2012

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Andrew Strange
CSIRO

Jonathon Ralston
CSIRO

Publication Details

A. Strange and J. Ralston, Safe automation: A practical guide to understand and manage sensor RF exposure risk, 12th Coal Operators' Conference, University of Wollongong & The Australasian Institute of Mining and Metallurgy, 2012, 305-314.

SAFE AUTOMATION: A PRACTICAL GUIDE TO UNDERSTAND AND MANAGE SENSOR RF EXPOSURE RISK

Andrew D. Strange and Jonathon C. Ralston

ABSTRACT: The increasing interest in remote and automation technology by the underground coal mining industry has resulted in the introduction of sensors and devices that emit electromagnetic radiation. The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) has defined clear maximum limits for exposure to electromagnetic radiation to ensure health and safety of people and the environment. However, it is often difficult to determine the actual radio frequency (RF) energy level a sensor radiates in a given operation context. Further, the ARPANSA regulation and associated Australian standards for electromagnetic radiation exposure can be complex to practically interpret. Unfortunately, this may leave the mining personnel in the position where they need to either solely rely on vendor device specifications or hope that the sensor is not presenting any radiation exposure risk. This paper provides an overview of the ARPANSA exposure regulations and sets out a practical approach to measure the radiation as per the Australian Standard. By focussing on an RF range from 3 kHz to 300 GHz, a number of commonly used active devices such as radars, wireless communication systems, and related RF imaging devices can be assessed. A simple method to allow basic in-house testing is described to allow end-users to make independent quantitative assessments of sensor radiation levels. The assessment method is demonstrated with a practical example using two ground penetrating radar systems as test cases.

INTRODUCTION

With the ongoing demand for automation and safety systems in underground coal mines, the rate of installation of devices and sensors that emit electromagnetic radiation will progressively increase. Sensors and devices in this domain include wireless communication (e.g. Wi-Fi), collision or proximity detection systems, radio frequency identification (RFID) and ground penetrating radar (GPR) systems. These types of devices function by transmitting electromagnetic energy from a transmitter to a receiver. The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) define the electromagnetic energy emissions limits for safe operation of these types of devices. ARPANSA has published restrictions with which these sensors and devices must comply (ARPANSA, 2002). One sensor that emits electromagnetic radiation and has the potential to enhance automation systems in the underground coal mining industry is GPR.

A GPR sensor, also called subsurface radar, is typically used to non-invasively determine information about the subsurface. The most common configuration of GPR involves an antenna module positioned in direct contact with the ground. When the antenna module is moved along a path, changes in the subsurface are shown on a display unit. During operation, the GPR system transmits extremely short pulses of electromagnetic energy into the ground. The electromagnetic energy is then reflected at interfaces beneath the ground and returns back towards the antenna module for processing and display. Previous research undertaken by CSIRO (Ralston and Hainsworth, 1999) and (Ralston, *et al.*, 2001) has shown that GPR can be used to measure coal thickness in underground coal mining operations. Therefore, it is important to consider the safety of this technology and assess if the electromagnetic fields emitted by standard commercial GPR systems are within the limits defined by ARPANSA.

An overview of the ARPANSA regulations that apply to the typical GPR sensors is presented. A procedure to measure the electromagnetic radiation level to determine compliance is described. Experiments were conducted where the electromagnetic radiation levels of two commercial GPR systems were measured. These experiments and the results are presented.

[1] *Research Engineer - Mining Technology Research Group, CSIRO Earth Science and Resource Engineering, andrew.strange@csiro.au*

ELECTROMAGNETIC FIELDS

Electromagnetic fields consist of two complementary fields - an electric field and a magnetic field. An electric field is created by the concentration of electric charge and a magnetic field is created by the motion of electric charge. Systems that utilise electromagnetic fields employ a transmitter antenna to radiate electromagnetic energy to a corresponding receiver antenna. For example, a broadcast TV system has a transmitter antenna which is usually located high on a mountain close to the TV studio. The transmitter antenna radiates the TV signals in the form of electromagnetic energy to the TV antennas in homes across the local region. The receiver antenna in this case is the TV antenna as it receives a portion of the electromagnetic energy transmitted by the transmitter antenna. In other cases such as airport radar systems, the transmitter and receiver antenna are the same physical infrastructure. For the radar case, the received signal is reflected back towards the antenna from a target such as an aeroplane.

