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Selection of radio astronomical observation sites and its dependence on human generated RFI

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Abstract We investigate the influence of population density on radio-frequency interference (RFI) affecting radio astronomy. We use a new method to quantify the threshold of population density in order to determine the most suitable lower limit for site selection of a radio quiet zone (RQZ). We found that there is a certain trend in the population density-RFI graph that increases rapidly at lower values and slows down to almost flat at higher values. We use this trend to identify the thresholds for population density that produce RFI. Using this method we found that, for frequencies up to 2.8 GHz, low, medium and high population densities affecting radio astronomy are below $150\ \mathrm{ppl\ km^{-2}}$, between $150\ \mathrm{ppl\ km^{-2}}$ and $5125\ \mathrm{ppl\ km^{-2}}$, and above $5125\ \mathrm{ppl\ km^{-2}}$ respectively. We also investigate the effect of population density on the environment of RFI in three astronomical windows, namely the deuterium, hydrogen and hydroxyl lines. We find that a polynomial fitting to the population density produces a similar trend, giving similar thresholds for the effect of population density. We then compare our interference values to the standard threshold levels used by the International Telecommunication Union within these astronomical windows.

Key words: telescopes — cosmology: observations — methods: data analysis — wave scattering

1 INTRODUCTION

The radio astronomy spectrum is increasingly polluted by intentional and unintentional human generated radio-frequency interference (RFI). This RFI is produced in dense residential and commercial areas. RFI is generated by essential human activities such as wireless internet access, satellites (GPS, GLONASS and IRIDIUM), television sets, mobile phones and other basic personal electrical equipment such as laptops, radios, electric heaters and vacuum cleaners. There is also basic infrastructure that generates RFI such as transportation vehicles, electrical power lines and power stations. It is important to quantify the effects of such RFI on the spectrum used in radio astronomy.

For example, a mobile phone signal is 10^{12} Jy, where 1 Jy is $10^{-32}\ \mathrm{Wm^{-2}\ Hz^{-2}}$. However, the typical spectral power flux density for a source in radio astronomy is at the level of mJy (Ponsonby 1991). Another example is the RFI measurements done at several locations by a group in New Zealand, associated with the Square Kilometer Array (SKA). Their results showed that rural sites

Table 1 Population Density for Several Major Telescopes around the World (Umar et al. 2012)

Location of Radio telescope/names	Diameter (m)	Pop. density (ppl km^{-2})
Australia, ASKAP	12	1
Australia, Mount Pleasant	26	125
Australia, Parkes	64	9
China, Delingha	13.7	8
Finland, Metsahovi	13.7	103
Ukraine, Crimea	22	77
Ukraine, Grakovo	12	80
Italy, Medicina	32	100
Italy, Sardinia	64	31
Japan, Nobeyama	45	158
New Zealand, Warkworth	12	30
South Africa, Indlebe	5	110
South Africa, MeerKAT	13.5	3
Russia, Ratan-600	600	18
Russia, RT-7.5	7.5	155
United States, GBT	100	17
United States, VLBA	25	1
United States, VLA	25	1

in Awarua and Kauri (2.8 ppl km^{-2}) have low RFI levels when compared to the city of Auckland (2900 ppl km^{-2}) and Mt. Wellington (Gulyaev & Banks 2012). Yet another example is the Atacama Large Millimeter/submillimeter Array (ALMA) which is located in a remote area of the Atacama Desert that not only has a small population density (18 ppl km^{-2}) but also shows low absorption by water vapor.

Some other sites around the world that have a radio telescope are listed in Table 1, along with the population density of those sites (Umar et al. 2012). These radio telescopes observe in parts of the spectrum allocated to radio astronomy and protected by the International Telecommunication Union (ITU) regulations as implemented by their national spectrum management administrations (Cohen et al. 2005). There are many radio telescopes in Europe that have a radio quiet zone (RQZ) with radius 1 km to 3 km for their deeper zone, 20 km to 30 km for their larger zone and 100 km for their largest zone (Küçük et al. 2012).

