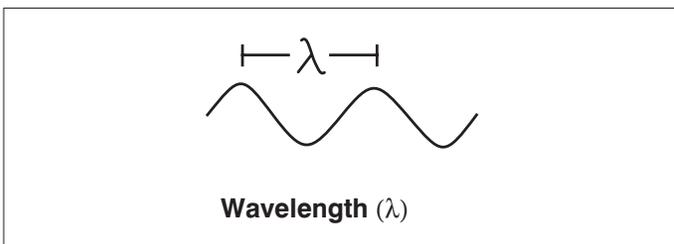


NON-IONIZING RADIATION GENERAL INFORMATION

WHAT IS RADIATION?

Radiation is a form of energy that arises when electric charges are accelerated. These moving electric charges induce an electromagnetic field within the region surrounding the charge source. This oscillation generates an electromagnetic wave that radiates energy from the region surrounding the charges, much like the expanding waves that are created when a rock is tossed into a body of water.

An electromagnetic wave consists of coupled electric and magnetic fields that oscillate at the same frequency as the charge source. Frequency is the term used to describe the rates at which these charges move from zero to maximum charge, back through zero to minimum charge, and finally back to zero. This action describes one complete cycle.



FREQUENCY vs. WAVELENGTH

The energy that is formed by the moving charges move at the velocity of light, which in free space is a distance of approximately 299.79×10^6 meters per second. Therefore, a single cycle per second, or one cps, would have a wavelength of almost 300 million meters or over 186 thousand miles.

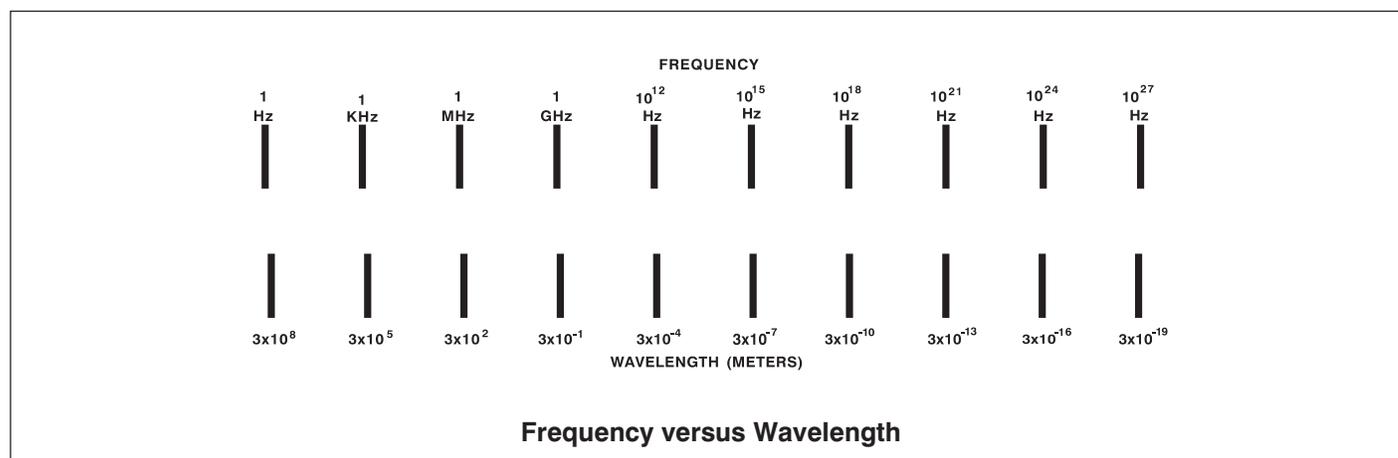
Simply put, the *wavelength* is determined by dividing 299,790 kilometers per second by the frequency. By dividing 299,790 kilometers by the wavelength (λ), one arrives at the frequency. In other words, this determines how many complete cycles are required for the radio waves to travel 299,790 kilometers. As the frequency increases, the wavelength decreases, because velocity is constant in free space (see the figure below).