Electromagnetic energy can be generated from a continuous or pulsed signal. A continuous signal is a signal that maintains full power. An example of a continuous signal is a TV broadcast signal which is continuously being transmitted. Conversely, a pulsed signal is one that consists of two distinct states that are repeated periodically. During an *on* state, a high level of power is being transmitted whereas during an *off* state, the transmitter power is typically very low. The rate at which the pulsed signal is repeated is called *the pulse repetition frequency* (PRF). Impulse GPR systems such as those evaluated as part of this investigation function as a pulse system.

OVERVIEW OF THE RADIATION PROTECTION STANDARD

The Radiation Protection Standard published by ARPANSA *"sets limits for human exposure to radiofrequency (RF) fields in the frequency range 3 kHz to 300 GHz"* (ARPANSA, 2002). Instructions and guidelines regarding the methods and instrumentation required to measure the levels of radiofrequency fields are outlined in Australian/New Zealand Standard AS/NZS 2772.2:2011 (Standards Australia Limited/Standards New Zealand, 2011). The guidelines described in these two documents may be used to determine if devices that emit electromagnetic radiation are safe during prolonged exposure.

The regulation published by ARPANSA provides mandatory limits of electromagnetic radiation exposure that contain *basic restrictions* which must not be exceeded to protect against adverse health effects. The physical parameters that must be measured to test compliance with the basic restrictions include current density, specific absorption rate, specific absorption and power flux density. These physical parameters, however, are often impractical to measure. Therefore, an alternative set of restrictions called *reference levels* are also provided in the regulations with parameters that are easier to measure. Essentially, the reference levels have been conservatively formulated such that compliance with the reference levels ensures compliance with the basic restrictions (ARPANSA, 2002).

Different exposure limits for two general groups are also included in the ARPANSA regulation. These two groups are the *occupational* group and the *general public*. The general public exposure group relates to the exposure of a member of the general public who would be unaware of their exposure to the electromagnetic field. The occupational group is defined as the exposure to a person being exposed to electromagnetic fields under controlled conditions as part of their work whilst on duty. The acceptable exposure limits for the occupational group are higher than for the general public. However, the occupational group limits are subject to certain risk management policies and are outlined in the standard (ARPANSA, 2002).

The restrictions provide two different limits for systems based on whether they radiate continuous or pulsed signals. These two limits are the *time averaged* and *instantaneous* limits. The restrictions imposed for the instantaneous fields are to prevent effects associated with high powered pulsed fields. The high powered short time pulsed fields are impractical to measure, therefore the time averaged approach addresses these impracticalities by imposing a six minute averaging time over which the radiated field must be measured. The device under test can be shown to satisfy compliance if, after the six minute time interval, the root-mean-square (RMS) signal does not exceed the time averaged restrictions.

The region surrounding a transmitting antenna can be separated into three zones based on the distance from the antenna: the *reactive near-field*; the *radiating near-field*; and the *far-field*. In the far-field, the electric and magnetic fields are directly related and hence, compliance can be shown with a measurement of either the electric or magnetic fields being less than the reference levels. However, the relationship between the electric and magnetic fields is usually unknown in the reactive and radiating near-field zone. Therefore, both the electric and magnetic fields must be measured in this case to show compliance. Table 1 summarises the radiation zones and also indicates the distance from the radiating antenna for each zone. The value of λ in Table 1 is the wavelength (in metres) of the electromagnetic field in free-space and is calculated as $\lambda = c/f$, where c = the speed of light (3×10^8 m/s) and f is the frequency of the electromagnetic field (in Hertz). The value of D in Table 1 is the largest dimension of the radiating antenna (in metres).

Table 1 - Summary of field types to be measured and distance ranges

Field Range Zone	Field to Measure	Min Distance	Max Distance
Reactive Near-field	Electric and Magnetic	0	$\lambda/_{2\pi}$
Radiating Near-field	Electric and Magnetic	$\lambda/_{2\pi}$	Greater of $2D^2/\lambda$ or $\lambda/2$
Far-field	Electric or Magnetic	Greater of: $2D^2/\lambda$ or $\lambda/2$	No limit

The distance from the radiating antenna where the field strength should be measured to show compliance can be determined from how the device to be tested is used in typical operation. If the typical operation of a sensor or device is for a person to be located close to the transmitter antenna, then a near-field evaluation of the electric and magnetic field is warranted. However, if someone is typically located at a distance further than the near-field far-field crossover distance, then only the measurement of the far-field of the antenna is required. The field strengths are highest close to the transmitter antennas. Therefore, Table 1 is important because testing for compliance at a location that is very close to the transmitting antenna could be unnecessary if that is not the normal mode of operation (i.e. a person is not usually close to the transmitting antenna).