To further protect these telescopes from interference, Green Bank observatory, for example, has rules on restricting electrical equipment in the area around their RQZ. The observatory operates an RFI monitoring van in the RQZ. There is an exclusion zone in which the only vehicles that are allowed are diesels (with no spark plugs) and bicycles. Inhabitants are only allowed to use electronic equipment that produces very high RFI at least 16 km away from the observatory site (Thompson 2004).

In our case, we are planning to install a radio telescope with RQZ protection that is less stringent if we can find a much lower RFI environment. We have identified population density as a major factor in this selection and we want to quantify the threshold of population density for our site selection criteria (Abidin et al. 2013).

2 METHODOLOGY

There are eight sites selected for this study with population densities ranging from 58 ppl km^{-2} to 7089 ppl km^{-2}. Table 2 also shows the distance from the site to the nearest town and the distance to the nearest city center which is presumed to have a much higher number of sources that generate RFI. Initial RFI testing was done at the University of Malaya for reference and for the purpose of calibration (Abidin et al. 2013). In our set up, we used a spectrum analyzer (with frequency up to

Table 2 Population Densities for Eight Sites (Department of Statistics 2007)

Sites	Population density (ppl km^{-2})	Distance from small town (km)	Distance from city center (km)
Setiu	58	13 (from Setiu)	30 (from Kuala Terengganu)
Tapah	70	6 (from Bidor)	30 (from Ipoh)
Teluk Intan	133	7 (from Langkap)	28 (from Ipoh)
Banting	248	5 (from Jenjarom)	20 (from Shah Alam)
Gombak	1085	2 (from Sentul)	5 (from Kuala Lumpur)
Klang	1309	1 (from Klang)	6 (from Shah Alam)
Petaling Jaya	3012	5 (from Kuala Lumpur)	8 (from Shah Alam)
Kuala Lumpur	7089	0 (from Kuala Lumpur)	0 (from Kuala Lumpur)

Department of Statistics 2007, Malaysia Year Book of Statistics 2007, Department of Statistics Malaysia Kuala Lumpur (Umar et al. 2012)

2.8 GHz) and 50 Ohm cables to connect to a low noise amplifier (LNA) with 28 dB gain and then to a discone antenna (optimized at 1420 MHz). Observations were taken for one hour at intervals of 15 minutes for each site (Abidin et al. 2010). We referred to the RFI measurement protocol for SKA candidate sites (Ambrosini et al. 2003). The average levels of RFI for the eight sites were plotted against their population density. The thresholds were determined by calculating the tangent of the increasing and the flattened parts of the curve. The average level of RFI in these thresholds was calculated at the reference level used by ITU and we identified how much these levels of RFI exceeded the limits set by ITU (Cohen et al. 2005).

3 RESULTS AND ANALYSIS

We determined how the population density affects threshold levels from $0 - 2.8$ GHz and we also calculated these threshold levels in all radio astronomical windows up to 2.8 GHz. A polynomial

