Mileura RFI Model for All-sky EOR Experiment

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Summary

I extracted a simple model of RFI at Mileura between 50 MHz and 250 MHz from a report made for the LOFAR/SKA site selection processes [Chippendale, 2003]. Fig. 1 shows a plot of the resulting table of model interferers. It represents the expected dB ratio of RFI power to ambient power at the antenna terminals for an all-sky EOR experiment with a low gain antenna (~7 dBi or $A_e/\lambda^2 = 0.40$). Each point should be accurate to approximately ± 5 dB given the assumptions made in this report.

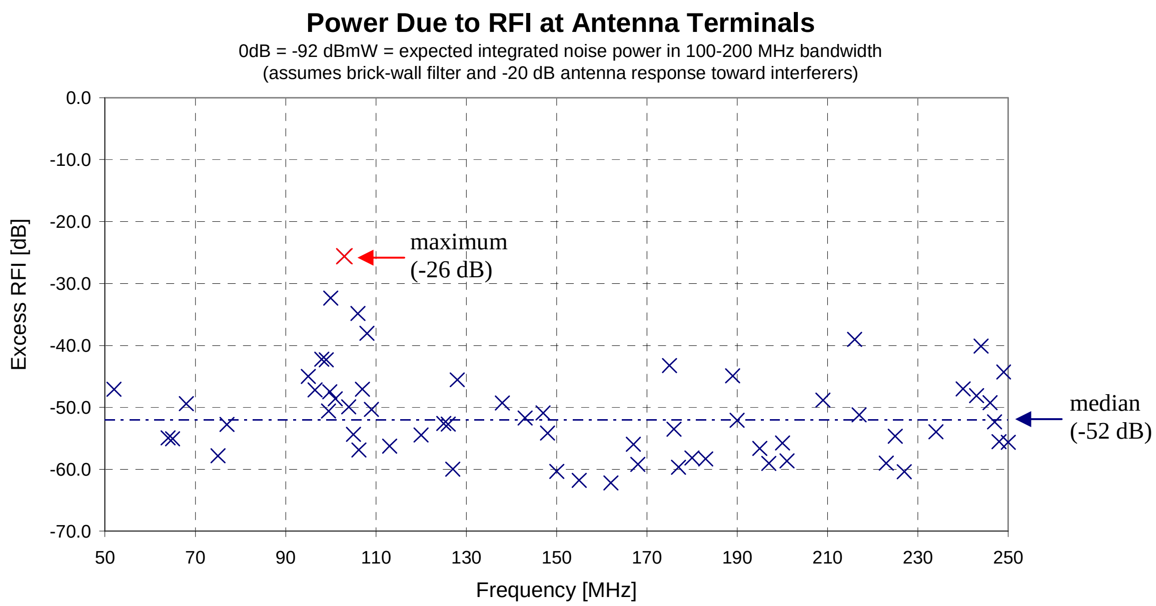


Fig. 1. Excess RFI power spectral density expected at the antenna terminals of a low-gain antenna directed toward the sky at Mileura. Tabulated version in Appendix A.

The model consists of 62 signals that are assumed to be carrier-like. The power from the strongest signal is -26 dB referred to the total expected noise power in the proposed 100-200 MHz receiving band for the EOR experiment. It is identified as an FM broadcast station at Meekatharra with an EIRP of 80 W and vertical polarisation.

The power from the median RFI signal is -52 dB. The model is presented in tabular form in Appendix A. Table 1 below presents a qualitative summary of the radio services operating in the band of interest.

Frequency Range [MHz]	**Service**	**Comments**
50 – 94		Low spectrum use
94 – 100	FM broadcast	Geraldton high-power service
100 – 108	FM broadcast	Meekatharra low-power service
108 – 137	Aeronautical	Low use short duration signals (mobile)
137 – 138	Satellite downlink	LEO
138 – 144	TV broadcast	
144 – 149.9		Low spectrum use
149.9 – 150.05	Satellite downlink	LEO
150.1 – 151	DRCS (Telstra phone/fax service)	Note: 150.05-153 MHz is an ITU radio astronomy allocation
151 – 174		Negligible band use
174 – 225	TV broadcast	Geraldton high-power service. Vacant 202 –209 MHz
225 – 243.8		Low spectrum use
243.8 – 250	Satellite downlink	Defence use

Table 1. Qualitative summary of radio activity at Mileura Station. Reconstructed from data in [Thomas, 1999b].