An extract of the reference levels for time averaged exposure to RMS electric and magnetic fields are shown in Table 2 (ARPANSA, 2002). A device can be shown to be compliant if the measured electric and magnetic fields are below these reference levels. The standard contains other frequency ranges not shown here as they are outside the range of the GPR sensors under test. Note that the frequency parameter in Table 2 is in the unit of MHz.

Table 1 - Extract of the reference levels for time averaged RMS electric and magnetic fields (ARPANSA, 2002)

Exposure Category	Frequency Range	Electric Field (V/m)	Magnetic Field (A/m)
General Public	10 MHz – 400 MHz	27.4	0.0729
	400 MHz – 2 GHz	$1.37 \times f^{0.5}$	$0.00364 \times f^{0.5}$
	2 GHz – 300 GHz	61.4	0.163
Occupational	10 MHz – 400 MHz	61.4	0.163
	400 MHz – 2 GHz	$3.07 \times f^{0.5}$	$0.00814\times f^{0.5}$
	2 GHz – 300 GHz	137	0.364

MEASUREMENT PROCEDURE

There are several techniques that may be used to determine the level of electromagnetic field a device radiates. The two most common techniques are called the *broadband* method and the *frequency selective* method. To test compliance using the broadband method, a specialised unit called a *broadband field meter* is used to measure the electromagnetic field strength over a wide bandwidth and reports a value indicative of the maximum field strength. This method is suited for determining if the electromagnetic radiation observed at a single location exceeds ARPANSA limits. This technique does not, however, provide information about the field strength radiated by a specific device or sensor. An example of a broadband sensor is the NARDA NBM-550 (Narda Safety Test Solutions, 2011).

The frequency selective method provides the tester more flexibility over the broadband method. This technique can be used to measure the field strength over specific frequency ranges or to determine the field strengths of certain devices or sensors whose radiated field strength might be weaker than other fields radiated in different frequency bands. The instrumentation required for this method includes an antenna and a spectrum analyser. In the case of measuring the levels of low electromagnetic field strengths, a pre-amplifier in between the test antenna and spectrum analyser can also be used to boost the received signal. Typical antennas used for measuring the electric field strength include biconical or log periodic antennas as they have a wide operating frequency band with respect to other antenna types. The loop antenna (magnetic probe) is usually used to measure the magnetic field strength. Figure1 shows a diagram representing the test configuration of a spectrum analyser and test receiver antenna and example transmitters of mobile phone and mobile phone tower.

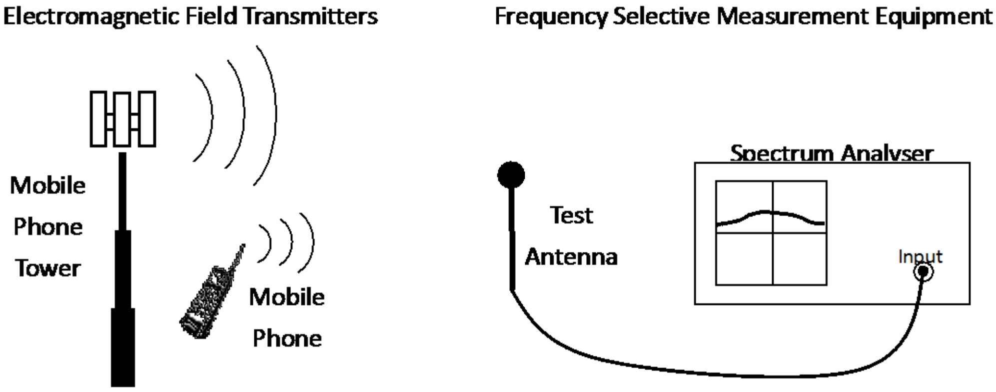


Figure 1 - Diagram of test configuration to measure radiated field strength using the frequency selective method and examples of electromagnetic field transmitters

In the configuration shown in Figure 1, the electromagnetic fields are radiated by transmitters such as mobile phones and mobile phone towers. Other examples include TV broadcast antennas, Wi-Fi enabled devices and radars. The radiated electromagnetic fields that intercept the *test* antenna are converted into an electrical voltage signal that is then displayed on a spectrum analyser as a frequency domain representation. The amplitude of the voltage signal displayed on the spectrum analyser is related to both the electromagnetic field strength intercepted by the test antenna and the characteristics of the test antenna.