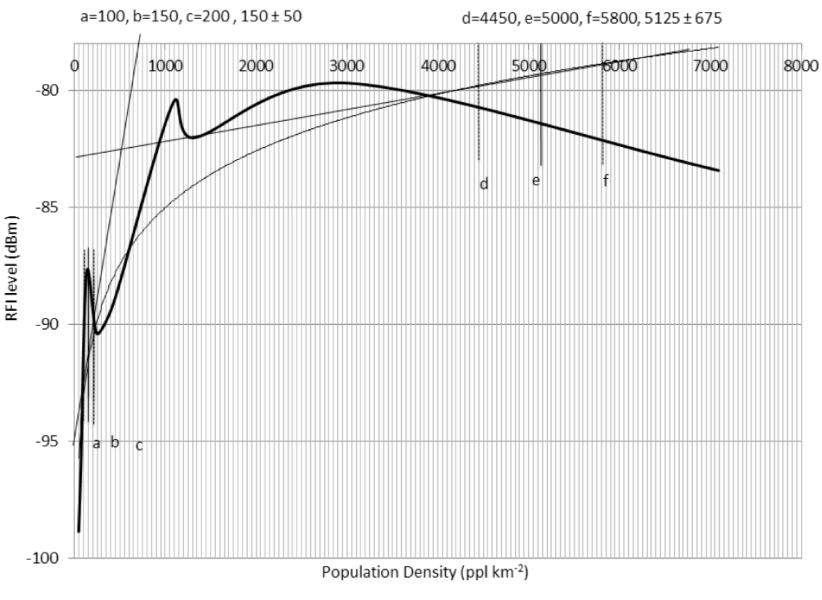

Fig. 1 RFI profile for all windows ($1 - 2800$ MHz).

Table 3 Typical Sources of Ground RFI Contamination

RFI source	Description	Solution/distance (m)
Electric lawnmowers	The motors used on electric lawn mowers are of the high-torque/high current variety.	Use a line filter on the motor.
Vacuum cleaners	Most modern vacuum cleaners are fairly well shielded for RFI/EMI. However, the inside of the motor will become fairly dirty since not all of the dust will be stopped by the collector bag.	Use a capacitor at the brushes.
Electric shavers	Most manufactures have built-in RFI/EMI suppression capacitors.	Use an external line filter.
Electric hot-water heaters	A typical electric hot-water heater has two heating coils controlled by separate thermostats. Since the coils draw a large amount of current, the contact on the thermostat switch may become pitted over a period time.	600 V capacitor should be sufficient.
Gas or oil heat burners and thermostats	There are several places for interference generated in an oil or gas heating system. Two or more motors can be used in this system.	Use a bypass capacitor and line filter when necessary.
Electric heat thermostats	Most electric heating systems use a combination thermostat/switch assembly for control of radiators.	Bypass each set of contacts.
Doorbell transformers	Some doorbell systems are equipped with transformers that have a temperature-sensing shutdown mechanism.	Find the problem in the system or replace the transformer.
Arc welders	Arc welders are capable of causing severe interference. Of course, there is no way to suppress the arc and keep the machine functioning.	A heavy duty line filter should be used directly at the primary transformer.
Electric fences	These are very common in rural areas. A transformer steps up the line voltage and an automatic switch sends a pulse down the fence once every few seconds.	A resistor placed in series with the fence wire will help to dampen the pulse. A capacitor across the switch also helps (5 m).
Fluorescent lights	Noise from a fluorescent light is caused by the arc that excites the gas in the tube. Most recently developed lights do not use starters, which are the sources of many interference problems.	Keep a distance of about 3–6 m (frequency from 10–100 MHz).
Neon signs	These are very similar to fluorescent lights.	A line filter directly mounted on the transformer and resistors in series with each high-voltage lead (3–6 m).
Light dimmers	Light dimmers can be a source of severe interference problems at low frequency and lower high frequency.	Bypass the capacitor for defects.
Television sets	The horizon and color burst oscillators are usually the cause. These amplifiers may malfunction and oscillate in the upper high frequency or very high frequency.	Add a high pass filter to the antenna terminal of the sets. Use an external line filter to reduce interference.
Microprocessor and microcomputers	The use of microprocessor control of various appliances is relatively new. Sewing machines, blenders and microwave ovens are only a few of the everyday items controlled in this way.	Move away at least 10 m.
Petrol vehicle	Petrol vehicle spark plugs produce RFI.	Use an electric car.
Hybrid vehicle	Hybrid vehicle produces RFI.	Use an electric car.
Power line	High voltage overhead power lines can produce RFI/EMI. Normally the frequency used is about 60 Hz.	Move away at least 1.6 km.