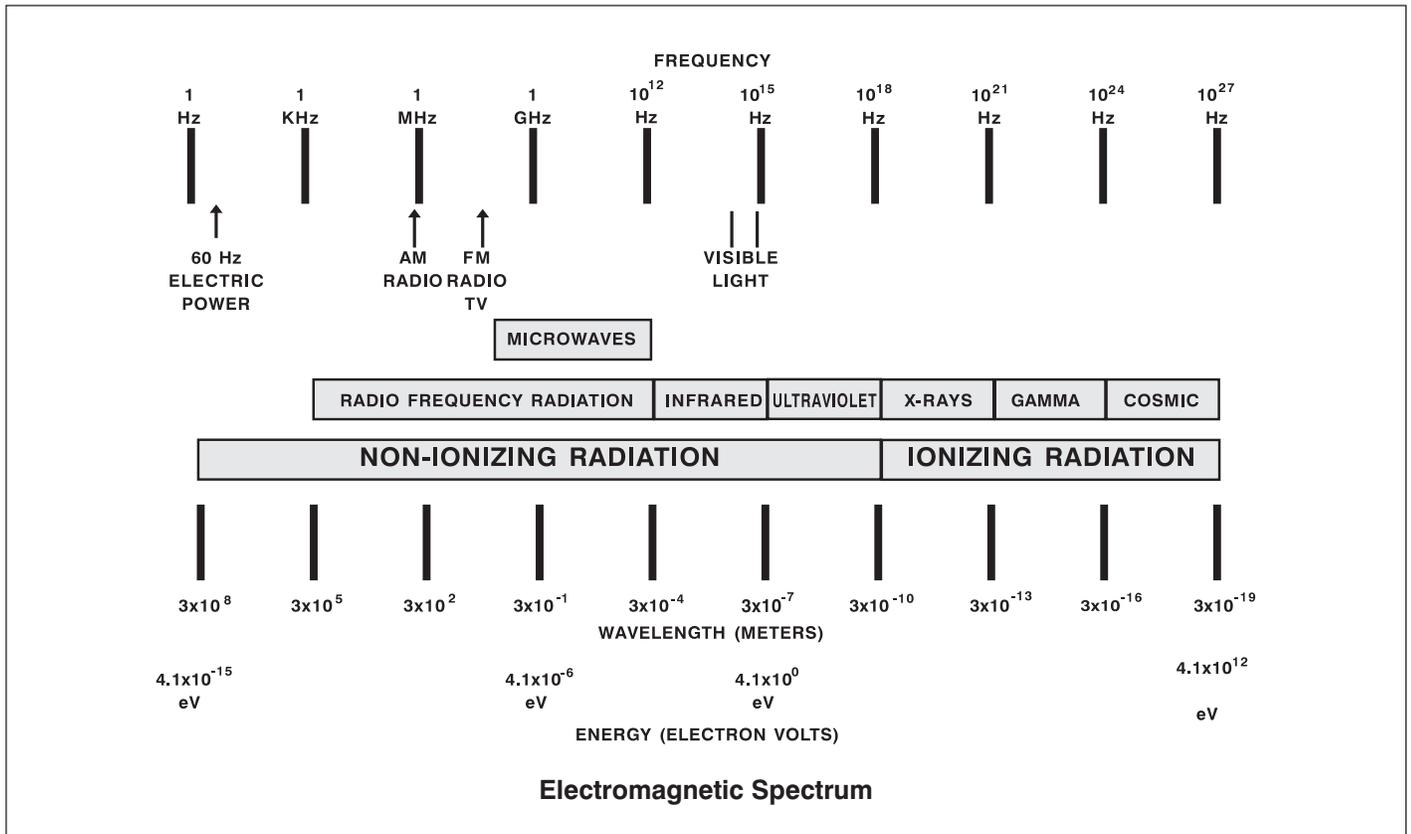
The term "Hertz" is synonymous with cycles per second. Instead of using the term "kilo cps" (1000 cycles per second), it is more commonly described as kHz (kilohertz). One million cycles per second is similarly described as one megahertz (MHz).

WHAT IS THE DIFFERENCE BETWEEN IONIZING AND NON-IONIZING RADIATION?

Electromagnetic waves caused by moving electric charges all carry energy. These are commonly called photons. Their energy level increases at higher frequencies and is measured in electron volts, or eV (referred to as Planck's constant, $Energy = hf$, where h is equal to 6.63×10^{-34} joule second and $f = frequency$).

At a frequency of approximately 2420 million MHz, the photon energy levels are approximately the same 12.4 eV as the energy binding electrons to atoms. At this energy level, water molecules can be ionized, therefore, at this part of the frequency spectrum, the energy is classified as "ionizing."





