Industry Canada Industrie Canada

TN-261
Issue 3
March 2015

Spectrum Management and Telecommunications

Technical Note

Safety Code 6 (SC6) Radio Frequency Exposure Compliance Evaluation Template (Uncontrolled Environment Exposure Limits)

Aussi disponible en français – NT-261

Canada

Preface

Technical Note TN-261, Issue 3, *Safety Code 6 (SC6) Radio Frequency Exposure Evaluation Template (Uncontrolled Environment Exposure Limits)*, replaces TN-261, Issue 2, published in December 2012.

Changes made:

1. Clarification regarding the need for further analysis when the evaluation template identifies locations where the general public would be exposed to radio frequency (RF) energy equal or above 50% of SC6 limits (uncontrolled environment)

2. **Section 3.2:** Clarification regarding the antenna tilts

3. **Annex A:** Clarification regarding the antenna tilts

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All Spectrum Management and Telecommunications publications are available on the following website: http://www.ic.gc.ca/spectrum.

Contents

List of Acronyms and Abbreviations

ALS	Assignment and licensing system
BPR	Broadcasting Procedures and Rules
CPC	Client Procedures Circular
e.i.r.p.	Equivalent isotropically radiated power
e.r.p.	Effective radiated power
EM	Electromagnetic
FCC	Federal Communications Commission
GL	Guidelines
LM	Land mobile
MW	Microwave
PCS	Personal Communications Service
RF	Radio frequency
SC6	Safety Code 6
TN	Technical Note
Z	Impedance

1.0 Purpose

The purpose of this document is to provide an evaluation tool to quickly assess the radio frequency (RF) exposure compliance of simple radiocommunication antenna sites. The intent is to provide a nationally consistent approach regarding the evaluation of compliance with Canadian RF exposure limits.[1] The method outlined in this document is only valid in the far-field region of antennas. It is not recommended for a detailed RF compliance analysis. For such an approach, an analysis technique based on sound engineering practices using the actual antenna pattern and taking into consideration the contribution of each antenna present at the site, including the radio environment, is required.

2.0 Introduction

As outlined in Industry Canada's Client Procedures Circular CPC-2-0-03, *Radiocommunication and Broadcasting Antenna Systems*, the Department requires that all radio installations be operated in a manner that complies with Health Canada's *Limits of Human Exposure to Radiofrequency Electromagnetic Energy in the Frequency Range from 3 kHz to 300 GHz — Safety Code 6* (SC6), for the purpose of protecting the general public. Applicants must consider, in addition to their own radio system, the contributions of all existing radiocommunication installations within the local radio environment, either when predicting field strength levels or when conducting field measurements.

For cases where clients (radiocommunication users, carriers and/or service providers) have demonstrated (either by means of field measurements or predictions) that the uncontrolled environment exposure limits established by SC6 for areas accessible by the general public are being respected, Industry Canada would not normally require corrective measures. Nevertheless, Industry Canada requires users, carriers and/or service providers of radiocommunication installations to ensure that supporting structures accessible by the general public include anti-climbing devices or other mechanisms to prevent access to areas on the supporting structures within which the uncontrolled environment limits may be exceeded.

For areas accessible by the general public where the uncontrolled environment limits would not be respected, where technical means such as reducing the transmitter power level or modification to the transmitting facility are not practical, appropriate means of area demarcation and/or access control will be required by the users, carriers and/or service providers as outlined in CPC-2-0-20, *Radio Frequency (RF) Fields — Signs and Access Control*. In addition, as soon as the RF emissions from the antenna systems are greater than or equal to 50% of the SC6 limits for uncontrolled environments at locations accessible to the general public, the operators of the antenna system are required to notify Industry Canada and demonstrate compliance.

To assist in field measurements, Industry Canada has published GL-01, *Guidelines for the Measurement of Radio Frequency Fields at Frequencies from 3 kHz to 300 GHz*, which provides guidance to interested parties on verifying compliance with SC6 requirements. These documents cover the measurement procedures for broadcast, microwave, land mobile, paging, cellular, PCS and radar installations.

1 Broadcasting Procedures and Rules BPR-1, *General Rules*, provides the specific requirements for broadcasting applications for demonstrating compliance with SC6. BPR-1 contains the description of the required analysis and alternatives depending on the results submitted by the proponent.

For many simple installations, the template described in this document provides a definitive assessment of compliance in the far-field, for given technical parameters such as power level, antenna height, antenna length, frequency and the distance to areas accessible to the general public. In the near-field or in a complex radio environment where several antenna towers are installed in the vicinity of a location of interest, a detailed analysis technique may be needed, using sound engineering practices that take into consideration the contribution of each antenna present. This may include an RF software assessment tool or complex spreadsheets.

This technical note outlines an evaluation procedure to determine RF exposure compliance with respect to SC6, which is the second step of the three-step evaluation approach outlined below.

3.0 Evaluation Process

The general SC6 compliance evaluation process consists of a three-step approach. It is anticipated that the evaluation methods applied in Step 1 and Step 2 will screen out most of the simple sites; while flagging those congested sites, such as publically accessible rooftops with multiple antennas, will require a more detailed analysis technique (Step 3).

Step 1 — Attestation or Analysis

The applicant must attest that its station (or the site if co-located) is in compliance with the uncontrolled environment limits set forth in SC6. This attestation can be submitted as part of Industry Canada's IC-2430 form entitled *Radiocommunication and Broadcasting Antenna Systems Attestation*. Otherwise, an acceptable SC6 analysis with a compliance statement can be used as attestation. If the application is not accompanied by form IC-2430, or another form of signed attestation or an acceptable analysis indicating compliance with the uncontrolled environment requirements of SC6, the application will not be processed until the required attestation is received. In all cases, the departmental officer processing the application is expected to exercise judgement on the validity of the submission. If there is any doubt about compliance, the process moves to Step 2.

Step 2 — Non-Exemption Zone Analysis

Use the technical parameters of the site and the simplified evaluation process outlined in sections 3.1 to 3.4 and 4 of this document to conduct the evaluation.