Only a small portion of the electromagnetic field radiated by the transmitter antenna is captured by the receiver antenna. Therefore, to determine the actual field radiated by the transmitter, a correction must be applied to the signal level displayed on the spectrum analyser. This is in the form of an antenna correction factor called the *antenna factor*. Fundamentally, the antenna factor is the ratio of the incident electric or magnetic field strength to the output voltage of the antenna. The antenna factor is a function of frequency and antenna gain and is typically measured by the manufacturer as part of a calibration process. Therefore, the antenna factor data is required when calculating the actual radiated field strength and hence should be provided by the antenna manufacturer.

The equations to calculate the electric and magnetic field strengths are as follows:

$$E = KV \tag{1}$$
$$H = KV \tag{2}$$

where E is the electric field strength in Volts per metre (V/m), H is the magnetic field strength in Amperes per metre (A/m), K is the antenna calibration factor (1/m), and V is the voltage recorded by the receiver (spectrum analyser) in the units of Volts.

For the case when the receiver voltage and antenna factor data are measured using the decibel scale, the electric and magnetic field strengths are calculated as follows:

$$E_d = K_d + V_d \tag{3}$$
$$\mathrm{H_d} = \mathrm{K_d} + \mathrm{V_d} \tag{4}$$

where the unit of E_d is dBμV/m, the unit of H_d is dBμA/m, the unit of K_d is dB/m, and the unit of V_d is dBμV. As the units of the electric and magnetic field strengths provided in the ARPANSA limits are V/m and A/m respectively, the field strengths must be converted from dBμV/m and dBμA/m to V/m and A/m. This can be achieved using the following relationships:

$$\mathrm{E} = 10^{-6} \times 10^{(\mathrm{E_d}/20)} \quad (5)$$
$$\mathrm{H} = 10^{-6} \times 10^{(\mathrm{H_d}/20)} \quad (6)$$

It is important to ensure that the spectrum analyser is configured correctly to be certain the measurements are accurate. The spectrum analyser has four parameters that need to be considered when taking a measurement. These parameters are the resolution bandwidth (RBW), video bandwidth (VBW), detection mode and output units. The settings chosen for these parameters are dependent upon the source that generates the electromagnetic field.

The RBW is related to the ability of the spectrum analyser to resolve individual spectral components. If the RBW is set too small, multiple narrowband signals very close to each other in terms of frequency will not be resolved. If the RBW is set too large, the amplitude of the frequency component is artificially amplified due to more energy being sampled for each frequency component. For the case where the source of the electromagnetic field is a pulsed system such as the GPR systems (short time impulse transmitted at a constant repetition rate), the RBW must be set to a value that is less than 30 % of the PRF. If the RBW is set greater than this value, then the signal shown on the spectrum analyser is artificially greater which will result in a higher reading. When the RBW is set correctly, the data displayed on the spectrum analyser represents the time averaged frequency spectrum of the pulsed signal. Hence, the reference levels in Table 1 can be used to test compliance of pulsed systems with the ARPANSA regulations.

The VBW is related to how the data is displayed on the spectrum analyser. It is recommended that this value be greater than or equal to the RBW for pulsed signals. The detector mode in the spectrum analyser relates to how the voltage from the test antenna is sampled. Some examples include *positive peak*, *negative peak* and *average*. The spectrum analyser also has a trace mode function. This is used to determine when the individual values of the trace on the display are updated. Some examples include *maximum hold*, *minimum hold*, and *average*. When using the maximum hold mode, the maximum value observed at a given frequency by the spectrum analyser will be held in memory until a higher value is recorded. To ensure that the maximum observed field strengths are measured, the positive peak detector mode and maximum hold trace mode may be used. Finally, the output units of the spectrum analyser can be in the form of RMS power (dBm or Watts), RMS voltage (dBμV or Volts) or RMS current (dBmA or Amps).

It is the intention of this work to provide a general method to determine if a device that emits electromagnetic radiation is compliant with the ARPANSA regulation. The Australian Standard for measuring these devices (Standards Australia Limited/Standards New Zealand, 2011) states that the user should have the correct experience and technical skills to understand the area of electromagnetic emissions. Therefore, it is recommended that the reader familiarises themselves with the ARPANSA regulation and Australian Standard prior to conducting evaluations. If any doubt with regards to the measurement process arises or if preliminary testing indicates that a device may exceed the limits imposed by ARPANSA, it is recommended that formal testing and certification be sought from a registered testing facility.