Microwave frequency photons carry considerably less energy (.001 eV) than the weakest chemical bonds and are therefore classified as “non-ionizing.”

WHAT GENERATES NON-IONIZING ENERGY?

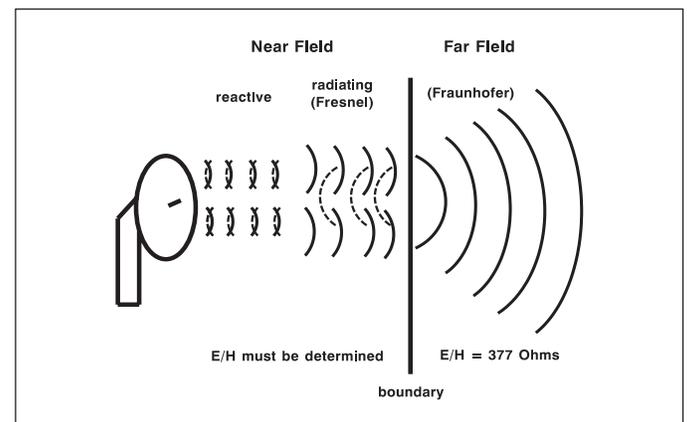
For millions of years, the principal generators of non-ionizing energy have been terrestrial sources such as lightning and extraterrestrial sources such as the sun. Even the human body generates thermal energy in the non-ionizing spectrum totalling approximately 0.3 $\mu\text{W}/\text{cm}^2$.

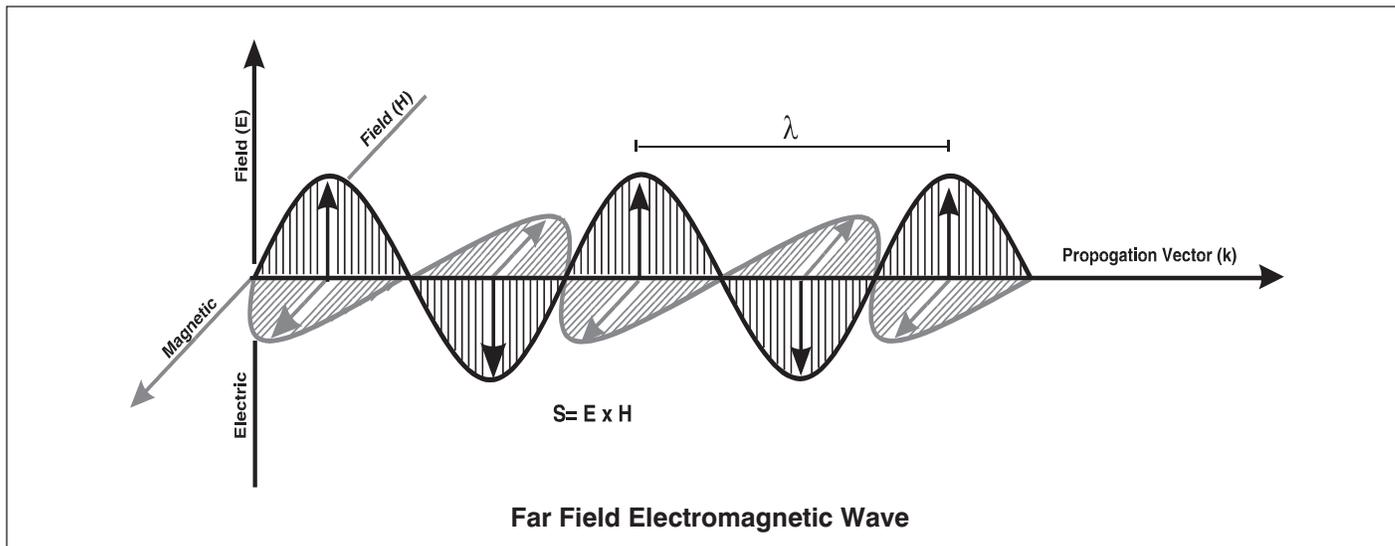
In the last century, a tremendous increase in man-made sources of non-ionizing energy has greatly increased the life quality – and even lifespan – of human beings. Medical systems such as diathermy, Magnetic Resonance Imaging (MRI) and electrosurgical devices use non-ionizing energy. Weather forecasting would be nearly impossible without satellite systems and weather radars and no one could be warned of emergency weather conditions without communications like TV or radio.

