Australian
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Guidelines on the assessment of installations against electromagnetic radiation (EMR) exposure limits

(Edition September 2000)

The material in this document is designed to assist licensees in determining whether a facility complies with the ACA standard. The information contained here may be used in its own right or in conjunction with the relevant ACA Self-Assessment booklet/s for each service category.

To evaluate compliance against the ACA standard, it is first necessary to understand the fundamental concepts introduced by the reference standard AS/NZS 2772.1 (Int):1998. The first part of this section briefly explains these concepts. The latter part outlines prediction methods that may be applied to most antenna and transmitter configurations to evaluate compliance.

1 Fundamental Concepts Introduced by the Reference Standard

1.1 Specific Absorption Rate / Field Strength

The fundamental limits in the ACA standard are based on a quantity known as Specific Absorption Rate (SAR, see Glossary). The SAR is a measure of the rate at which energy is absorbed from an electromagnetic field into biological tissue.

The SAR measure must be used when the transmitter is operated in close proximity to the human body.

Where the transmitter is not normally used in close proximity to the human body, the exposure limits can be derived by defining the exposure levels in terms of:

- S - power density (units of watts per square metre: W/m^2);
- E - electric field strength (units of volts per meter: V/m); and
- H - magnetic field strength (units of amperes per meter: A/m).

Because the derived limits are generally easier to measure, they are more convenient to use where the RF transmitter is not used in close proximity to the human body. Due to conservative assumptions made in the calculation of the derived limits, exceeding the derived limits does not necessarily mean the fundamental SAR limits have been exceeded. An installation may still be compliant in this situation, but demonstration of compliance will rely on the more difficult SAR measurements for comparison with the fundamental limits.

1.2 Electric and Magnetic Fields

Where the electric field vector (E), the magnetic field vector (H), and the direction of propagation are all mutually orthogonal ("plane-wave" conditions, see Figure 1), which is approximately the case in the far-field of a transmitting antenna, these quantities are related by Equation 1[1].

$$S = E \times H = \frac{E^2}{377} = 377H^2 \qquad (1)$$

where: S = power density (W/m^2)

E = electric field strength (V/m)

H = magnetic field strength (A/m)

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[1] Note that this equation is written so that power density is expressed in units of W/m^2. Power density is also often expressed in units of m W/cm^2. The impedance of free space, 377 ohms, is used in deriving the equation.

Closer to a transmitting antenna, or in the “near-field”, Equation (1) does not apply. The terms "far-field equivalent" or "plane-wave equivalent" power density are often used to indicate a quantity calculated by using the near-field values of E^2 or H^2 as if they were obtained in the far-field. In some circumstances, it is necessary to measure both the electric and magnetic fields in order to determine compliance.