This report explains how I derived the model of Fig. 1 from the data in the LOFAR report. First, it discusses the equipment used for the RFI survey. Second, it discusses the calibration applied in the LOFAR RFI report [Chippendale, 2003] and the extensions made here to produce the model shown in Fig. 1.

Data are available from 30 MHz through to well above 1 GHz. This report is restricted to the sub-range 50-250 MHz as I assume that the RF filters in the receiver for the all-sky reionisation experiment will strongly attenuate any RFI outside this band.

Equipment & Layout

A contractor to the Government of Western Australia, in conjunction with Dr. Bruce MacA Thomas (formerly of CSIRO ATNF), made all measurements with the set-up shown in the Fig. 2 below [Thomas, 2001].

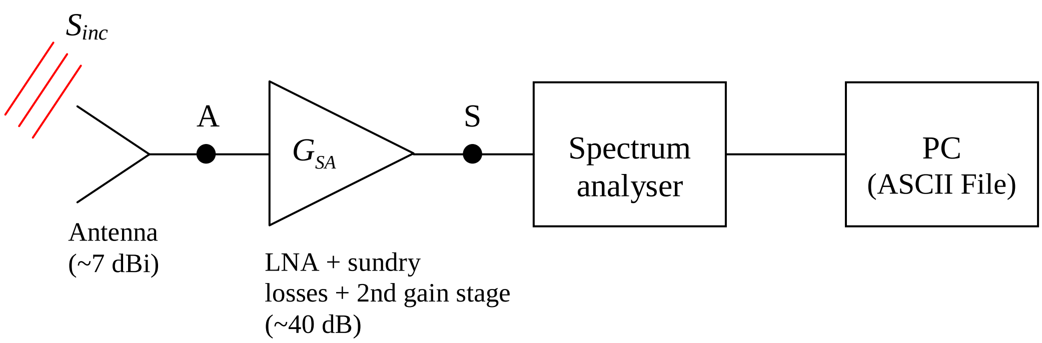


Fig. 2. Measurement set-up for Mileura RFI site test.

Band	Frequency Range	Antenna Type	Manufacturer	Antenna Gain (G_A)
A	30-150 MHz	Log Periodic	Com-antenna	~7 dBi
B1	148-175 MHz	Grid-Pack	ZCG Scalar P/L	8.0 ± 0.5 dBi
B2	175-222 MHz	Grid-Pack	ZCG Scalar P/L	7.3 ± 0.5 dBi
C	222-250 MHz	Log Periodic	Maldol	~5 dBi

Table 2. Band designations and corresponding antenna details.

The LOFAR frequencies were covered in four bands with three antennas as shown in Table 2 above. For each measurement, the relevant antenna was placed upon a 9.6 m guyed tower. The spectrum analyser and computer were located 45 m to the northeast of the antenna, and the generator a further 100 m in the same direction. Measurements were taken on three bearings (110°, 200° and 330°) which are illustrated on a map of the greater region in Appendix B.

RF Gain and Sensitivity

The noise figure of the low noise amplifier (LNA) and subsequent gain prior to the spectrum analyser were specified to ensure that the limiting factor to overall sensitivity was Galactic noise. It was found that an effective gain prior to the spectrum analyser of approximately 40 dB was appropriate. A list of the RF system gains and equivalent noise temperatures for each band is given in Table 3 below.

Band	Frequency Range	System Gain (G_{SA})	Noise Temperature	Noise Figure
A	30-150 MHz	40 dB	220 K	2.5 dB
B1	148-175 MHz	39 dB	140 K	1.7 dB
B2	175-222 MHz	39 dB	140 K	1.7 dB
C	222-250 MHz	41 dB	110 K	1.4 dB

Table 3. Receiving system gain and equivalent noise temperature.

Due to the isolated location of the test site, the system did not suffer overload from either in-band or out-of-band signals. Consequently, RF bandpass filters were not required except for the low frequency system extending down to 30 MHz. In this case a highpass filter with a 3 dB corner frequency of 25 MHz was used. The stability of the overall system gain was monitored visually from time to time as the data were collected.

Calibration

The original RFI measurements at Mileura yielded a raw measurement of power at the terminals of the spectrum analyser P_s (see Fig. 2). The LOFAR report converted these to a measurement of the flux incident on the antenna S_{inc}. In this report I calculate the RFI component of the power spectral density (PSD) at the antenna terminals of a hypothetical, low-gain (~7 dBi) antenna intended for an all-sky epoch of reionisation experiment.