Man-made energy sources use devices such as klystrons, magnetrons and semiconductor sources to generate the non-ionizing energy required to communicate over long distances or to provide thermal energy.

HOW DOES ELECTROMAGNETIC RADIATION TRAVEL (PROPAGATE) THROUGH FREE SPACE?

Electromagnetic waves that are generated by man-made devices usually travel along two conductor (coaxial) cables or hollow piping called waveguide. A device called an antenna or applicator is used at the end of the coaxial or waveguide lines to transmit the energy into free space. Moving electron charges on the surface of the antenna mostly propagate outward, forming an electromagnetic wave that travels through free space.





If we could freeze the motion of an electromagnetic wave travelling in free space, it would look like the waveform above when it is in the “far field” or “Fraunhofer” region. The electromagnetic field in the far field is very consistent. The electric field is always perpendicular to the direction of propagation and the magnetic field is always perpendicular to both the electric field and the direction of propagation. The two regions very close to the antenna are called the *reactive near field* and the *radiating near field*. In the reactive near field energy does not radiate, it is recovered and re-emitted during successive oscillations. In the radiating near field, energy is both stored and radiated. While the strength dissipates over distance in the far field, it may increase – or even stay the same – until the distance from the antenna approaches the far field region.

Free space has a resistance to electromagnetic radiation, otherwise no forms of radio or TV communication could exist. When a plane-wave condition exists, the impedance is a constant value of 377 ohms. In the near field, the impedance will vary with the ratio of the E (electric) to H (magnetic) fields. A higher impedance indicates a stronger E field while a lower impedance indicates a stronger H field, and neither may be constant until the distance approaches the far field. When performing measurements in the near field you must measure both field components separately while in the far field you need to measure only one (usually the E field). Standards used to determine compliance may also specify what measurements are to be made. IEEE C95.1-1991 specifies 300 MHz as the crossover point between measuring both fields or only one. More information on calculating field strengths is contained in the Narda Survey Application Note.

HOW IS ELECTROMAGNETIC RADIATION CHARACTERIZED?

Free Space Impedance Calculation

The magnitude of the power density in a wave can be calculated from the vector product:

$$|E \times H| = |E| |H| \sin \theta$$

For angle of 90°, as is the case in the far field ($\sin 90^\circ = 1$):

$$|E \times H| = |E| |H|$$

When we look at our free space electromagnetic wave where the ratio of electric to magnetic fields is the free space impedance, we can say:

$$Z_0 = |E/H|$$

Z_0 is the impedance as a ratio of E to H and is independent of their magnitudes. Free space has a resistance to electromagnetic radiation, therefore, it has a permeability (ratio of magnetic flux density produced in a medium to the magnetic field strength that produced it) and a permittivity (ratio of electric flux density in a medium to the electric field that produced it), therefore via Maxwell’s equations:

$$Z_0 = \sqrt{\mu_0/\epsilon_0}$$

$$Z_0 = \sqrt{1.257 \times 10^{-6} \text{ F/m} / 8.855 \times 10^{-12} \text{ H/m}}$$

$$Z_0 = \sqrt{141953.6985}$$

$$Z_0 = 376.767$$

The characteristic impedance of free space is, therefore, 377 ohms.

Since we have already seen that the electric and magnetic field intensities are related through the impedance of space (Z_0), which is 377 ohms, we can say:

$$(E)/(H) = 377 \text{ ohms}$$

$$S = (E) \times (H), S = W/m^2 \text{ (10 W/m}^2 = 1 \text{ mW/cm}^2\text{)}$$

$$S = (W/m^2) = 377 \times H^2 \quad S(\text{mW/cm}^2) = 37.70 \times H$$

$$S = (W/m^2) = E^2/377 \quad S(\text{mW/cm}^2) = E^2/3770$$

RMS Average

The power density of an electromagnetic wave is related to the electric and magnetic intensities in that it is the product of the two. When we speak about power density, we use the RMS average, which is the root mean square of the maximum amplitude of the field multiplied by $1/\sqrt{2}$ (.707) thus:

$$W = H_0 / \sqrt{2} \times E_0 / \sqrt{2} = E_0 H_0 / 2$$

Power and Field Intensity

An electromagnetic wave represents a flow of energy in the direction of propagation. The intensity, or strength, of an electromagnetic field depends on the transmitter's power level, the antenna used, and the distance from the antenna. The field is specified by its intensity that passes through a unit area. Electric (E) fields are usually expressed in Volts per meter (V/m) or its mean squared value (V^2/m^2).