Alternatively, as the site becomes more complex, the departmental officer may use internal RF exposure compliance software for assessing land fixed and land mobile stations in place of the above simplified evaluation process. This software is based on the propagation model and default antenna patterns used in the simplified evaluation process and differentiate between the near-field and far-field region of antennas. Other nearby radio stations in the local environment, within the distances prescribed in Section 3.4, are also taken into consideration.

With either method, if it is determined that the site is in compliance then there is no need for further evaluation. However, if the site fails the screening method employed in this step (that is, if the general public has access to locations in the near field of the antennas or where the predicted levels are greater than or equal to 50% of the SC6 limits for uncontrolled environments) then proceed to Step 3.

Step 3 — Detailed Analysis, Field Measurements or Mitigation Measures

The procedure outlined in Section 3.4 for dealing with multiple antennas and frequency bands is a conservative approach that overestimates the RF signal levels. As the number of antennas and frequency bands increase, the estimated results become less realistic, producing predicted levels that are greater than what would be expected to be measured. A different approach would therefore be required.

The departmental officer may present several options to the applicant in order to demonstrate compliance with SC6. The applicant may (i) submit detailed calculations, (ii) take measurements, and/or (iii) implement mitigation measures at the site.

(i) Detailed calculations based on sound engineering practices shall be done for all areas accessible by the general public to demonstrate compliance with the uncontrolled environment limits outlined in SC6. The calculations should include accurate technical parameters for each transmitting antenna, including the vertical and horizontal antenna patterns, frequency, effective radiated power (e.r.p.), antenna height and tilt and, in the case of multiple antenna supporting structures, the horizontal position and orientation of each antenna referenced to the point of calculation. The calculations may be done using spreadsheets or computational modeling software and should take into consideration near-field and far-field regions, as well as the applicable SC6 limits. The departmental officer should verify the calculations and in cases where the detailed calculation identifies areas accessible to the general public where the RF intensity is above 50% of the uncontrolled environment limit or if the departmental officer is not convinced that the site is in compliance with SC6, the officer may direct the applicant to take measurements (as outlined in (ii) below) and/or implement mitigation measures to demonstrate compliance.

(ii) Detailed measurements shall be made to demonstrate that, in areas accessible to the public, the radio frequency fields comply with SC6 uncontrolled environment limits. The applicant must submit a report (see GL-08[2]) to the Department, showing details of the measurements. For further information, refer to GL-01, *Guidelines for the Measurement of Radio Frequency Fields at Frequencies from 3 kHz to 300 GHz*. The departmental officer may specify measurements to be taken in certain areas, e.g. areas which are frequented by the public. If the results do not demonstrate compliance, the applicant must implement mitigation measures. The Department reserves the right to verify the measurements taken by conducting field audits. On rare occasions, the departmental officer may choose to observe the measurements being taken.

(iii) To comply with SC6, the applicant may choose to propose mitigation measures in lieu of, or as a supplement to, field measurements. These may include, but are not limited to, reducing power, changing antennas, or restricting public access (see CPC-2-0-20, *Radio Frequency (RF) Fields — Signs and Access Control*). The departmental officer may specify other mitigation measures if the ones proposed by the applicant are not considered adequate. The applicant should advise the Department when the mitigation measures have been implemented.

Although compliance with CPC-2-0-03, *Radiocommunication and Broadcasting Antenna Systems*, and SC6 is a standard condition of authorization, the departmental officer may require that additional specific conditions be met, e.g. the applicant must demonstrate compliance by measurements or

[2] GL-08, *Guidelines for the Preparation of Radio Frequency (RF) Exposure Compliance Reports for Radiocommunication and Broadcasting Antenna Systems*

mitigation measures before issuing the final authorization will be issued. As well, other ongoing conditions may be added to the authorization.

3.1 Overview of the Non-Exemption Zone Analysis

This method is based on a modified free-space formula (see Annex A), which takes into consideration 60% reflection (Section 3.3), and the *cosine* reduction (Section 3.2) rather than the vertical antenna pattern. Horizontally speaking, the antenna is assumed to be omnidirectional.

The non-exemption zone analysis is mainly intended for single service cases (single frequency band), e.g. cellular systems, where the e.i.r.p. is the summed e.i.r.p. of all the transmitters and channels (Section 3.4). However, the method can also be applied to multiple service cases (multiple frequency bands) using a conservative approach where all the e.i.r.p. values are summed and applied to the centre of the lowest mounted antenna. The limit at the observation point is assessed against the lowest limit outlined in SC6 for the frequency bands present. Also, the largest antenna and the lowest frequency are used to determine where the far-field starts (see Section 3.4 for multiple service radio environments).

Before applying this method, one must first determine whether the point of interest (i.e. the point where compliance evaluation is required) is in the far-field region of the antenna, as outlined in Section 4 and Annex A. It is important to establish this distance because this method cannot be used to evaluate the near-field situations, as the restricted zone generated is based on the modified free-space formula, which is only valid in the far-field. As shown in Figure 1, the sphere surrounding the antenna represents the near-field/far-field spherical boundary, within which the point of interest cannot lie when applying this method.