Calibration for LOFAR Report

The raw measurement of the Mileura RFI survey is the power at the terminals of the spectrum analyser P_s in dBmW*. From this, the incident flux ahead of the antenna S_{inc} is deduced in units of dBmW/m^2. This section describes the process of this flux calibration.

The effective gain G_{SA} of the system between the antenna and the spectrum analyser was accurately calibrated so that raw power P_s at the terminals of the spectrum analyser could be referred to the antenna terminals (point A in Fig. 2) through

$$P_A = P_S - G_{SA} \text{ dBmW.}$$

G_{SA} consists of the LNA gain, transmission losses, and the filter insertion loss where a filter was used. It was carefully measured for each band and was always approximately 40 dB. Nominal values are reported in Table 3 above.

* 0 dBmW = 1mW. The more usual label dBm is not used so as to avoid later confusion with the effective collecting area in decibel meters squared (dBm^2).

The LOFAR report assumed that all received signals were aligned to the peak response of the antenna. This allowed the flux ahead of the antenna S_{inc} to be estimated by

$$S_{inc} = P_A - A_e \text{ dBm/m}^2.$$

A_e is the effective collecting area of the antenna expressed in dBm^2 as given by

$$\begin{aligned} A_e &= 10\log_{10}\left(\frac{\lambda^2}{\Omega_A}\right) \\ &= 10\log_{10}\left(\frac{c^2 D}{4\pi f^2}\right) \end{aligned}$$

where D is the directivity of the antenna, f is the frequency in Hz, and Ω_A is the solid angle of the antenna pattern in steradians. The directivities of the antennas used are listed in Table 2. The expression for calculating the effective area in decibels may be simplified to

$$A_e = G_A - 20\log_{10} F + 38.6\,\text{dBm}^2$$

where G_A is the directivity of the antenna in dBi and F is the frequency in MHz. An estimate of the error in calibration is given below.

Band	**SA Error**	**Pre SA gain error**	**Antenna Gain Error**	**Estimated Total Calibration Error**
A	± 0.5 dB	± 0.5 dB	± 1 dB	± 2 dB
B1	± 0.5 dB	± 0.5 dB	± 0.5 dB	± 1.5 dB
B2	± 0.5 dB	± 0.5 dB	± 0.5 dB	± 1.5 dB
C	± 0.5 dB	± 0.5 dB	± 1 dB	± 2 dB

Table 4. Estimate of the calibration error for the antennas used.

Extracting the RFI Power from the LOFAR Report

Next we desire to know what RFI PSD to expect at the terminals of a hypothetical antenna in an all-sky epoch of reionisation experiment at Mileura.

First I read the incident flux at the monitoring antenna terminals S_{inc} in dBm/m^2 from the graphs in the LOFAR report. I subsequently calculated the PSD W_A measured at the monitoring antenna terminals by

$$W_A = \frac{P_A A_e}{RBW} \text{ W.Hz}^{-1}$$

where P_A is the power at the antenna terminals in Watts, A_e is the effective area in m^2 and RBW is the resolution bandwidth of the spectrum analyser in Hz. Most measurements were made with a resolution bandwidth of 3 kHz, but a small quantity were made with 1 kHz.

Second I calculated the PSD expected at the test antenna terminals due to the galactic background, ground radiation, and instrumental noise. The monitoring antenna was pointed toward the horizon so I assumed that 50% of its pattern was directed toward the sky and the other 50% was directed toward the ground. Hence the PSD expected at the antenna terminals due to the sky brightness is

$$W_{sky} = \frac{\eta_R k T_{sky}}{2} \text{ W.Hz}^{-1}$$

and that due to thermal emission from the ground is

$$W_{gnd} = \frac{\eta_R k T_{gnd}}{2} \text{ W.Hz}^{-1}$$

where $\eta_R \cong 1$ is the radiation efficiency of the antenna, k is Boltzmann's constant, T_{sky} is the sky brightness temperature and T_{gnd} is the brightness temperature of the ground which we assume is 300 K.

At these frequencies, sky emission is dominated by the Galaxy and can be characterised by

$$T_{sky} = T_{S0}\lambda^{2.55}$$

where T_{S0} is $60 \pm 20\,\mathrm{K}$ for galactic latitudes 10°-90° [Bregman, 1999].