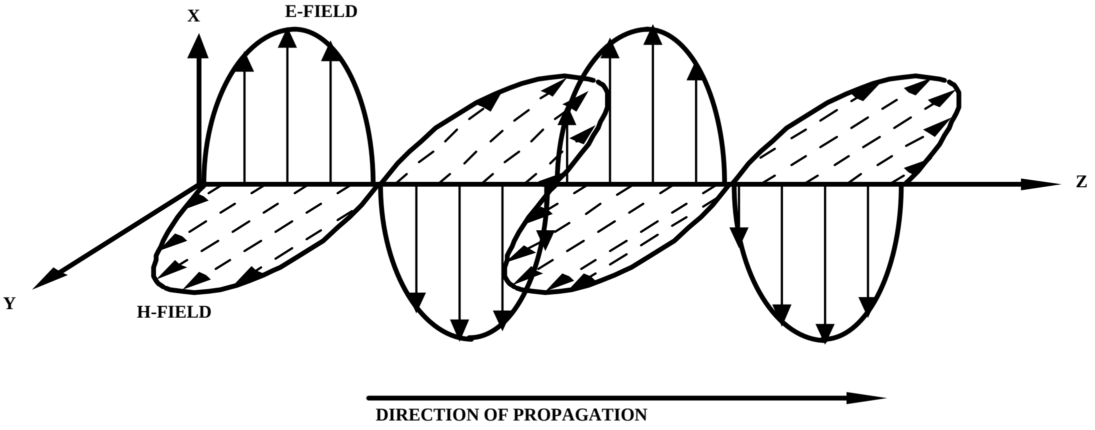

Figure 1: Pictorial representation of plane wave electromagnetic radiation

1.3 Whole Body - Partial Body Exposure

Exposure to an electromagnetic field may be such that the whole body is exposed equally to the field, or it may be that there is considerable local variation in the electromagnetic field over the volume of the body.

The local variation in exposure will depend on proximity to the antenna, and may also depend on the size or type of antenna used by the transmitting device.

The ACA standard allows the measurement of the electromagnetic field to be averaged over an area of 30 cm × 30 cm, where measurements are taken at each corner and at the centre of the square. When averaged in this way, the result must not exceed the derived field limits, which are based on the assumption of whole body average SAR. However, the local field in any small volume within this area cannot be so great that the resultant SAR exceeds the fundamental limits set down in the ACA standard for spatial peak SAR. The measurement of SAR in this situation is very complex and is not treated in this document. For the purposes of these guidelines, all exposures are assumed to be whole body.

1.4 Time Averaging

The ACA exposure guidelines also allow measurements of electromagnetic fields to be averaged over a period of any six minutes with the average not to exceed the limit for continuous exposure[2]. Averaging in this way allows, for example, that during any given six-minute period an individual could be exposed to twice the applicable power density limit for three minutes as long as the individual was not exposed at all for the preceding or following three minutes. Similarly, exposure could be at three times the limit for two minutes as long as no exposure occurs during the preceding or subsequent four minutes, and so on.

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[2] There are also limits for peak exposure specified in the ACA EMR standard. However, these are generally only applicable to radar type signals.

It is often not possible to characterise exposures for the public to the extent that averaging times can be applied. It is therefore necessary to assume continuous exposure where the general public are concerned. That is, the measured power density can never exceed 0.2 mW/cm^2.

This concept is generalised in Equation 2. The sum of the products of the exposure levels and the allowed times for exposure must not exceed the product of the appropriate maximum exposure limit and the time-averaging interval of six minutes.

$$\sum S_{\text{exp}} t_{\text{exp}} \le S_{limit}\, t_{avg} \qquad (2)$$

where: S_{exp} = power density level of exposure (mW/cm^2)

S_{limit} = appropriate power density MPE limit (mW/cm^2)

t_{exp} = allowable time of exposure for S_{exp}

t_{avg} = MPE averaging time (6 minutes)

For example, where the exposure limit is 0.2 mW/cm² (as it is for frequencies above 10 MHz), the right-hand side of the relation becomes 1.2 mW-min/cm² (0.2 mW/cm² × 6 min). Therefore, if an exposure level is determined to be 0.4 mW/cm², the allowed time for exposure at this level during any six-minute interval would be a total of 3 minutes, since the left hand side of the relation must not exceed 1.2 (hence 0.4 mW/cm² × 3 min).

Many other combinations of exposure levels and times may be involved during any given six minute period. However, as long as the sum of the products on the left side of the relation does not exceed the right hand side, the *average* exposure will comply with the allowable exposure limit. It is important to note that time-averaging applies to *any* six minute interval.

Therefore, in the above example, consideration would have to be given to the exposure situation both before and after the allowed three-minute exposure. The time-averaging interval can be viewed as a "sliding" period of six minutes.

2 Prediction Methods

The following information does not consider all possible configurations of antennas and transmitters. However, general techniques that provide reasonable approximations of field strength near a transmitting antenna may be applied to many situations, and these techniques are used in the ACA Self Assessment Booklets.