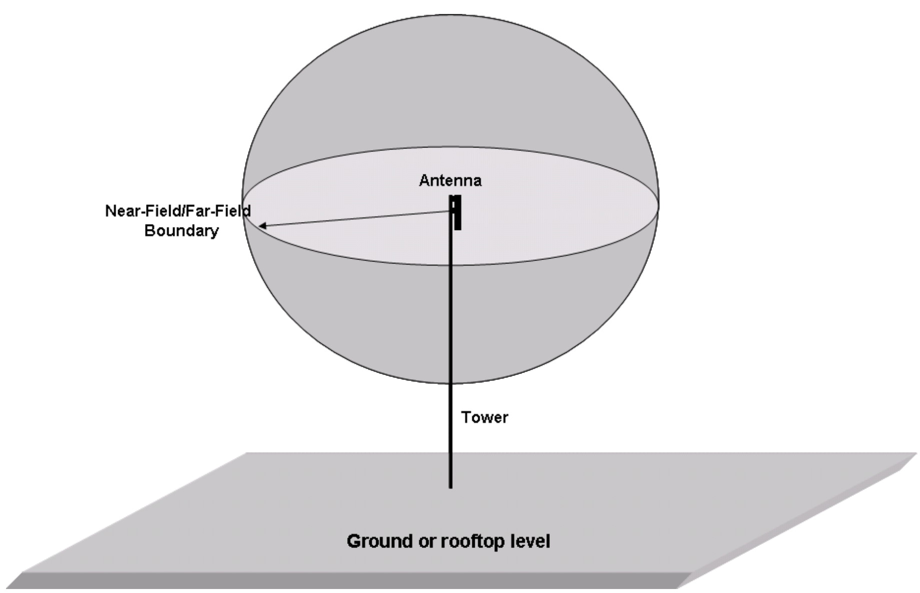

Figure 1 — Near-field/far-field boundary around an antenna

The next step involves using the technical parameters of the antenna and the modified free-space formula to generate a restricted zone around the antenna based on 50% of the applicable SC6 limit for uncontrolled environments, within which the point of interest also cannot lie. This restricted zone is represented by a cylinder surrounding the antenna, where the top of the cylinder lies in the horizontal plane passing through the centre of the antenna. It is assumed that the same restriction applies above the antenna, so a mirror image of the cylinder is placed above the horizontal centre axis of the antenna. The result is a larger cylinder with the antenna in the centre, as shown graphically in Figure 2. In this case, X is the horizontal distance outward from the antenna centre and Y is the vertical distance below the antenna boresight direction. The total volume of the cylinder now represents the overall restricted zone, where the point of interest cannot lie.

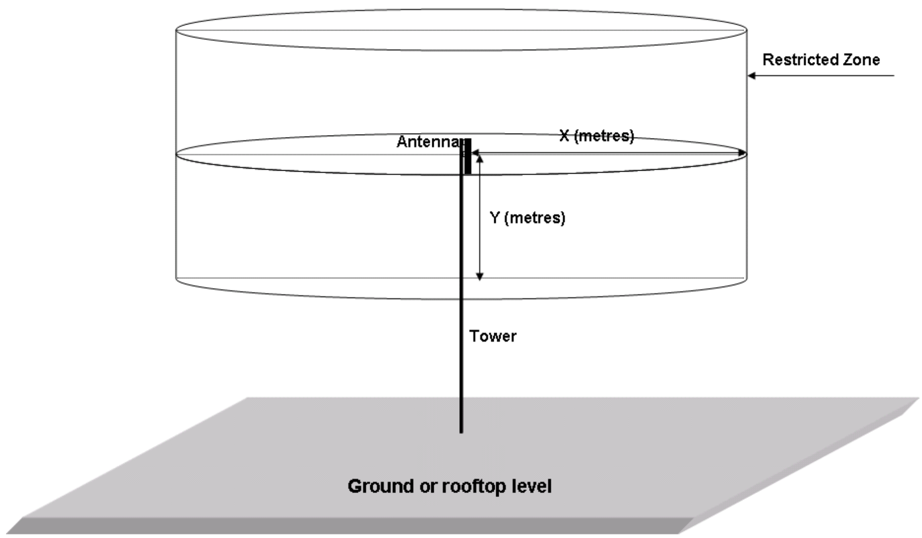

Figure 2 — Graphical representation of the restricted zone around an antenna

Once established, the near-field/far-field boundary must be used in conjunction with the restricted zone. **The overall larger dimension of both volumes combined is used to determine the new *non-exemption* zone**. If the public only has access to the areas outside the overall non-exemption zone, the installation is in compliance with SC6. Figure 3 shows a scenario where the restricted zone is larger than the far-field spherical boundary; therefore, the overall non-exemption zone is the same as the restricted zone.