The equivalent thermal noise expected at the antenna terminals due to instrumental noise in the receiver system is

$$W_{RX} = kT_{RX} \quad \mathrm{W.Hz^{-1}}$$

Where T_{RX} is the equivalent noise temperature of the receiver. In total, at the monitoring antenna terminals, the survey measured a total PSD with the following breakdown

$$\begin{aligned} W_A &= W_{sky} + W_{gnd} + W_{RFI} + W_{RX} \\ &= W_n + W_{RFI} \end{aligned}.$$

Here $W_n = W_{sky} + W_{gnd} + W_{RX}$ is the PSD at the antenna terminals due to all noise like components. It defines the noise floor of the RFI monitoring effort.

In channels where RFI is detected above the noise floor W_n, the contribution to the total PSD made by the RFI is then expected to be

$$W_{RFI} = W_A - W_n.$$

Let us now turn to the hypothetical experimental setup for the EOR experiment. Using primed variables to represent elements in the proposed EOR detection system rather than the existing RFI monitoring system, the PSD at the antenna terminals of the EOR antenna is

$$\begin{aligned} W'_A &= W'_{sky} + W'_{gnd} + W'_{RFI} + W'_{RX} \\ &= W'_n + W'_{RX} \end{aligned} .$$

The same sky model is used as above ($T'_{sky} = T_{sky}$) but the PSD due to the sky is doubled as the antenna pattern is now directed wholly toward it

$$W'_{sky} = \eta_R k T_{sky} \text{ W.Hz}^{-1}.$$

For the same reason I assume negligible ground radiation ($W'_{ground} \cong 0$).

Instrumental noise is given by

$$W'_{noise} = kT'_{RX} \text{ W.Hz}^{-1}$$

where T'_{RX} is the equivalent noise temperature of the reionisation experiment receiving system. Assuming a 0.4 dB noise figure for the receiving system yields an equivalent noise temperature of $T'_{RX} = 28\,\text{K}$.

We are interested in the strength of RFI signals with respect to the mean operating signal level. We hence define the excess RFI PSD factor as

$$\alpha_{RFI} = \frac{W'_{RFI}}{W'_n} = \frac{W'_{RFI}}{W'_A - W'_{RFI}} = \frac{W'_{RFI}}{W'_{sky} + W'_{ground} + W'_{noise}}$$

such that

$$W'_A = (1 + \alpha_{RFI}) W'_n .$$

Next, I assume that the antenna we use for the reionisation experiment will be of similar effective collecting area to those used in the Mileura RFI testing (i.e. have a similar antenna gain to those listed in Table 2). I also assume that, in the true experiment, we will point the antenna toward the sky and not the horizon as was the case for the monitoring effort at Mileura. Hence we expect terrestrial RFI power to be reduced by the front to side ratio G'_{FS} of the antenna used for the reionisation experiment. I define G'_{FS} as the ratio of antenna gain on-axis to that exhibited ~90° away from this axis. Terrestrial interference power seen by the reionisation antenna directed toward the sky W'_{RFI} will thus be less than that seen by the RFI measurement antenna directed toward the horizon W_{RFI} by a factor of G'_{FS} according to

$$W'_{RFI} = \frac{W_{RFI}}{G'_{FS}} .$$

I estimate $G'_{FS} \cong 100$. The excess RFI power factor then becomes

$$\alpha_{RFI} = \frac{W'_{RFI}}{W'_n} \cong \frac{W_{RFI} / G'_{FS}}{W'_{sky} + W'_{ground} + W'_{noise}} .$$

However, what we are really interested in is the ratio of power in the i^{th} interferer P_{RFI_i} to the integrated noise power in our 100 MHz band P_{n100}. Let us define this ratio for the i^{th} interferer as $\beta_{RFI\,i}$ where

$$\beta_{RFI_i} = \frac{P_{RFI_i}}{P_{n100}} = \frac{\int_{BW_i} W'_{RFI}\, df}{\int_{100\,\mathrm{MHz}}^{200\,\mathrm{MHz}} \mathrm{W}'_{\mathrm{n}}\, df} .$$

The integral in the numerator is taken over the bandwidth *BW* of the i^{th} interferer. Assuming that all signals are narrow band compared to the 3 kHz RBW of the RFI survey, we can make the following approximation

$$\beta_{RFI_i} = \frac{W'_{RFI} BW_i}{\int_{100\,\mathrm{MHz}}^{200\,\mathrm{MHz}} \mathrm{W}'_{\mathrm{n}}\, df} .$$