The paragraphs below describe how to estimate field strength and power density levels in the vicinity of generic radiators which may include aperture antennas such as microwave and satellite dish antennas, and also antennas used for paging and mobile communications.

2.1 On Axis Predictions of RF Fields

In the case of a single generic radiating antenna, a prediction for power density in the far-field of the antenna can be made by use of the general Equations 3 or 4 below (for conversion to electric or magnetic field strength see Equation 1). These equations are generally accurate in the far-field of an antenna but will over-predict power density when close to the antenna (or in the “near field”). In this case they may still be used for making a "worst case" or conservative prediction.

$$S = \frac{PG}{4\pi R^2} \qquad (3)$$

where: S = power density (W/m^2)

P = power input to the antenna (W)

G = linear power gain of the antenna in the direction of interest relative to an isotropic radiator

R = distance to the centre of radiation of the antenna (m)

or:

$$S = \frac{EIRP}{4\pi R^2} \tag{4}$$

where: EIRP = equivalent isotropic radiated power

When using these and other equations it is important to use the correct units for all variables. Other units may be used, but care must be taken to use correct conversion factors when necessary. For example, in Equation 3, if power density is expressed in units of mW/cm² (normally the case) then power should be expressed in mW and distance in cm. Also, it is important to note that the power gain factor, *G*, in Equation 3 is *linear* isotropic gain. Isotropic power gain expressed in logarithmic terms (dBi) may be converted to linear isotropic gain using Equation 5:

$$G = 10^{\frac{dBi}{10}} \tag{5}$$

For example, a logarithmic power gain of 14 dB is equivalent to a linear gain of 25.12.

In some cases operating power may be expressed in terms of "effective radiated power" or "ERP" instead of EIRP. ERP is power referenced to a half-wave dipole radiator instead of to an isotropic radiator. To convert ERP into EIRP for use in the above equations, multiply the ERP by a factor of 1.64 (2.15dB), which is the linear gain of a half-wave dipole relative to an isotropic radiator. For example, if ERP is used in Equation 4 the relation becomes:

$$S = \frac{EIRP}{4\pi R^2} = \frac{1.64\ ERP}{4\pi R^2} \tag{6}$$

An increase in the power density at a given position may result if there is a reflection from a surface such as the ground or on a rooftop. The U.S. Environmental Protection Agency (EPA) has developed models for predicting ground-level field strength and power density for FM radio and television broadcast antennas in this situation [5]. The EPA model suggests that a realistic approximation for ground reflection is obtained by assuming a maximum 1.6-fold increase in field strength leading to an increase in power density of 2.56 (1.6 × 1.6). Equation 4 can then be modified to:

$$S = \frac{2.56\ EIRP}{4\pi R^2} = \frac{0.64\ EIRP}{\pi R^2} \tag{7}$$

Note: The increase due to reflection has *not* been taken into account in the ACA Self Assessment Booklets.

For example, if a facility is transmitting at a frequency of 100 MHz with a total nominal EIRP (including all polarisations) of 10 kW (10,000 W) from a tower-mounted antenna, and the height above ground level to the centre of the antenna is 50 m (Figure 2), the formulae above predict the maximum power density that could be expected at a point 2 m above ground (approximate head level) and at a distance of 20 m from the base of the tower is

$$S = \frac{0.64\,(10{,}000\ W)}{\pi\,(52\ m)^2} \approx 0.75\ \ W/m^2 \approx 0.075\ \ mW/cm^2$$

where the distance R has been calculated using simple trigonometry [$\sqrt{48^2 + 20^2} = 52$ m] assuming essentially flat terrain.