Similarly, the magnetic (H) field is specified in A/m or (A^2/m^2). The product of the two is the power density (voltage times current equals power per Ohms law). The resulting units are watts per meter squared (W/m^2) or, more commonly, milliwatts per centimeter squared (mW/cm^2). There are instruments available that can display field levels in field strength, mean squared field strength, or equivalent power density. At this time, units that display power density actually measure mean squared field strength. A true measurement of power density would require separate amplitude and phase information for each axis (X, Y and Z). Equipment to measure true power density does not exist commercially.

When using a meter that displays equivalent power density to measure both fields, the amplitude and field must be specified (i.e., 12 mW/cm^2 E field and 5 mW/cm^2 H field). Readings may be converted to field strength – or mean squared field strength – by using the equations above for comparison to a particular standard.

In this way, meters that display equivalent power density, but measure mean squared field strength, are usable in the near field as well as the far field.

If a source radiates power uniformly in all directions, the power density at a distance r from the source will be the total radiated power (P) divided by the area (A) of the sphere(s):

$$W = P/As = P/4\pi r^2$$

Looking at the above equation, it can be said that the power density decreases as the distance to the source increases, and that the power density is inversely proportional to the square of the distance from the source.

This is the inverse square law of radiation. It is true for an emitter that radiates in all directions, or for an emitter that radiates over a limited portion of a sphere.

HOW IS RF ENERGY ABSORBED INTO THE BODY?

There are many factors involved in determining how RF energy is absorbed into the body, such as:

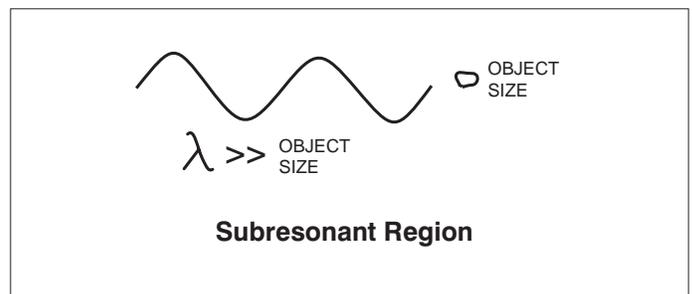
1. Dielectric composition
2. Size of the body
3. Shape and orientation of the body and the polarization of the field
4. Complexity (near field) of the RF field

1. Dielectric Composition

Absorption characteristics vary for different parts of the body. As a general rule, RF energy passes through fatty tissue and is deposited in the muscle or brain tissue with the depth of penetration varying inversely with frequency.

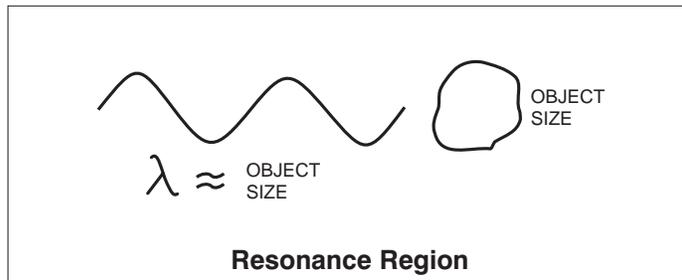
2. Body Size

Although we have previously discussed frequency and wavelength, this section focuses on the different absorption characteristics of the human body vs. wavelength. Three scenarios are examined: (1) where the body is less than the size of the wavelength, (2) where they are roughly equal, and (3) where the body is larger. In instances

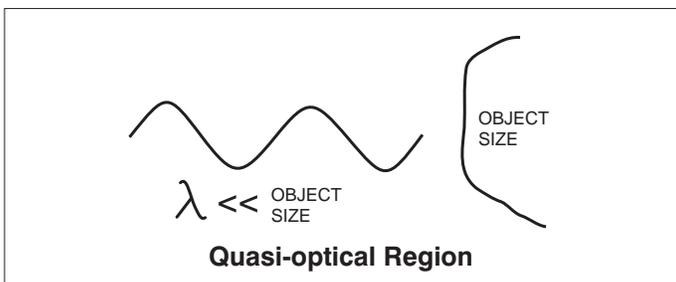


Application Notes

where the size of the body is less than the wavelength, there is little absorption and a uniform, or equal, distribution of energy. In this range, the body becomes increasingly resistive as frequency is decreased.