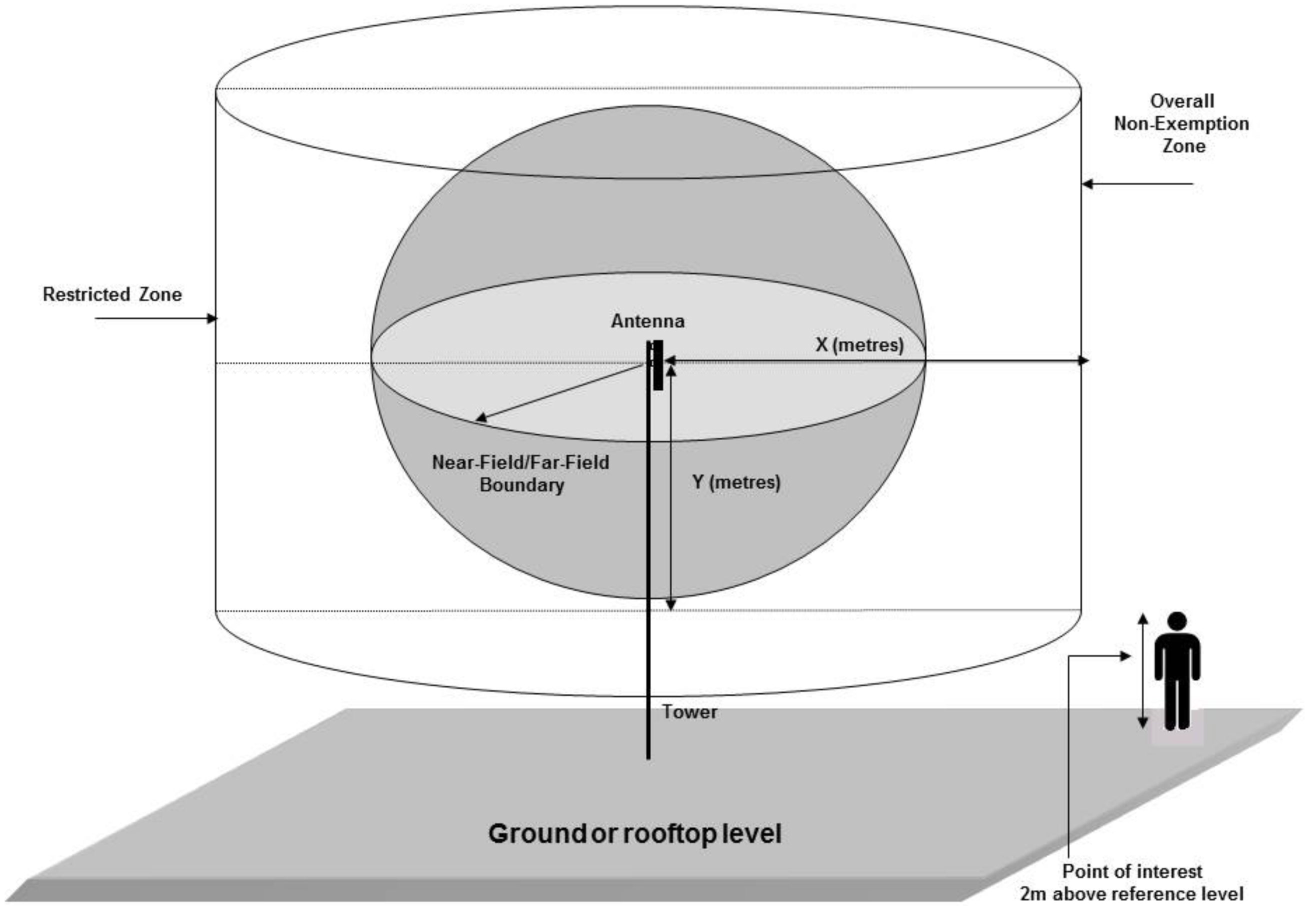

Figure 3 — An ideal situation for applying the exemption template

In Figure 4, the restricted zone is smaller than the near-field/far-field spherical boundary. Since the restricted zone is calculated assuming far-field conditions, as the point of interest moves outwards further than the far-field spherical boundary, the far-field conditions will be satisfied, and the propagation calculations at the point of interest will become valid. Therefore, in this scenario (Figure 4), if the public has no access to the near-field region, by deduction, the installation should also be in compliance with SC6 and the overall non-exemption zone is assumed to be the near-field/far-field spherical boundary.

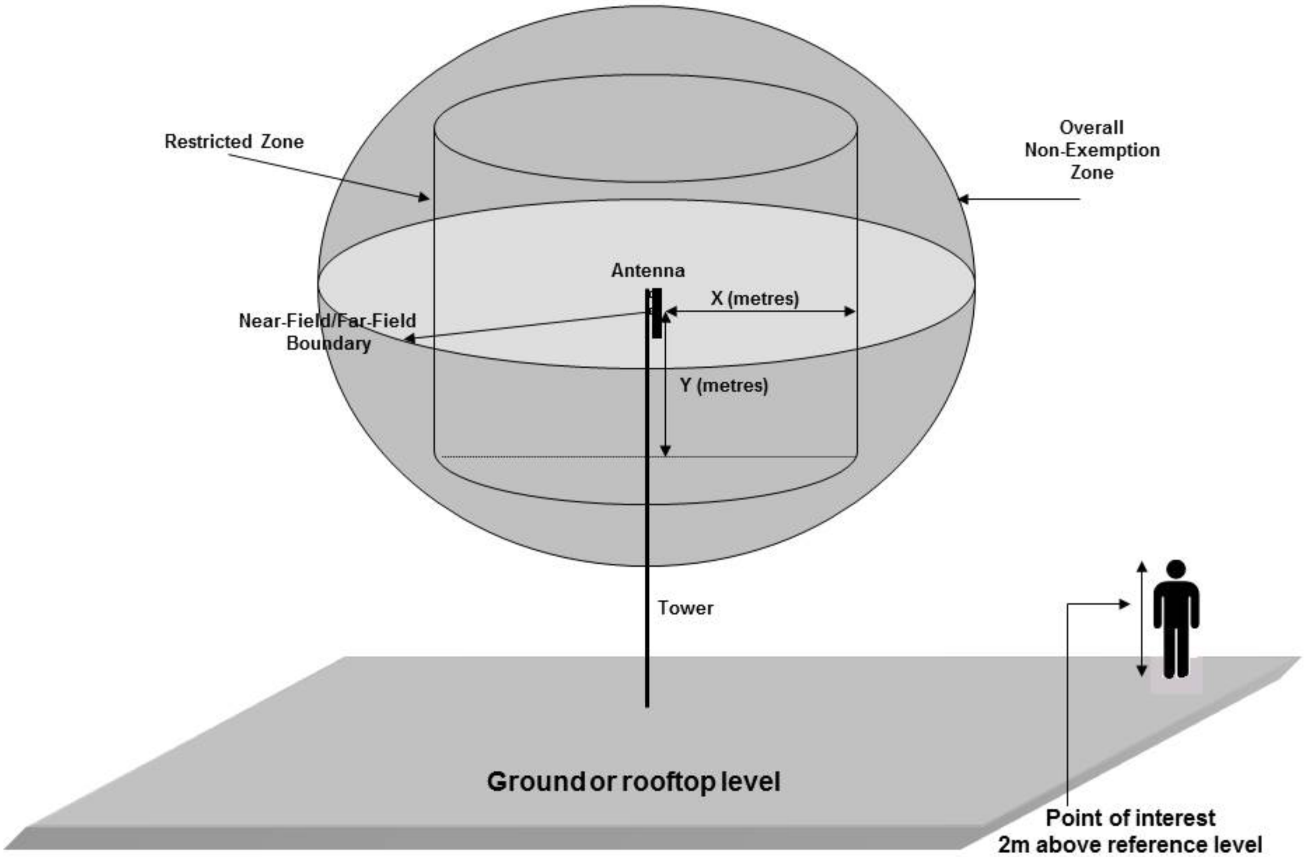

Figure 4 — If the restricted zone is in the near-field, the near-field/far-field boundary becomes the new overall non-exemption zone

There may be situations where there is a partial overlap of the near-field/far-field spherical boundary and the restricted zone (cylinder), in which case, the overall non-exemption zone will take the shape of the combined volume as shown in figures 5 and 6.