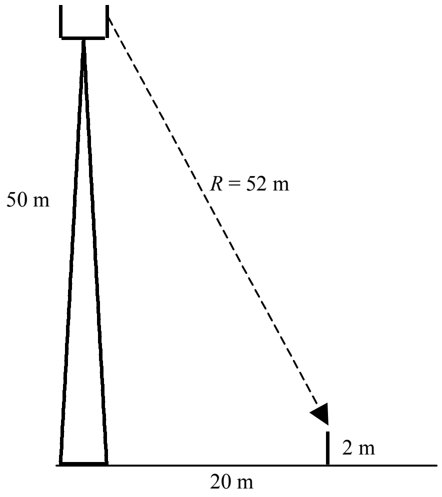

Figure 2: Example calculation of power density at ground level from antenna on tower.

The limit for exposure at 100 MHz is 0.2 mW/cm^2. Thus, even using conservative assumptions, this calculation indicates that the facility easily complies with the general public limits at a distance of 20 m from the tower. Similar calculations may be made to ensure compliance at other locations.

Note that this type of analysis does not take into account the elevation (vertical) pattern of the antenna, ie no information on directional characteristics of signal propagation is considered. Charts in the ACA Self Assessment Booklets marked “boresight”, that plot EIRP against distance from the antenna for a given power density (which corresponds to the general public limit for that service) also use this form of analysis. Use of actual elevation pattern data for the antenna would most likely significantly reduce ground-level exposure predictions from those calculated above, resulting in a more realistic estimate of the actual exposure levels. This is discussed below.

2.2 Off Axis Predictions of RF Fields

The above equations can be used to calculate fields from a variety of radiating antennas, such as omnidirectional radiators, dipole antennas and antennas incorporating directional arrays. However, in many cases the use of equations such as Equations 3 and 4 will result in an overly conservative prediction of the maximum field at a given point. Alternatively, if information concerning an antenna's radiation pattern is known, a relative field factor (relative gain) derived from such a pattern can be incorporated into the calculations to arrive at a more accurate representation of the field at a given point of interest.

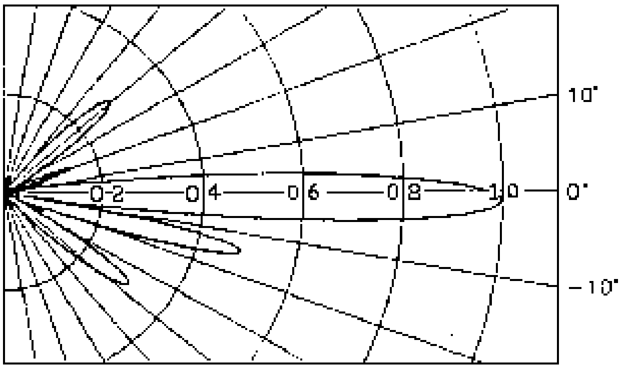

Figure 3: Example of radiation pattern for a directional antenna showing variation of antenna gain with angle from antenna boresight. Variation is shown relative to boresight gain which is normalised to 1.0. Note that antenna sidelobes may have significant gain.

An example of the radiation pattern for a directional antenna is shown in **Error! Reference source not found.**. This is a vertical pattern, but antennas may be directional in the horizontal plane also. In the case of an antenna pointing toward the horizon, if the relative gain in the main beam is 1.0, then in other directions downward from horizontal the field may be significantly less than 1.0. Therefore, RF transmissions from the antenna directly toward the ground may be significantly reduced from the omnidirectional case assumed previously and a more realistic prediction of the field can be obtained for the point of interest.

In the previous example, it can be shown from trigonometry that the angle below horizontal of the line between the antenna and the observation point 2 m above ground level at a distance of 20 m from the antenna, is about 68°. Assume that the antenna in this example has its main beam (boresight) pointed approximately toward the horizon and that at an angle of 68°, the field relative to the main beam (relative gain) is –6 dB (a factor of 0.5 in terms of field strength and 0.25 in terms of power density). The previous calculation then becomes:

$$S = \frac{0.64\, F \times EIRP}{\pi R^2} = \frac{0.64\,(0.25)\,(10{,}000\ W)}{\pi (52\ m)^2} \approx 0.19 \quad W/m^2 \approx 0.019 \quad mW/cm^2$$

where: F = the relative linear gain (power density)