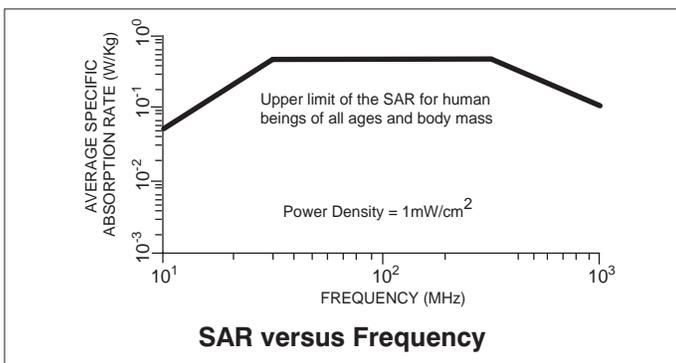


When the wavelength is roughly equal to the size of the body, there is the highest absorption with unequal distribution of the energy. Consequently, "hot spots" may be generated.



Where the wavelength is less than the size of the body, there is lower absorption and the heating is confined to the irradiated area.

Specific Absorption Rate (SAR) is the basis of most safety standards. It is the rate of energy absorption per unit of body mass. At an absorption level of 4 W/kg, *reversible* behavioral disruption has been noted. Levels above 5 W/kg have resulted in *permanent* adverse effects. Therefore, most standards have been based on SAR's of 0.4 W/kg to conservatively limit exposures to 1/10th of these levels to account for biological uncertainty and to add an additional safety factory. The rate of energy absorption is

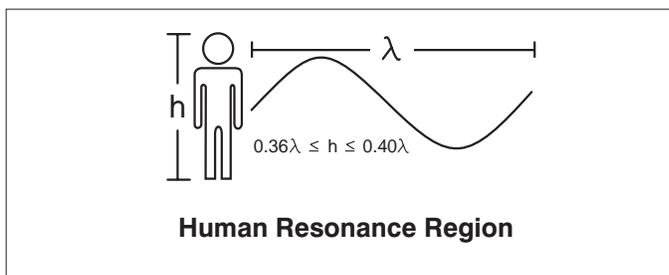


not constant over varying frequencies and wavelengths. An example of this is the *whole body human resonance region* where the human body is close in size to the wavelength. You can approximate your own resonant frequency (ungrounded) by using 114 divided by your height in meters. For a person who is 5'9", the frequency would be:

$$5'9" = 69" \times 0.0254 = 1.75 \text{ meters}$$

$$114 \text{ divided by } 1.75 = 65.1 \text{ MHz (divide in half for grounded resonance)}$$

If you were to input the height of a newborn child and that of a very tall adult person – and factor in whether they are

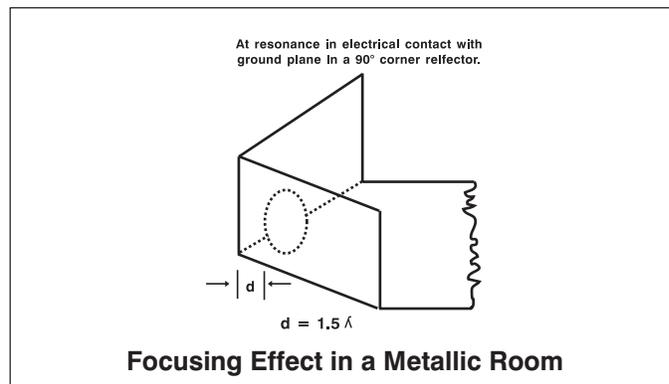


grounded – you would begin to see where the highest absorption takes place for a general population (as a function of frequency only). For example, the human resonance region according to IEEE C95.1-1991 is from 30 MHz to 300 MHz.

3. Shape, Orientation, and Polarization

Absorption varies with the shape and orientation of the body in the field. A human standing in the vicinity of a vertically polarized field absorbs much more energy (10 times) than the same person standing in front of a horizontally polarized signal.