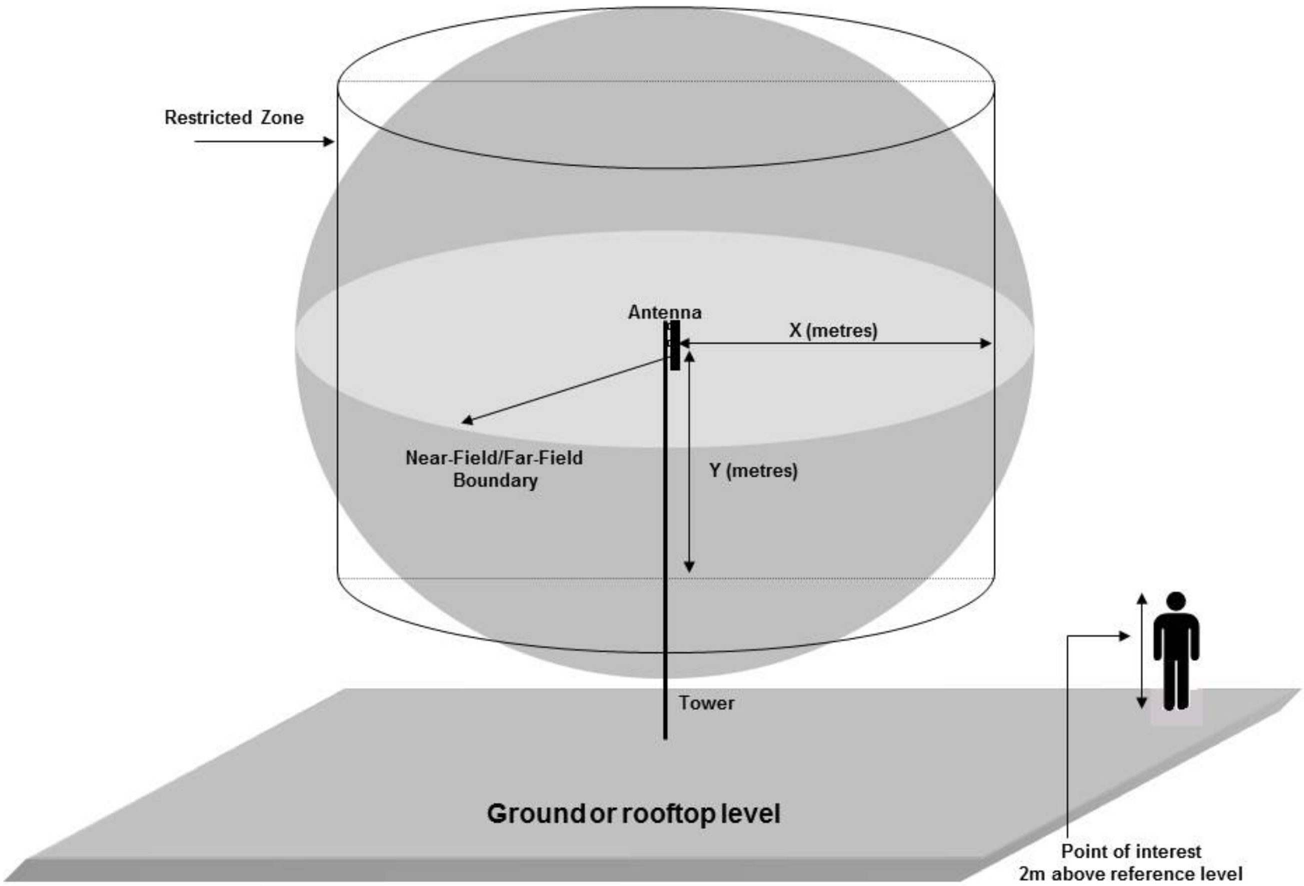

Figure 5 — If the near-field/far-field boundary (sphere) and the restricted zone (cylinder) intersect, the overall non-exemption zone is the combination of the sphere and cylinder