Clearly, the power densities calculated in locations which are off- axis to the main beam of the antenna are much reduced. This is typically the case where the antenna is mounted high above the ground (such as on a tower) and the point of interest (the point of closest public access) is near ground level. The charts in the ACA Self Assessment Booklets marked “Off-Axis” use a simplified analysis to account for the off axis relative linear gain factor *F*. Based on a review of a range of different manufacturers’ specifications for the types of antennas in common use [6-10] and also other measured antenna data [3], the ACA has determined that the off axis relative linear gain at any angle greater than 45° from the main beam may be conservatively approximated by a 10 fold reduction from main beam gain (ie *F*=0.1). For angles less than 45° from the main beam direction, relative linear gain is assumed to be 1.0.

Note that while off axis calculations may be appropriate where the point of interest is close to the ground (for high mounted antennas), this may not be so where the point of interest is also high above ground level. Such cases occur when, for example, a building or rooftop may be in the vertical main beam of a radiator on another nearby roof. If the point of interest is also in the horizontal boresight direction of the antenna, then it is appropriate to apply the main beam calculations of Equations 3 and

4, or use the ACA Self Assessment Booklet charts marked “boresight”. For rooftop locations it is also important to note that exposures *inside* a building will be reduced by at least 10-20 dB due to attenuation caused by building materials in the walls and roof [1].

2.3 Near Field Gain Reduction

It has already been noted that Equations 3 and 4 will considerably over predict the power density produced by an antenna when the point of interest is not in the far field of the antenna. When in the near field of the antenna, the gain of the antenna is effectively reduced. Additionally, the power density decays directly with increasing distance from the antenna rather than the square of the distance as suggested by Equations 3 and 4. To refine predictions of power density in the near field of an antenna, a more sophisticated model is required.

The near field of an antenna is defined in various ways by different sources depending on the particular convention adopted [1, 2, 11]. The convention in [11] is adopted here and also in the ACA Self Assessment Booklets, such that the distance from the antenna to the transition point where far field conditions approximately exist, R_T, is generally given by

$$R_T = \frac{0.5\,D^2}{\lambda} \tag{9}$$

where D is the maximum lineal dimension of the aperture of the antenna (the diagonal in the case of a rectangular aperture) and λ is the wavelength at the frequency of operation. This distance represents ¼ of the distance to the antenna far field as it is commonly defined.

The models used in the ACA Self Assessment Booklets for predicting field strength incorporating the affects of near field on an antenna are shown in Figures 4 and 5. Figure shows the predicted field strength for a rectangular aperture antenna (such as any whip or dipole antenna, or a panel antenna such as used in mobile phone base stations) where adjustment has been made for near field reduction at distances closer than R_T. Figure shows the same information for a circular aperture antenna, where D is now the diameter of the aperture. Note that R_T is reduced to $0.16D^2/\lambda$ in the case of circular aperture antennas.

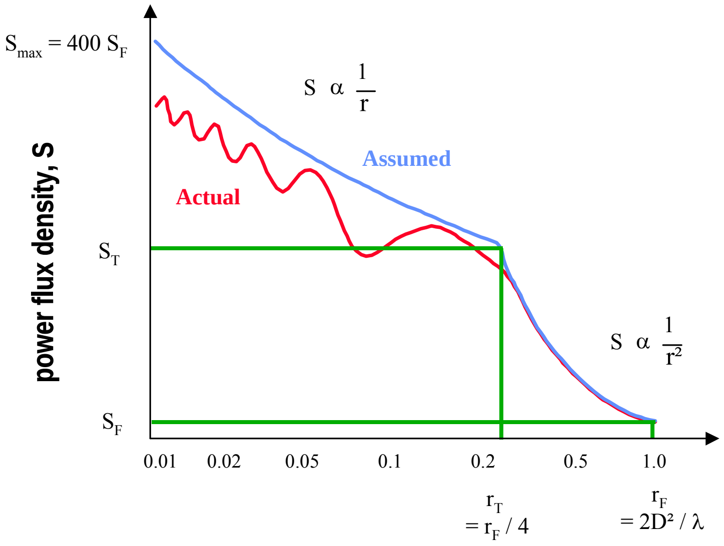

Figure 4: Power density versus distance with near field reduction, rectangular aperture[3]

