$

For any given direction of incidence ψ, A is a function of ψ and is related to the directivity $D(\psi)$ by

$$A(\psi) = \epsilon \frac{\lambda^2}{4\pi} D(\psi) \tag{4}$$

where ϵ is the antenna efficiency and λ is wavelength. Vertically-polarized dipoles and discones have $D \sim 2$ along the horizon (other antennas will of course have greater directivity, so this value gives us an approximate lower bound). We have that S_0 along the horizon is approximately

$$S_{0h} = \frac{4\pi k}{c^2} \frac{T_{sys} f^2}{\epsilon} \tag{5}$$

If we assume reasonable values of $\epsilon = 0.9$ (i.e., assuming the antenna is reasonably well matched at the frequency of observation) and $T_{sys} = 300$ K, we find

$$S_{0h} \sim 64.2 f_{GHz}^2 \text{ MJy} \tag{6}$$

For example: At $f = 1$ GHz, we can detect a signal of 64.2 million Jy, and it takes an integration time of $\tau = B^{-1}$ to do so. If τ is increased to improve sensitivity, we have:

$$S_{0h} \sim \frac{64.2 f_{GHz}^2}{\sqrt{B\tau}} \text{ MJy} \tag{7}$$

It is important to note that this assumes $B \leq B_m$; if $B > B_m$, then we have instead:

$$S_{0h} \sim \frac{64.2 f_{GHz}^2}{\sqrt{B_m \tau}} \text{ MJy} \tag{8}$$

B Relating the Power at the Terminals of Single Horizon-Monitoring Antenna to Incident Spectral Flux Density

Here, we consider the relationship between the power P_s generated at the terminals of a single horizon-monitoring antenna due to an RFI signal incident with a specified spectral flux density, S (W m^{-2} Hz^{-1}). The power generated at the antenna terminals is

$$P_s = \frac{1}{2} S A B_s \tag{9}$$

where A is the effective aperture of the antenna and B_s is the bandwidth occupied by the signal. The factor of $\frac{1}{2}$ arises because we only measure one of two orthogonal polarizations, and we assume that the incident power is equally divided between them. Thus:

$$S = \frac{2P_s}{AB_s} \tag{10}$$

using the expression for A obtained in the previous appendix, we find:

$$S = \frac{4\pi}{c^2} \frac{P_s f^2}{\epsilon B_s} \tag{11}$$