The integral in the denominator is evaluated as

$$\begin{aligned}
P_{n100} &= \int_{100\,\mathrm{MHz}}^{200\,\mathrm{MHz}} \mathrm{W}'_{\mathrm{n}} df \\
&= \int_{100\,\mathrm{MHz}}^{200\,\mathrm{MHz}} (W'_{sky} + W'_{ground} + W'_{noise}) df \\
&= k\int_{100\,\mathrm{MHz}}^{200\,\mathrm{MHz}} (\eta_R T_{S0} \lambda^{2.55} + T'_{RX}) df \\
&= \frac{k\eta_R T_{S0} c^{2.55}}{1.55} \left[f^{-1.55} \right]_{200\,\mathrm{MHz}}^{100\,\mathrm{MHz}} + kT'_{RX}\,(100\,\mathrm{MHz}) \\
&= 6.18 \times 10^{-13}\ \mathrm{W} = \text{-}92\,\mathrm{dBm}
\end{aligned}$$

so we arrive at

$$\beta_{RFI_i} = \frac{W'_{RFI}\, RBW}{6.18 \times 10^{-13}}.$$

Fig. 1 is a plot of $10\log_{10}\beta_{RFI}$ for selected signals measurably above the noise floor in the LOFAR RFI report for Mileura.

Selection of Signals

Here I describe how I selected signals from the charts in the LOFAR reports and how I dealt with duplicate signals at common frequencies.

I first worked through the LOFAR report recording the frequency, median power in dBmW/m^2, relative bandwidth, polarisation and bearing of each signal with median power measurably greater than the median noise.

Second, I sorted all signals in ascending order of frequency. I removed multiple entries for single frequencies leaving only the strongest signal in each case. The calibration assumes that all signals were received through the peak of the antenna pattern. This causes the power from off-axis interferers to be underestimated. Thus, the maximum measured power from a given interferer over all measured directions yields the best estimate of the true interfering power.

There are two exceptions to the logic of retaining only the strongest interferer where there are detections over multiple directions. The first is signals from satellites at high elevations. These should be recognisable as their measured signal strength should not vary largely for RFI measurements at widely spaced azimuths on the horizon. As the antenna is rotated in azimuth, the power from a high elevation satellite would always leak into the side of the beam and hence experience less variation in antenna gain than a RFI source on the horizon. The second exception is simultaneous transmissions at the same frequency by sources at different bearings.

The first order RFI model presented in Fig. 1 does not take these two exceptions into account. In the case of the hypothesised, high elevation satellite signals, we should multiply their strength by the front to side ratio, not divide. I will return to such details at a later stage if we decide they are important.

Nature of Signals

In designing the signal processing path for the all-sky epoch of reionisation experiment, it is important to understand the spectral nature of the interferers as well as their amplitude. Are the signals narrow-band or broad-band, carrier like or noise like, continuous or intermittent?

Such questions can be answered by studying the original Mileura RFI reports [Thomas, 1999a] & [Thomas, 1999b]. These reports contain higher resolution plots of the raw data (power measured at the spectrum analyser terminals in dBmW). They also contain tables with signal classification and, where possible, identification. We may refer to the reports if we desire a more detailed description of typical interference at Mileura than given by Fig. 1 and Table 2.