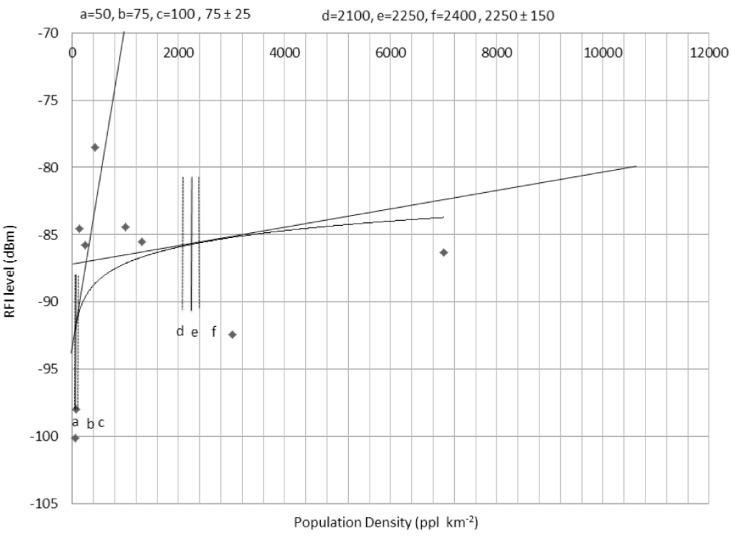

Fig. 2 RFI profile for the hydrogen line $(1400 - 1420\ \mathrm{MHz})$.

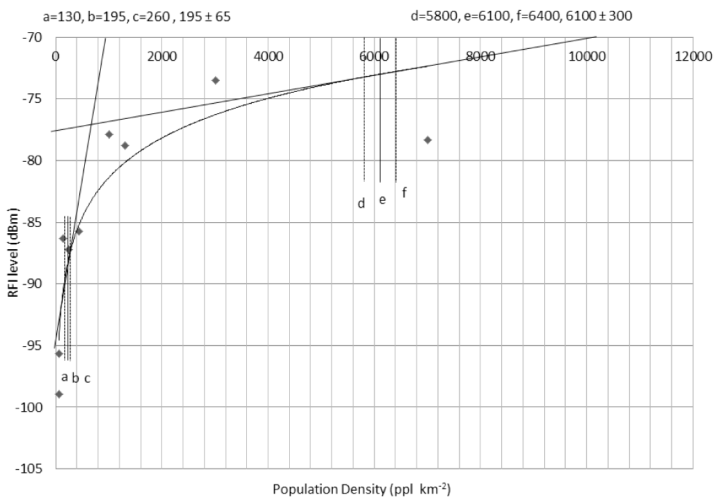

Fig. 3 RFI profile for the hydroxyl line-1 $(1610 - 1675\ \mathrm{MHz})$.

fitting was applied to the graph (Figs. 1 to 5). We also study possible RFI sources used by humans that might contribute to the RFI at a radio telescope. We list these sources in Table 3.

The threshold level that we calculated within these astronomical windows is summarized in Tables 4–8. The average RFI up to $2.8\ \mathrm{GHz}$ gives us three thresholds for population density that represent low, medium and high population densities, i.e. below $150\ \mathrm{ppl\ km^{-2}}$, between $150\ \mathrm{ppl\ km^{-2}}$ and $5125\ \mathrm{ppl\ km^{-2}}$ and above $5125\ \mathrm{ppl\ km^{-2}}$ respectively. We also calculated the total RFI received by our spectrum analyzer. We used the average RFI level in the windows, for example at $-94\ \mathrm{dBm}$ for a low population density within 0 to $2.8\ \mathrm{GHz}$ (see Table 4). For the distance from the receiver to