EXPERIMENTS

The electric and magnetic fields strengths radiated by some GPR systems were measured. The test equipment for the electric field measurements consisted of an Aaronia HyperLOG 4060 antenna and Rohde & Schwarz ZVL6 Vector Network Analyser (VNA) with the spectrum analyser option. For these experiments, the VNA was configured to spectrum analysis mode, hence is herein referred to as the spectrum analyser. The antenna type is log periodic and has a frequency range of 400 MHz to 6 GHz. The antenna factor data for the antenna was provided by the manufacturer. For the magnetic field measurements, an Aaronia PBS-H2 magnetic field probe was used as the test antenna. The log periodic antenna and magnetic field probe were mounted on plastic tripods. The test equipment is shown in Figure 2.

Figure 2 - Test equipment used to measure the electric and magnetic fields radiated from the GPR systems include the spectrum analyser (left), 400 MHz to 6 GHz log periodic antenna (top right), and 12 mm loop antenna (bottom right).

The GPR systems tested were the Geophysical Survey Systems Incorporated (GSSI) 900 MHz and 1 500 MHz antenna modules powered by the SIR-3000 control unit. These are broadband systems and often have a bandwidth that approaches the centre frequency of the antennas. The broadband nature of GPR systems means that the spectrum of the radiated electromagnetic fields is broad rather than narrowband spikes. The antenna modules are shielded bi-static antennas, therefore, each antenna module contains a separate transmitter and receiver antenna enclosed within the antenna module. These antennas also have internal shields which focus the electromagnetic energy into the ground rather than behind the antenna. These systems can penetrate through coal up to approximate ranges of 1 m (900 MHz) and 0.5 m (1 500 MHz). These systems are shown in Figure 3.

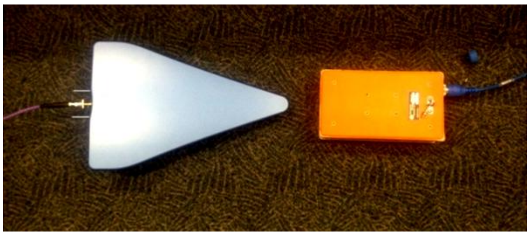
(a) (b)

Figure 3 - Commercial GPR equipment under test. The equipment includes the (a) GSSI 900 MHz antenna (orange unit) and (b) GSSI 1500 MHz antenna (red unit). The display unit on the left side of each image is the GSSI SIR-3000 control unit.

The standard method of GPR operation involves the GPR antenna on the ground with the energy radiating directly into the ground. However, it is possible that an operator could lift the antenna whilst the system is still in operation. Therefore, three configurations were tested where the test antenna was within 50 mm of the GPR antenna. Based on Table 1, the minimum far-field distances for these GPR antennas are 160 mm for the 900 MHz unit and 100 mm for the 1500 MHz unit. In this case, the test antenna is within the near-field therefore both the electric and magnetic fields must be measured.

The first scenario was to test the standard operating practice with the operator to the side or behind the GPR antenna whilst it is in direct contact with the ground. The second scenario was to determine the field strengths for the case when the antenna was pointing directly at the operator. Therefore, the electric and magnetic fields were measured directly in front of the antenna, which is the point of the strongest field as it is the main beam. The third scenario was with the GPR antenna pointing away from the test receiver antenna to determine the effectiveness of the shielding within the GPR antennas. A background test was also conducted to determine the level of ambient electromagnetic noise with the GPR systems inactive. Note that the antennas have a specific polarisation, therefore, the test antenna was oriented to ensure that the maximum field strengths were observed during these experiments.

The test scenarios for both the log periodic antenna and magnetic field probe are shown in Figure 4 and Figure 5 for the 900 MHz GPR antenna.