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[3] [11], p.35

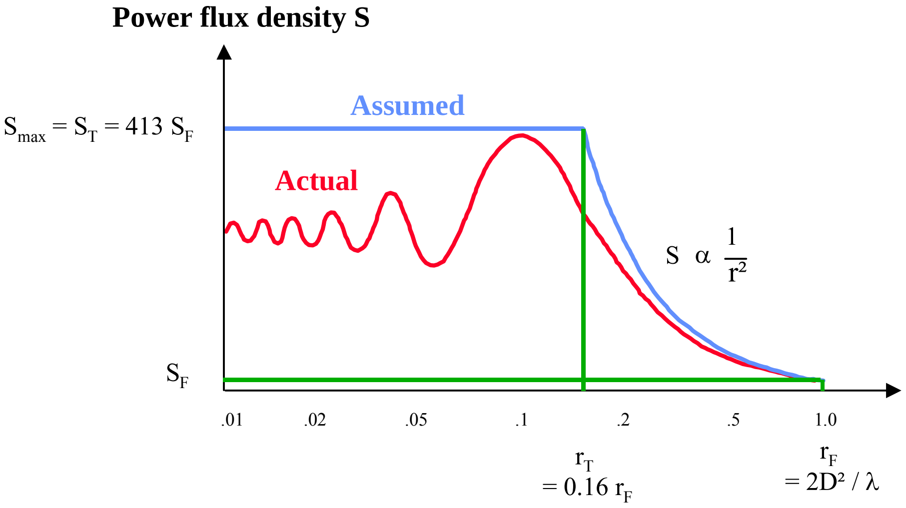

Figure 5: Power density versus distance with near field reduction, circular aperture[4]

In the above figures, S_F and S_T are the power densities at the far field point and the transition point respectively, and r_F and r_T are the distances to the far field point and the transition point respectively.

The rectangular and circular models differ in the assumed dependence of power density with distance from the antenna in the region up to the transition point. For rectangular apertures, the dependence is assumed to be a $1/R$ relationship, while for circular apertures there is no dependence on distance up to the transition point, and the assumed constant power density is defined by the worst case. The distance to the transition point is also reduced for circular apertures as has been previously noted.

The charts in the ACA Self Assessment Booklets marked "Near Field Correction" use one of the two models described above, depending on the types of services to which the booklet applies. Since the distance to the transition point depends on λ the results in the charts are somewhat frequency dependent, so that the booklets are separated into types of services primarily on the basis of frequency. Care should thus be taken to select the appropriate booklet for the service under consideration.

Where the ACA Self Assessment Booklets are not directly suitable for a particular application, it may still be possible to use the approximation described in the above curves by observing the following procedure (applicable for frequencies above 10 MHz where power density considerations such as these are appropriate [2]).

2.3.1 Rectangular Apertures

- First, estimate the distance from the antenna at which the general public exposure limit occurs, assuming near field correction is applied. This may be achieved using Equation 10 below.

$$d_{public} = \frac{23.9 \times EIRP}{D^2 f} \qquad (10)$$

  where D is as previously defined and *f* is the frequency of operation in MHz.

- Calculate the distance to the transition point R_T using Equation 11 below (derived from Equation 9).

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[4] [11], p.34

$$R_T = \frac{D^2 f}{600} \tag{11}$$

- If the distance calculated in step (1) is greater than that calculated in step (2) then re-calculate the distance to the general public limit using Equations 3 and 4 (ie no near field correction is necessary). Otherwise, keep the result obtained in step (1).