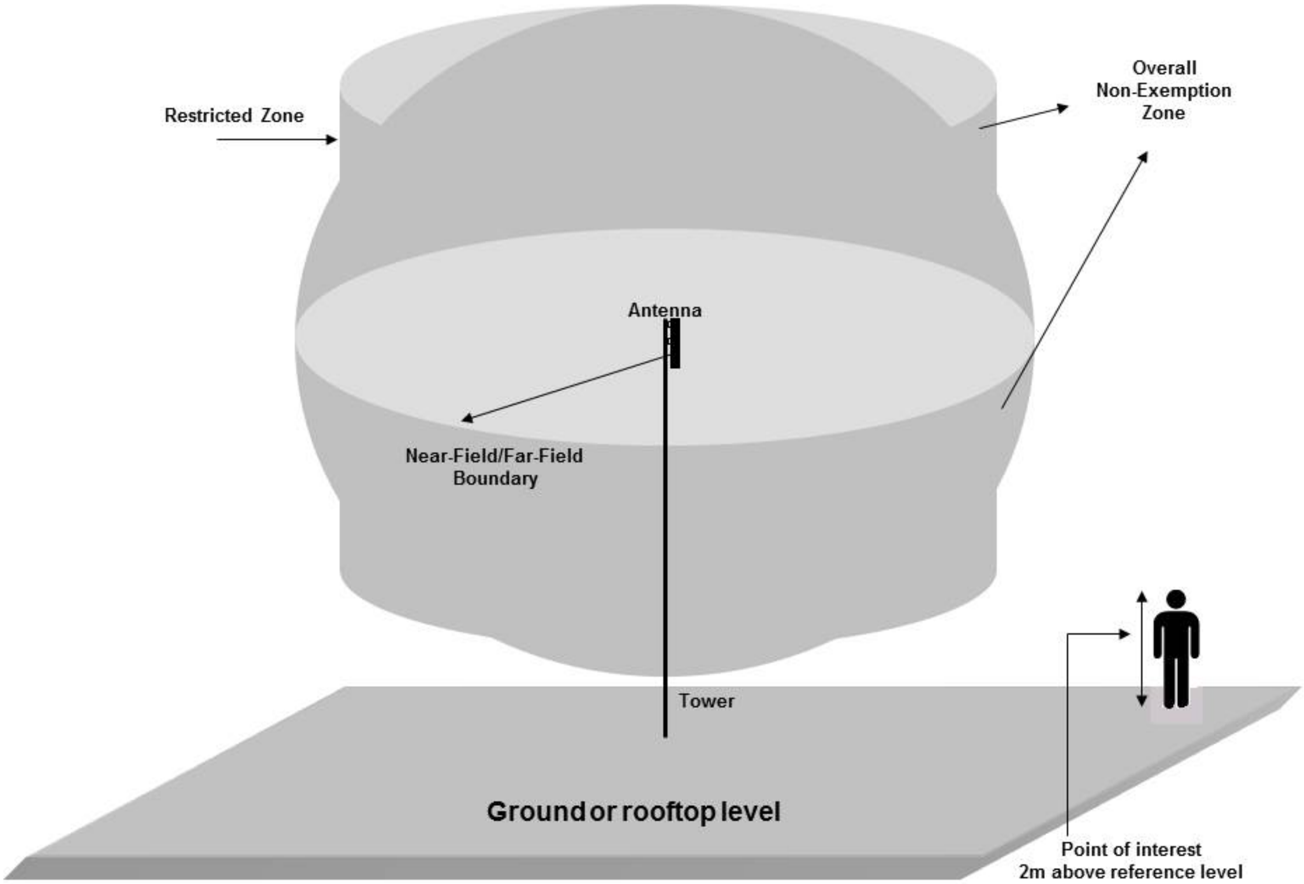

Figure 6 — The overall non-exemption zone is the combination of the sphere and cylinder

Figure 7 shows a scenario where the public access is within the overall non-exemption zone, implying that the methodology fails to demonstrate compliance. In this scenario, a detailed analysis is required to determine whether the site is in compliance. As result, it is necessary to proceed to Step 3 (Section 3.0) of the evaluation process.

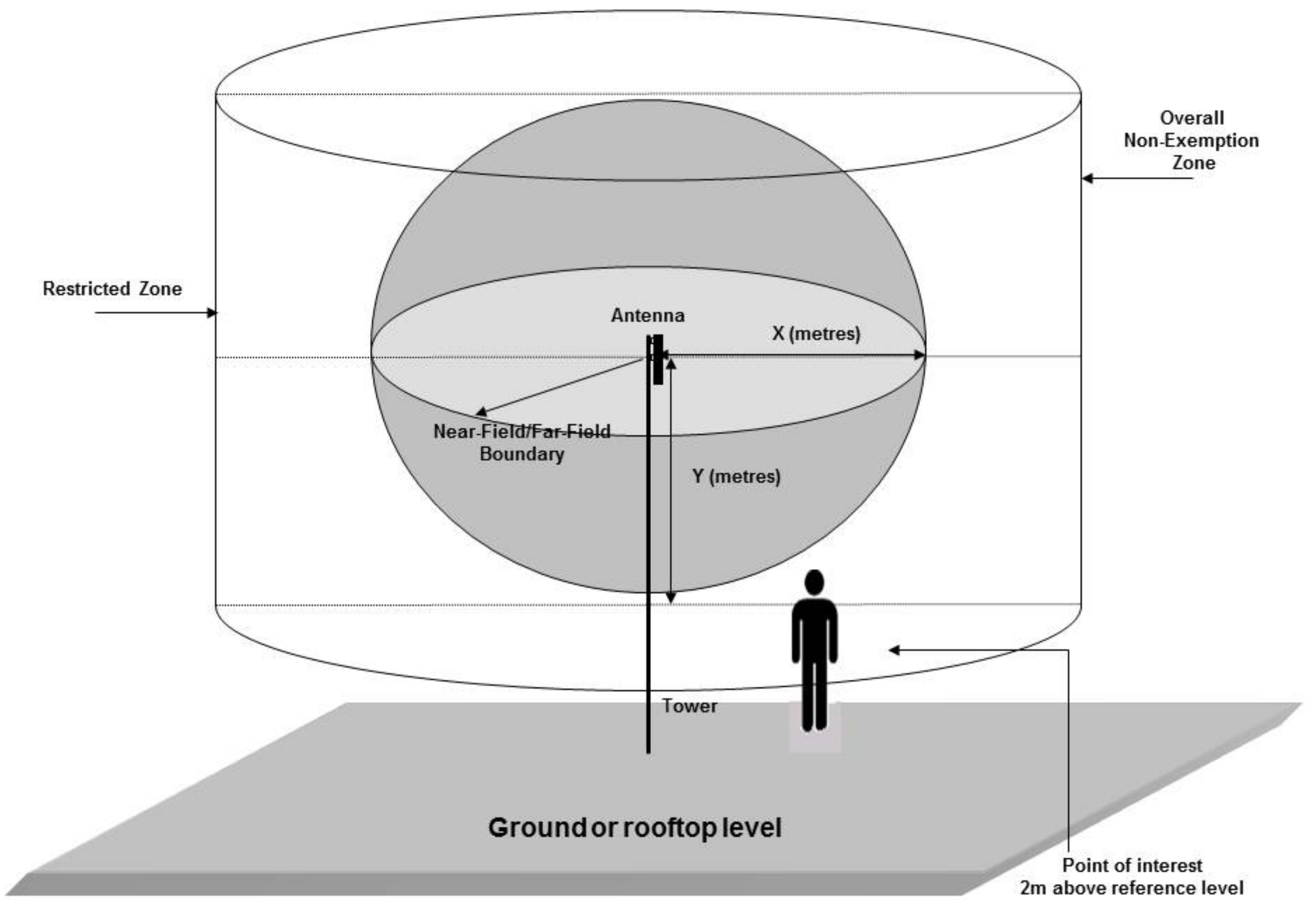

Figure 7 — Compliance is not demonstrated because the point of interest is located in the non-exemption zone

For more complex situations where several antenna towers are installed in the vicinity of a location of interest, a detailed analysis, based on sound engineering practices, is required. In this instance, the contribution of each antenna must be considered. Complex analyses can be performed using spreadsheets or computational modeling software.