Workplace exposure conditions can be difficult to calculate. In a metallic shelter or screen room, the RF energy may be focused at a particular point or area. Experimental measurements on a spheroid model of man immersed in a 10 mW/cm² field have shown considerable increases in



the Specific Absorption Rate . At the resonant frequency and while standing in the corner of a shielded room (in contact with the ground plane) at a distance of 1.5 wavelengths, models have been calculated to be absorbing as much as 116 W/kg. Standards usually allow no more than 1 mW/cm² in this resonance range, but in focused environments there still is the potential to exceed the SAR's the standards are based on.

4. Field Complexity

Most standards are based on the far field plane wave relationships and their interaction on the body. As discussed previously in this document, the near field is complex in its energy distribution and nearly impossible to calculate. When you add this to the three factors that determine absorption, the total variables become staggering.

HOW ARE FIELD LEVELS CALCULATED?

To perform calculations, information should be obtained from engineering personnel or the manufacturer concerning the following:

1. Operating Frequency
2. Transmitter Power
3. Modulation Characteristics, if any (AM, FM, Pulsed)
4. Number of Sources
5. Spurious Frequencies or Harmonics
6. Intermittence of Output (may be scanning, or direction finding)

Just as important are the propagation characteristics:

1. Distance to Source
2. Type of Antenna (Size, Gain, Beamwidth, Orientation)
3. Polarization of E and H field
4. Existence of Absorbing or Scattering Objects

When calculating the distance to the source, determine if measurements are to be made in the near field or far field. For circular antennas, the near field extends to approximately $D^2/4\lambda$ and for other types, it typically extends to $G\lambda/4\pi^2n$ (where G is the gain of the antenna and n is the efficiency factor). As stated previously, if measurements are to be made in the near field, both E and H fields need to be measured. The reactive near field can become important when monitoring resonant "Whip", or "Dipole" antennas (to name two) at frequencies below 100 MHz and at power levels of only a few watts. The reactive near field typically extends out to a distance of $\lambda/2\pi$ to $\lambda/2$ wavelengths, depending on the antenna.

At frequencies above 300 MHz, most standards assume you are in the far field, therefore, only one field needs to be measured – almost always the electric field.

Calculations

Calculations are useful when performing a survey in the far field region. For those instances where a survey will be performed in the near field, calculations are not normally accurate. The survey should start in the far field region at a position calculated to be well within safe limits. It is also recommended that the electric field be measured first in order to minimize any shock or burn hazard.

Antenna gain is defined as the power density at a spot in front of an antenna divided by the power density at the same spot if the antenna were radiating in all directions, or isotopically. For any well-matched circular antenna, where all of the energy supplied to it is transmitted, the ratio of G to A is:

$$G = 4\pi A/\lambda^2$$

where G = Numerical Gain

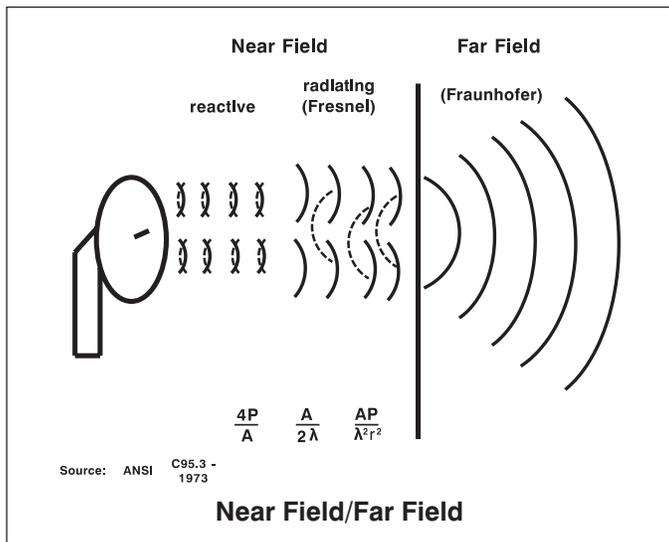
A = Area (meters)

NOTE: All equations use numerical gain, G

Below is a table of typical antenna gains listed logarithmically and numerically $G_{num} = (G \text{ dB}/10)$ antilog:

LOGARITHMIC vs. NUMERICAL GAIN

dB	Numerical	dB	Numerical	dB	Numerical
1.0	1.26	11.0	12.59	21.0	125.89
2.0	1.58	12.0	15.85	22.0	158.49
3.0	2.00	13.0	19.96	23.0	199.53
4.0	2.51	14.0	25.12	24.0	251.19
5.0	3.16	15.0	31.62	25.0	316.23
6.0	3.98	16.0	39.81	26.0	398.11
7.0	5.01	17.0	50.12	27.0	501.19
8.0	6.31	18.0	63.10	28.0	630.96
9.0	7.94	19.0	79.43	29.0	794.33
10.0	10.00	20.0	100.00	30.0	1000.00