(a)

(b)

(c)

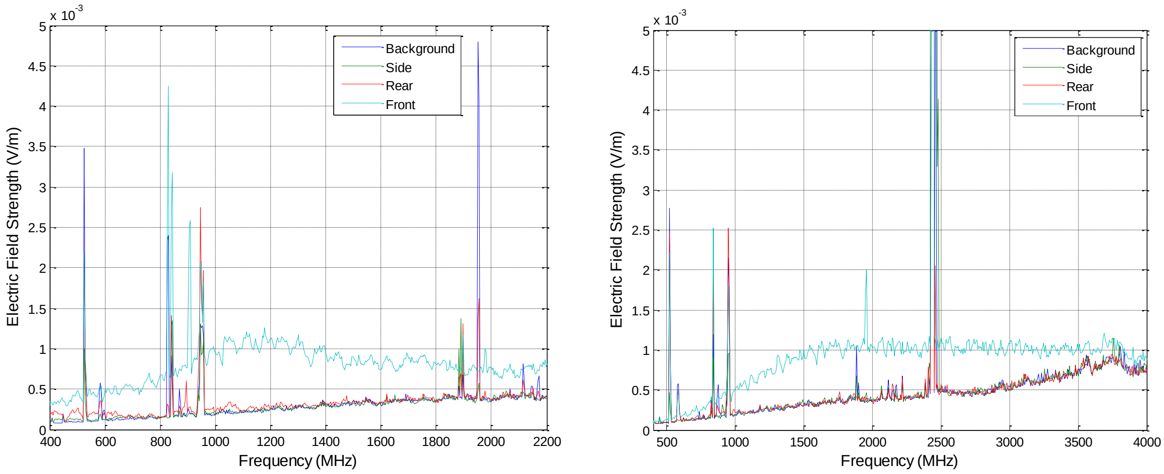
Figure 4 - Configurations for the electric field measurements include test antenna (a) to the side of the GPR antenna; (b) in front of main beam; and (c) behind main beam. Note that the main beam of the GPR antenna is outwards through the white plastic base in (b).

(a) (b) (c)

Figure 5 - Configurations for the magnetic field measurements include magnetic probe (a) to the side of the GPR antenna; (b) in front of main beam; and (c) behind main beam. Note that the main beam of the GPR antenna is outwards through the white plastic base in (b).

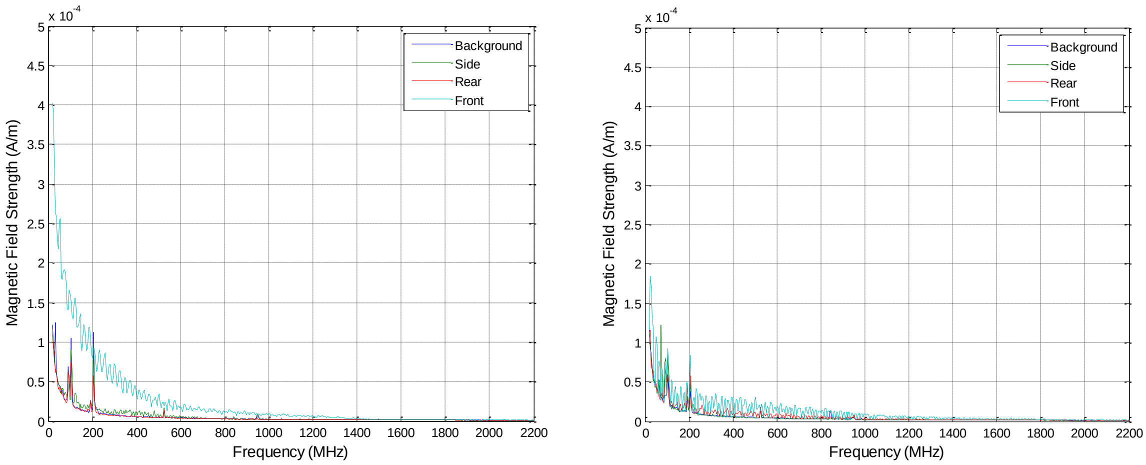
For these experiments, the spectrum analyser was configured such that the trace mode was set to maximum hold and the detector mode was set to positive peak. These parameters were chosen to ensure that the maximum possible level of signal strength radiated from the GPR was measured to test the worst case scenario and hence confirm compliance with the ARPANSA limits. The test antennas and probes were also moved around the antenna to ensure that the configuration shown in Figure 4 (b) and Figure 5 (b) indicate the maximum field strength values. When the maximum field strength position was found, the test antenna and probe were left in position for six minutes as required for the time averaged test. The RBW setting on the spectrum analyser was set to 30 kHz. The PRF of the GPR systems was 100 kHz so the RBW of 30 kHz was at the upper limit for satisfactory measurement.