3.2 Antenna Gain

Antenna gain G varies as a function of the off-axis angle, both horizontally and vertically. For the purpose of the simplified evaluation process outlined in Section 3.0, Step 2, a simple approach has been selected where the actual antenna patterns are not taken into consideration, neither are the mechanical nor the electrical tilts of the antenna. As such, the antenna's main beam is assumed to be pointing into the horizon. See Annex A, under "Power Density Analysis," for a detailed explanation of how these parameters can be taken into consideration.

As mentioned in Section 3.1, the antenna will be considered omnidirectional for the purpose of the evaluation of the restricted zone around the antenna. As such, the normalized numerical horizontal antenna gain is set to one (1). Studies of several antennas at various frequency bands have shown that the normalized numerical vertical antenna gain of radiocommunication antennas can be approximated and simplified into two functions: $\cos(\alpha)$ variation for frequency band of 30 to 54 MHz, and $\cos^3(\alpha)$ variation above 54 MHz where α is the vertical depression angle between the horizontal radiation plane and the direction of the observation point (**Note:** This simplified evaluation process was not validated for frequencies below 30 MHz).

In symbolic terms, for a simple situation where no tilt is applied, this can be shown as:

$$G(\alpha,\theta) = G_{\max} \times G_v(\alpha) \times G_h(\theta) = G_{\max} \times G_v(\alpha) \times 1 = \begin{cases} G_{\max} \times \cos(\alpha) & 30\,\text{MHz} \le \text{f} \le 54\,\text{MHz} \\ G_{\max} \times \cos^3(\alpha) & 54\,\text{MHz} < \text{f} \end{cases}$$

Where:

$G(\alpha, \theta)$ represents the antenna gain in the direction of the observation point
α is the vertical depression angle (°) (see Figure 8 for situation where no tilt is applied)
θ is the horizontal discrimination angle from the antenna main beam (°)
G_{max} is the maximum antenna gain
$G_v(\alpha)$ is the normalized numerical vertical antenna gain as a function of cosine ($0 \le G_v(\alpha) \le 1$)
$G_h(\theta)$ is the normalized numerical horizontal antenna gain ($0 \le G_h(\theta) \le 1$). *Note: As the antenna is considered omnidirectional,* $G_h(\theta) = 1$.

$\cos(\alpha)$ can be expressed as $\frac{X}{\sqrt{X^2+Y^2}}$ or $\frac{X}{R}$, where $R = \sqrt{X^2+Y^2}$ is the distance from the antenna centre to the observation point (see Figure 8).

See Annex A, under “Power Density Analysis,” for a detailed explanation of more complex situations where mechanical and electrical tilts are applied and the antenna pattern is taken into consideration.

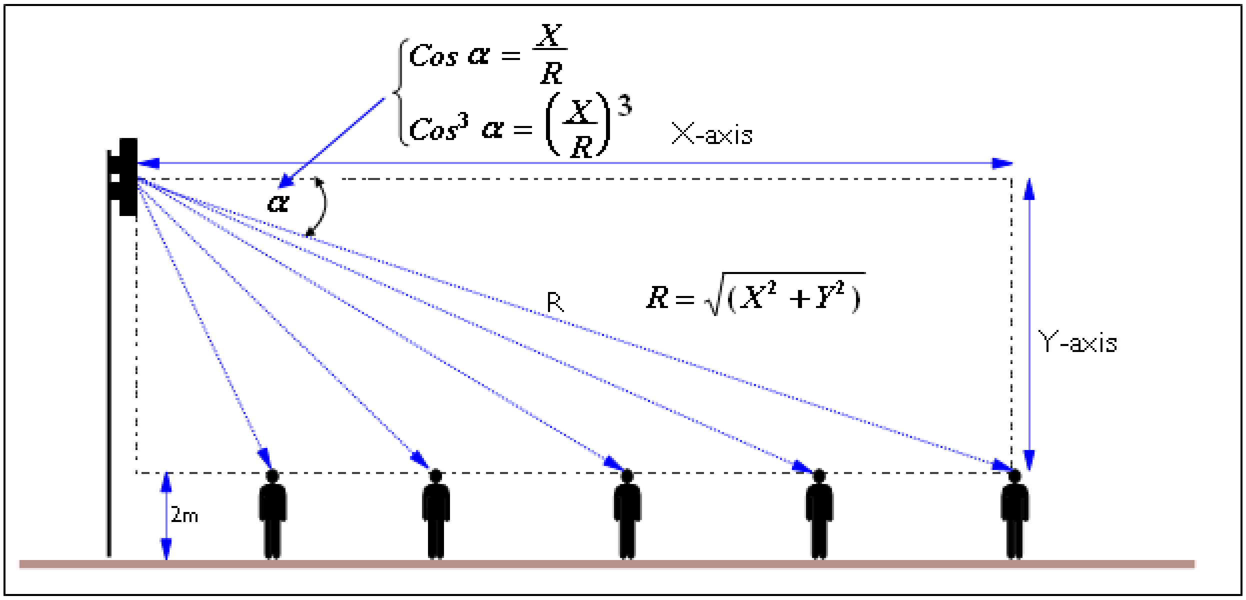

Figure 8 — Antenna gain as a function of cosine (with no tilt applied)

3.3 Reflection

Reflection is considered in all cases. In this situation, it is assumed that the observation point is at 2 m above the reference level, that is, the ground level or rooftop level. The ground wave reflection used is based on a survey conducted for the U.S. Federal Communications Commission (FCC), which shows that the indirect waves contribute, on average, an additional 60% to the direct beam. Therefore, reflection is taken as 60%. That is, the field strength of the reflected electric waves is assumed to be 60% of that of the direct waves at any point of observation (Gailey, P.C., and Richard A. Tell, *An Engineering Assessment of the Potential Impact of Federal Radiation Protection Guidance on the AM, FM, and TV Broadcast Services,* U.S. Environmental Protection Agency, April 1985). As further detailed in Annex A, the propagation model using this simplified reflection contribution is called modified free space propagation.