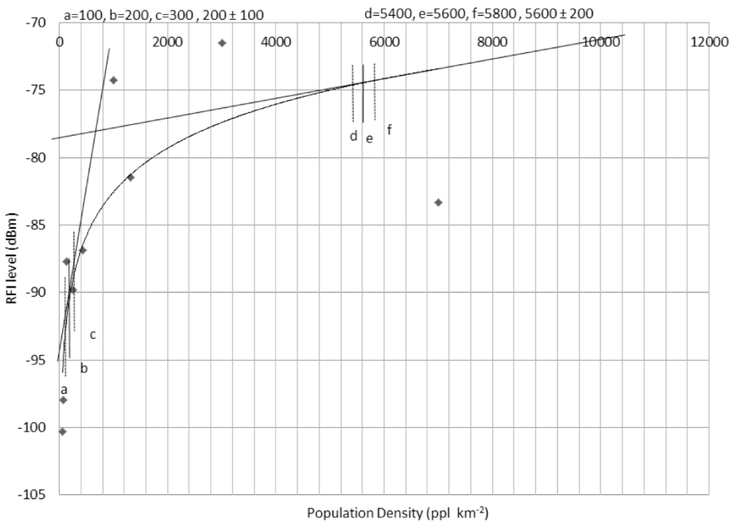

Fig. 4 RFI profile for the hydroxyl line-2 $(1718.8 - 1722.2 \text{ MHz})$.

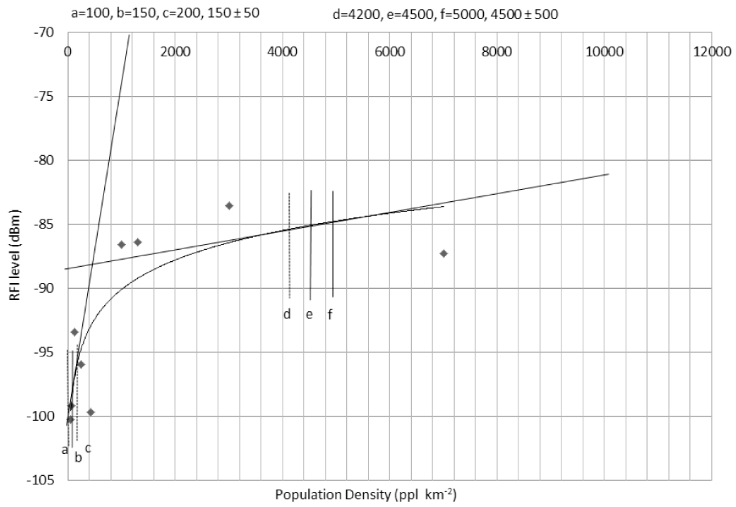

Fig. 5 RFI profile for the deuterium line $(322 - 328.6 \text{ MHz})$.

the antenna, d, we determined a power level using the formula (Ambrosini et al. 2003);

$$\text{FSPL} = 20 \log 10 \times \left(\frac{4\pi df}{c} \right). \tag{1}$$

We calculated the value of the FSPL for the windows in Table 4 as 50 dBm. The total RFI seen at the focus of the antenna is then $-94+(50) = -44 \text{ dBm} = -74\text{dBW}$. However, as recommended

Table 4 Average RFI (below 2.8 GHz)

Group	Population density (ppl km^{-2})	Average RFI level (dBm)	Freq/Highest peaks (MHz/dBm)	RFI at the antenna (dBm)	ITU Threshold level (dBW)	Exceeds ITU by (dB)
A	0–150±50	–94±9	1860/–55	–28		147
B	150–5125±675	–83±6	945/–54.9	–17	–205	158
C	5125 and above±675	–83±7	947.5/–54	–17		158

Table 5 Average RFI Survey for the Hydrogen Line ($1400 - 1427$ MHz)

Group	Population density (ppl km^{-2})	Average RFI level (dBm)	Freq/Highest peaks (MHz/dBm)	RFI at the antenna (dBm)	ITU Threshold level (dBW)	Exceeds ITU by (dB)
A	0–75±25	–100±1	1417.5/–77	–34		156
B	75–2250±150	–90±1	1425/-83	–24	–220	166
C	2250 and above±150	–90±1	1427.5/–85	–24		166

Table 6 Average RFI Survey for the Hydroxyl-1 Line ($1610 - 1675$ MHz)

Group	Population density (ppl km^{-2})	Average RFI level (dBm)	Freq/Highest peaks (MHz/dBm)	RFI at the antenna (dBm)	ITU Threshold level (dBW)	Exceeds ITU by (dB)
A	0–150±50	–94±6.1	1650/–62	–27		163
B	150–4500±300	–81±6.0	1662.5/–60	–14	–220	176
C	5125 and above±675	–78±7	1632.5/–64	–11		179