Far field power density is calculated from the Friis free-space formula:

$$W = GP/4\pi r^2 = AP/\lambda^2 r^2$$

where λ = wavelength

P = Power output of antenna

W = power density on a surface at distance r from the antenna

It is convenient to use the above equation as long as the distance (r) is a far-field distance. The far field would begin at a distance of:

$$r = 0.6 D^2/\lambda$$

for a circular antenna. For these antennas, the effective area is less than the actual area, usually on the order of 50% to 80%. If the gain of a circular antenna is not known, it can be approximated by:

$$G = 4\pi An/\lambda^2$$

where n would be on the order of 0.5 to 0.8 in order to account for the actual area used. Equations are also available to solve for a power density at a certain distance from an antenna. This is calculated from the output power measured at the input to the antenna, and the known antenna gain (G).

$$D = \sqrt{\frac{P_{avg} \times G_{num}}{4\pi(W/m^2)}}$$

Where D = distance in meters, P_{avg} = Avg. Power in Watts

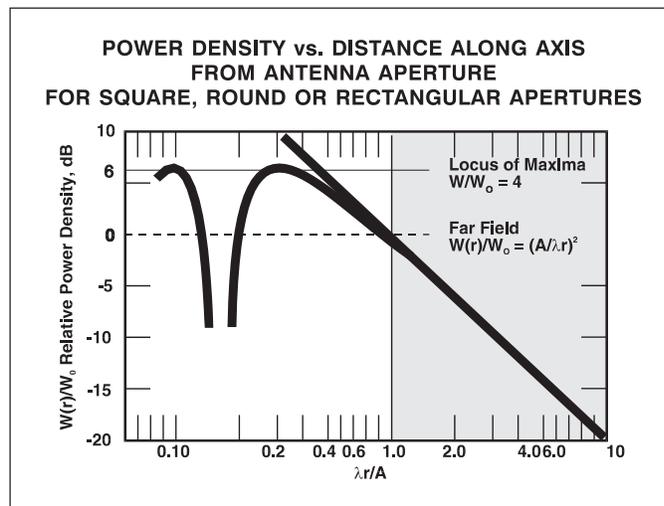
The result is in W/m^2 (Remember $1 \text{ mW/cm}^2 = 10 \text{ W/m}^2$)

WHY IS A SURVEY REQUIRED?

A survey is required to have a real understanding of the RF environment. Calculations can only provide an estimate of the field strengths involved, and are merely a starting point. Caution must be employed for the surveyor's safety and to protect expensive surveying equipment from excessively high field levels. Performing the survey is the only way to truly know the field levels and to implement the correct strategy that is the most cost effective.

Before performing the survey, it is important to know what instruments will be needed. To determine this, you must familiarize yourself with the measurement area and match instrument capability to the environment in this area.

For more information on performing surveys, refer to the Narda's application note on surveys.



REFERENCES

Biological Effects of Radiofrequency Radiation

edited by D.F. Cahill and J.A. Elder

Environmental Protection Agency

Report No. EPA-600/8-83-026F, 1984.

IEEE Standard for Safety Levels with respect to Human Exposure to Radio Frequency Fields, 3 kHz to 300 GHz.

New York: The Institute of Electrical and Electronics Engineers, Inc., IEEE C95.1-1991

(for copies, phone 800-678-IEEE).

Leonowich, John A., Ph.D.

“Sources of Microwave/Radiofrequency Radiation,” 1987

“Fundamentals of Electromagnetics,” 1987.

Osepchuk, John M., Ph.D.

1992 Book Review of *Nonionizing Radiation Questions and Answers*, by M.G. Yost.

Questions and Answers About Biological Effects and Potential Hazards of Radiofrequency Radiation

Federal Communications Commission,

FCC OET Bulletin No. 56, 3rd Edition, 1989.

Radio Frequency and Microwave Radiation

prepared by R.T. Hitchcock

American Industrial Hygiene Association, 1988.

Yost, Michael G.

Nonionizing Radiation Questions and Answers

San Francisco: San Francisco Press, 1988.