2.3.2 Circular Apertures

- Estimate the distance from the antenna at which the general public exposure limit occurs using Equations 3 and 4 (ie assuming no near field correction is necessary).
- Calculate the distance to the transition point using Equation 12 below.

$$R_T = \frac{D^2 f}{900} \tag{12}$$

- If the distance calculated in step (1) is greater than that calculated in step (2), then keep the result from step (1). Otherwise, there is no distance limit in front of the antenna (ie there is no distance from the antenna at which the general public exposure limit is exceeded, by this approximation).

3 References

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4 Glossary

Average (temporal) power	The time-averaged rate of energy transfer.
Averaging time	The appropriate time period over which exposure is averaged for purposes of determining compliance with RF exposure limits.
Continuous exposure	Exposure for durations exceeding the corresponding averaging time.
Decibel (dB)	Defined by the equation $dB = 10\log_{10}\left(\frac{P_1}{P_2}\right)$ where P_1 and P_2 are power levels.
Duty factor	The ratio of pulse duration to the pulse period of a periodic pulse train. Also, may be a measure of the temporal transmission characteristic of an intermittently transmitting RF source such as a paging antenna by dividing average transmission duration by the average period for transmissions. A duty factor of 1.0 corresponds to continuous operation.
Effective Isotropically Radiated Power (EIRP)	The product of the power supplied to the antenna and the antenna gain in a given direction relative to an isotropic antenna.
Effective radiated power (ERP)	The product of the power supplied to the antenna and the antenna gain in a given direction relative to a half-wave dipole antenna.
Electric field strength (*E*)	A field vector quantity that represents the force (*F*) on an infinitesimal unit positive test charge (*q*) located at a given point. Electric field strength is expressed in units of volts per meter (V/m).
Electromagnetic field	Comprises alternating electric and magnetic fields. A radiofrequency field is a field which specifies the electric and magnetic states of a medium or free space, quantified by vectors representing the electric field strength and the magnetic field strength. From a radiating source, it is convenient to distinguish between the reactive near field, radiating near field, and far field regions. (a) Reactive near field - that region of the field immediately surrounding the antenna. (b) Radiating near field - that region of the field of an antenna between the reactive near field region and the far field region wherein radiation fields predominate and the angular field distribution is dependent

upon distance from the antenna.

(c) Far field - the region of the field of an antenna where the angular field distribution is essentially independent of distance from the antenna.

Electromagnetic radiation (or energy) Electromagnetic radiation is the transmission of energy in the form of waves which have an electrical and magnetic component. The most familiar forms of electromagnetic radiation are radio waves and light waves. Less familiar forms of electromagnetic radiation are infrared radiation, ultraviolet light, X-rays and gamma rays, which together constitute the electromagnetic spectrum.

Electromagnetic waves at low frequencies are referred to as 'electromagnetic fields', and those at very high frequencies are called 'electromagnetic radiations.' According to their frequency and energy, electromagnetic waves can be classified as either 'ionizing radiations" or non-ionizing radiations":

- Ionizing radiations are extremely high frequency electromagnetic waves (X-rays and gamma rays) which have enough proton energy to produce ionization (create positive and negative electrically charged atoms or parts of molecules) by breaking the atomic bonds that hold molecules in cells together.
- Non-ionizing radiations (NIR) is a general term for that part of the electromagnetic spectrum which has photon energies too weak to break atomic bonds. They include ultraviolent (UN) radiation, visible light, infrared radiation, radiofrequency and microwaves fields, extremely low frequency (ELF) fields, as well as static electric and magnetic fields.

Even high intensity NIR cannot cause ionization in a biological system. However, NIT have been shown to produce other biological effects such as heating, altering chemical reaction or inducing electrical currents in tissues and cells (World Health Organization Fact Sheet N182).

Exposure Exposure occurs wherever a person is subjected to electric, magnetic or electromagnetic fields other than those originating from physiological processes in the body and other natural phenomena.