Table 7 Average RFI Survey for the Hydroxyl-2 Line ($1718.8 - 1722.2$ MHz)

Group	Population density (ppl km^{-2})	Average RFI level (dBm)	Freq/Highest peaks (MHz/dBm)	RFI at the antenna (dBm)	ITU Threshold level(dBW)	Exceeds ITU by (dB)
A	0–195±65	–95±2	1717.5/–70	–28		162
B	195–6100±300	–79±1	1720/–71	–12	–220	178
C	6100 and above±300	–83±1	1722.5/–70	–16		174

Table 8 Average RFI Survey for the Deuterium Line ($322 - 329$ MHz)

Group	Population density (ppl km^{-2})	Average RFI level (dBm)	Freq/Highest peaks (MHz/dBm)	RFI at the antenna (dBm)	ITU Threshold level (dBW)	Exceeds ITU by (dB)
A	0–200±100	–94±1	322.5/–81	–41		144
B	200–5600±200	–87±2	327.5/–80	–34	–215	151
C	5600 and above±200	–86±1	330/–76	–33		152

by ITU, we need to add correction values by using the following formula (Ambrosini et al. 2003)

$$\text{Correction} = 10 \log \left(\frac{6.6 \times 10^6}{180 \times 10^3} \right). \tag{2}$$

We calculated this value as 16 dB. Therefore, the total RFI power generated at this particular site is expected to be the difference between the total RFI at the antenna and the correction value by ITU which is -28 dBm. This threshold is about 147 dB higher than the recommended limit set by ITU. By using the same method, we calculated all the power levels for radio astronomical windows and compared them to the threshold level set by ITU. These are listed in Tables 4 to 8.

4 DISCUSSION AND CONCLUSIONS

We found that polynomial fitting is useful for identifying limits by determining a threshold for population density that affects RFI in radio astronomy. We suggest that the threshold between low and medium population density is $150\ \mathrm{ppl\ km^{-2}}$. The limit between medium and high population density is $5152\ \mathrm{ppl\ km^{-2}}$. The average levels of RFI in these categories of population density are 94, 83 and $83\ \mathrm{dBm}$, respectively (see Table 4). The frequencies with the highest peaks in these categories are $1860\ \mathrm{MHz}$ $(55\ \mathrm{dBm})$, $945\ \mathrm{MHz}$ $(55\ \mathrm{dBm})$ and $947.5\ \mathrm{MHz}$ $(54\ \mathrm{dBm})$, respectively.

The values derived above can be approximately used for the deuterium, hydrogen and hydroxyl spectral lines as well. However, the same methodology can be used to determine more precise population thresholds for these spectral lines, as given in Tables 5 to 8.

Our conclusion is that to build a radio telescope, one has to find a site with population density below $150\ \mathrm{ppl\ km^{-2}}$. The population density that will be very detrimental to radio astronomy observations is above $5125\ \mathrm{ppl\ km^{-2}}$. When we investigate population density around the telescopes in Table 1, we can conclude that most of these radio telescopes are located in very sparsely populated areas and their population densities are mostly lower than the threshold we suggest in this paper (i.e. $150\ \mathrm{ppl\ km^{-2}}$).

Besides the RFI contribution from the population density, the equipment used for observations can also produce internal RFI in the measurements. We recommend that all such equipment should be carefully shielded.

We also study possible RFI sources used by humans that might contribute to the RFI at a radio telescope. These sources produce unintentional interference that might be more important if they exist in the observatory itself. We noticed that most of these ‘personal’ RFI sources from humans produce short-distance RFI and it will not affect radio astronomical observations beyond perhaps 100 to 200 meters. We recommend such equipment be housed in Faraday cages.

For future work, we suggest that the RFI measurements should be repeated in the middle of a residential or commercial area to see how RFI varies due to human activities. In the current work, the site selection is taken randomly.

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