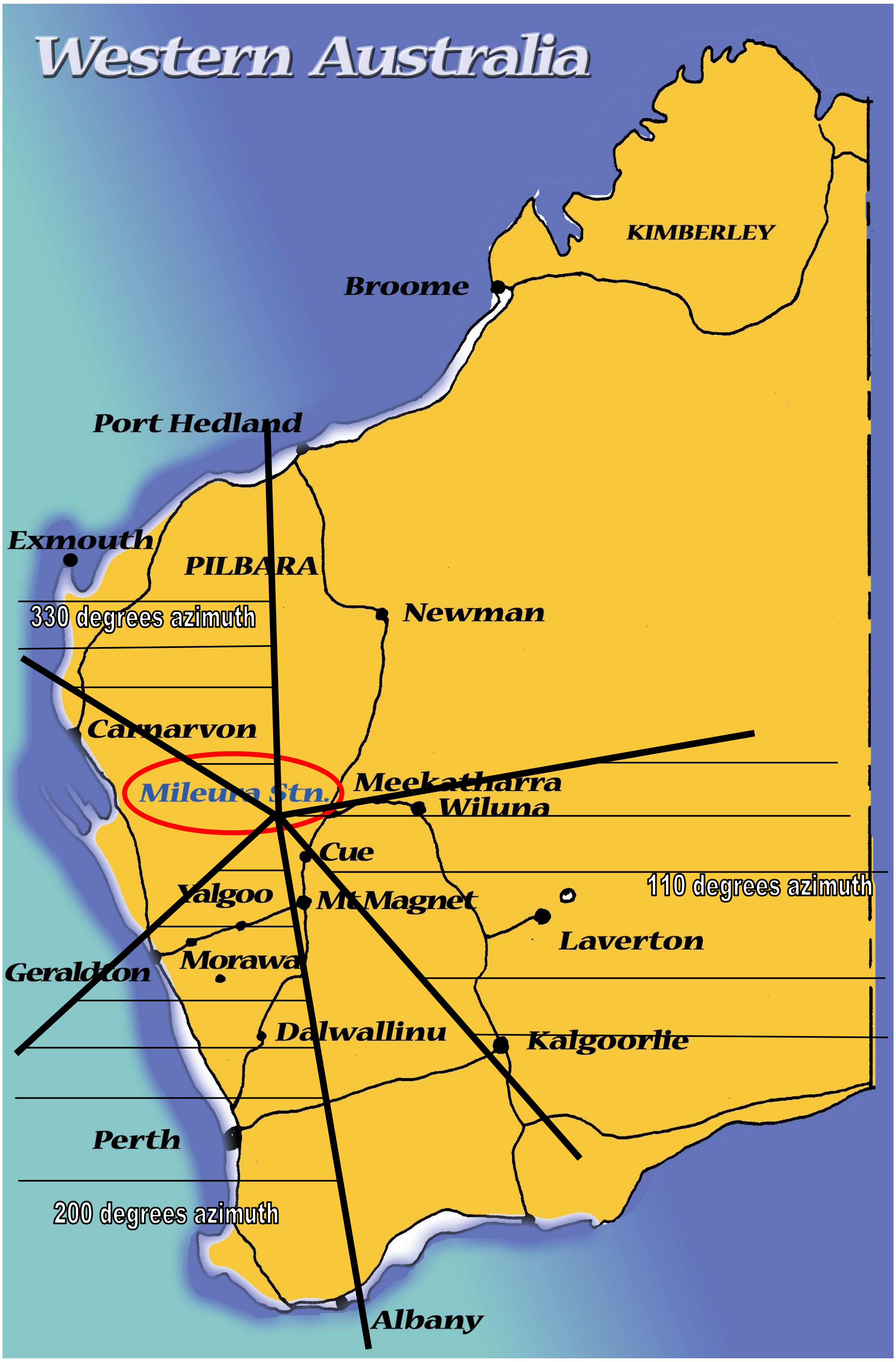
For now, I assume that all signals are carrier like and can thus be represented by a discrete collection of sinusoids with amplitudes defined by Fig. 1.

Appendix A – Table of Model Interferers

Note: 0 dB = -92 dBm = expected ambient power in 100 MHz bandwidth

Freq [MHz]	**Excess RFI Power** [dB]
52.0	-47
64.0	-55
65.0	-55
68.0	-49
75.0	-58
77.0	-53
95.0	-45
96.5	-47
98.0	-42
99.0	-42
99.5	-51
99.8	-48
100.0	-32
101.0	-49
103.0	-26
104.0	-50
105.0	-54
106.0	-35
106.2	-57
107.0	-47
108.0	-38
109.0	-50
113.0	-56
120.0	-55
125.0	-53
126.0	-53
127.0	-60
128.0	-46
138.0	-49
143.0	-52
147.0	-51
148.0	-54
150.0	-60
155.0	-62
162.0	-62
167.0	-56
168.0	-59
175.0	-43
176.0	-54
177.0	-60
180.0	-58
183.0	-58
189.0	-45
190.0	-52
195.0	-57
197.0	-59
200.0	-56
201.0	-59
209.0	-49
216.0	-39
217.0	-51
223.0	-59
225.0	-55
227.0	-60
234.0	-54
240.0	-47
243.0	-48
244.0	-40
246.0	-49
247.0	-52
248.0	-56
249.0	-44
250.0	-56

Appendix B – Map of Surveyed Region



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