Exposure, partial-body Partial-body exposure results when RF fields are substantially non-uniform over the body. Fields that are non-uniform over volumes comparable to the human body may occur due to highly directional sources, standing-waves, re-radiating sources or in the near field of a source. See **RF "hot spot".**

Far-field region That region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna. In this region (also called the free space region), the field has a predominantly plane-wave character, ie, locally uniform distribution of electric field strength and magnetic field strength in planes transverse to the direction of propagation.

Gain (of an antenna)	The ratio, usually expressed in dB, of the power required at the input of a loss-free reference antenna to the power supplied to the input of the given antenna to produce the same field strength or the same power density at the same distance in a given direction. When not otherwise specified, the gain refers to the direction of maximum radiation. Gain may be considered for a specified polarisation. Gain may be referenced to an isotropic antenna (dBi) or a half-wave dipole (dBd).
Hertz (Hz)	The unit for expressing frequency, (f). One hertz equals one cycle per second.
Magnetic field strength (*H*)	A field vector that is equal to the magnetic flux density divided by the permeability of the medium. Magnetic field strength is expressed in units of amperes per meter (A/m).
Maximum permissible exposure (MPE)	The average and peak rms electric and magnetic field strength, their squares, or the plane-wave equivalent power densities associated with these fields to which a person may be exposed without harmful effect and with an acceptable safety factor.
Near-field region	A region generally in close proximity to an antenna or other radiating structure, in which the electric and magnetic fields do not have a substantially plane-wave character, but vary considerably from point to point. The near-field region is further subdivided into the reactive near-field region, which is closest to the radiating structure and contains most or nearly all of the stored energy, and the radiating near-field region where the radiation field predominates over the reactive field, but lacks substantial plane-wave character and is complicated in structure. For most antennas, the outer boundary of the reactive near field region is commonly taken to exist at a distance of $\lambda/2\pi$ from the antenna surface.
Power density (*S*)	Power per unit of area normal to the direction of propagation, usually expressed in units of watts per square metre (W/m^2) or, for convenience, units such as milliwatts per square centimetre (mW/cm^2) or microwatts per square centimetre (µW/cm^2). For plane waves, power density, electric field strength (E) and magnetic field strength (H) are related by the impedance of free space, ie, 377 ohms. Although many survey instruments indicate power density units ("far-field equivalent" power density), the actual quantities measured are E or E^2 or H or H^2.
Power density, plane-wave equivalent or far-field equivalent	A commonly-used term associated with any electromagnetic wave of given E field or H field strength, whether plane wave or not, equal in magnitude to the power density of a plane wave having that value of E field or H field strength.
Re-radiated field	An electromagnetic field resulting from currents induced in a secondary, predominantly conducting, object by electromagnetic waves incident on that object from one or more primary radiating structures or antennas. Re-

	radiated fields are sometimes called "reflected" or more correctly "scattered fields." The scattering object is sometimes called a "re-radiator" or "secondary radiator".
Root-mean-square (rms)	The effective value, or the value associated with joule heating, of a periodic electromagnetic wave. The rms value is obtained by taking the square root of the mean of the squared value of a function.
Short-term exposure	Exposure for durations less than the corresponding averaging time.
Specific absorption rate (SAR)	A measure of the rate of energy absorbed by (dissipated in) an incremental mass contained in a volume element of dielectric materials such as biological tissue. SAR is usually expressed in terms of watts per kilogram (W/kg) or milliwatts per gram (mW/g). Guidelines for human exposure to RF fields are based on SAR thresholds where adverse biological effects may occur. When the human body is exposed to an RF field, the SAR experienced is proportional to the squared value of the E field strength induced in the body.
Wavelength (λ)	The wavelength (λ) of an electromagnetic wave is related to the frequency (f) and velocity (v) by the expression $v = f\lambda$. In free space the velocity of an electromagnetic wave is equal to the speed of light, ie, approximately 3×10^8 m/s.