The raw signal strength data measured by the spectrum analyser was the RMS voltage from the test antenna and was in the units of dBμV. The antenna factor data for the HyperLOG4060 antenna and PBS-H2 probe were added to the raw spectrum analyser data as per equations (3) and (4). These measurements were then converted into the units of V/m and A/m for direct comparison with the ARPANSA regulations. The final field strengths measured for the 900 MHz and 1500 MHz GSSI antennas are shown in Figure 6 (electric field) and Figure 7 (magnetic field) respectively.



(a) **(b)**

Figure 3 - Measured electric field strengths for the (a) 900 MHz and (b) 1500 MHz GPR antennas. The maximum electric field strengths from these GPR systems are well below the ARPANSA limits of 47 260 x 10^{-3} V/m (900 MHz antenna) and 56 490 x 10^{-3} V/m (1500 MHz antenna).



(a) **(b)**

Figure 4 - Measured magnetic field strengths for the (a) 900 MHz and (b) 1500 MHz GPR antennas. The maximum magnetic field strengths measured from these GPR systems are well below the ARPANSA limit of 729 x 10^{-4} A/m.

DISCUSSION

The frequency range for the electric field strength measurements of the 900 MHz and 1500 MHz antennas were 400 MHz to 2200 MHz and 400 MHz to 4000 MHz respectively as shown in Figure 6.

The measurements indicate that the electric field strength measured at the side and rear of the GPR antennas is very similar to the background ambient noise. This means that in normal operation with the GPR antenna in direct contact with the ground, the electric field radiated towards an operator by the GPR systems is negligible. However, the maximum electric field measured very close to and in front of the main beam of the GPR antenna is approximately 0.0013 V/m at 1190 MHz for the 900 MHz system and 0.0011 V/m at 1700 MHz for the 1500 MHz system. From Table 2, the maximum time averaged reference level electric field strength for the general public at these frequencies is calculated to be 47.26 V/m (1190 MHz) and 56.49 V/m (1700 MHz). This shows that the maximum electric field strengths measured in the main beam of these antennas is approximately 36 000 times lower than the reference level limit for the 900 MHz system and 43 000 for the 1500 MHz system.

The results in Figure 6 also show spikes in the electric field at certain frequencies. These spikes are due to far-field transmissions by external systems observed during the experiments. These specific frequency bands are as follows: 527 MHz is the analogue broadcast of the SBS television station (SBS, 2011); 825 MHz to 960 MHz is mobile phone communications systems (ACMA, 2011a); 1880 MHz to 1900 MHz is for cordless telecommunications devices (ACMA, 2011b); 1950 MHz is used by 3G mobile devices (ACMA, 2006); 2400 MHz is used by Wi-Fi enabled devices. A special note must be made regarding the large spike in Figure 6 (b) at 2400 MHz. This spike was due to a Wi-Fi access point located within several metres of the experiment. The peak electric field measurement for this frequency is not shown as the figure is zoomed in to focus on the broadband GPR signal. However, the peak electric field value measured was 0.03 V/m, which is 2000 times lower than the ARPANSA limit of 61.4 V/m at 2400 MHz.

The frequency range for the magnetic field strength measurements of both GPR systems was 20 MHz to 2200 MHz. These plots indicate that the frequency of the maximum magnetic field strength radiated by these GPR antennas is outside the bandwidth of the electric field. The general trend is the magnetic field decreases as the frequency increases. Note that these maximum magnetic field values were only observed when the magnetic probe was in direct contact with the base of antenna unit as shown in Figure 5 (b). The maximum measured magnetic field strength was 0.0004 A/m for the 900 MHz GPR antenna and 0.0002 A/m for the 1500 MHz GPR antenna, both at 20 MHz. The maximum magnetic field strength reference level at this frequency is 0.0729 A/m. Therefore, the measured magnetic field strengths are approximately 180 and 360 times lower than the reference levels.

SUMMARY

This paper provided an overview of the ARPANSA regulations for the exposure to electromagnetic radiation. A practical approach to measure electromagnetic radiation was presented based on the Australian Standard. The method was demonstrated with the measurement of two commercial GPR systems to determine if they are compliant with the ARPANSA regulations for safe prolonged exposure. In summary, the electric and magnetic fields measured from the GPR systems are well below the general public reference limits, which are the most conservative limits published by ARPANSA. Therefore, it is concluded that these devices are safe to use in terms of electromagnetic radiation.

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