3.4 Single Service/Multiple Services and the Radio Environment

For the single service cases (single frequency band), such as a simple tower or single antenna installation on rooftop, with a land mobile, cellular or Personal Communications Service (PCS) antenna, the e.i.r.p. is the summed e.i.r.p. of all the transmitters and/or channels.

For the multiple service cases (multiple frequency bands), such as a combination of land mobile, cellular and PCS antennas, a detailed analysis technique is required, using sound engineering practices that take into consideration the contribution of each antenna at the site. However, for the purpose of this document, a worst-case scenario approach which affords the greatest protection to the public (for tower sites and some very simple rooftop sites) can be used, employing a conservative approach. For this approach, the e.i.r.p. values can be summed and applied to the centre of the lowest mounted antenna, which is assumed to be the antenna with the greatest far-field distance. The electrical field strength or power density at the point of interest (the observation point) is assessed against the lowest value of the SC6 limit of the frequency bands in question.

Nearby transmitting antennas, other than those at the site being studied, can also affect the evaluation, especially if they are high-power. Therefore, it is important to assess the radio environment when analyzing compliance. Mathematical predictions and field measurements have demonstrated that wireless stations beyond 100 m are shown to have a negligible impact on the overall exposure level. For broadcast stations, close attention should be paid to those within 1 km of the proposed site. If it is suspected that there are nearby stations that may increase RF levels at the site being studied, those stations must be taken into account in a detailed analysis (see Section 3.0, Step 3).

4.0 Non-Exemption Zone

As indicated in Section 3.1, the overall non-exemption zone is derived by taking into account both the far-field boundary and the restricted zone (which is based on 50% of the applicable SC6 limit for uncontrolled environments). For a given e.i.r.p. and antenna size, the point of interest **must** lie in the far-field **and** outside the restricted zone. If the point of interest falls **inside** the overall non-exemption zone, then more sophisticated methods must be used to evaluate compliance (see Section 3.0, Step 3).

Table 1 shows the formulas used to determine the near-field/far-field boundary. Refer to Section 3.4 before applying to sites with multiple antennas.

Table 1 — Near-field/far-field boundaries

For electrically small antennas ($D \leq \lambda$)	$R_{\textit{far-field}} = \lambda/2\pi$
For electrically large antennas ($D > \lambda$)	$R_{\textit{far-field}} = ½D^2/\lambda$

Where: D is the largest dimension of the antenna (m),
$R_{\textit{far-field}}$ is the distance from the radiation centre to the near-field/far-field (m) boundary,
and
λ is the wavelength (m) [$\lambda = c/f$, where c is the speed of light ($3x10^8$m/s) and f is the operating frequency (Hz)].

Example: *For a cellular antenna, with length 1.22 m at 875 MHz:*
$D=1.22$ *m*, $\lambda = 0.34$ *m*, $D>\lambda$, *therefore* $R_{\textit{far-field}} = ½D^2/\lambda = 2.17$ *m*

5.0 Conclusion

This technical note proposes an evaluation tool that can be used to quickly assess radio frequency exposure compliance with Health Canada's SC6 guideline for simple antenna sites. The method applies to single antenna sites, but can also provide a conservative assessment for multiple antennas, simplifying the evaluation process. However, this method in not recommended for detailed radio frequency compliance analysis. For such cases, use techniques that are based on sound engineering practices that take into consideration the contribution of each antenna at the site.

References

1. Health Canada. *Limits of Human Exposure to Radiofrequency Electromagnetic Energy in the Frequency Range from 3 kHz to 300 GHz − Safety Code 6*

2. Health Canada. *Technical Guide for Interpretation and Compliance Assessment of Health Canada's Radiofrequency Exposure Guidelines*

3. Industry Canada. Broadcasting Procedures and Rules BPR-1, *General Rules*

4. Industry Canada. Client Procedures Circular CPC-2-0-03, *Radiocommunication and Broadcasting Antenna Systems*

5. Industry Canada. Client Procedures Circular CPC-2-0-20, *Radio Frequency (RF) Fields — Signs and Access Control*

6. Industry Canada. GL-01, *Guidelines for the Measurement of Radio Frequency Fields at Frequencies from 3 kHz to 300 GHz*

7. Industry Canada. GL-08, *Guidelines for the Preparation of Radio Frequency (RF) Exposure Compliance Reports for Radiocommunication and Broadcasting Antenna Systems*

Annex A — General Antenna Theory

Antenna Field Regions

Antennas are grouped into two categories as defined in Health Canada's Technical Guide: electrically small and electrically large antennas. Electrically small antennas are defined as those where D, the largest dimension of the antenna (usually taken as the length), is less than the wavelength of the recommended operating frequency (D < λ). Electrically large antennas are defined as those where the largest dimension is greater than the wavelength of the recommended operating frequency D > λ.

At close proximity to an antenna, the characteristics of electromagnetic fields are unpredictable and the E-field can dominate at one location, while the H-field can dominate just a few centimetres away. Predictions are very difficult in this region and antenna engineers have defined boundary regions to categorize the behaviour/characteristic of electromagnetic (EM) fields as a function of distance from the radiator. Reflection is another characteristic that adds to the complexity. All waves experience reflections, and EM waves are no exception. Further to its research, the U.S. Federal Communications Commission (FCC) recommends that, for the reflected wave, the electric field strength be assumed to be 60% of that of the direct waves at any point of observation.

In general, the space surrounding an antenna is divided into field regions defined as: near-field region (reactive/evanescent near-field), radiating (Fresnel) near-field region, transition zone (intermediate-field region) and the far-field (Fraunhofer) region (see Figure A1).

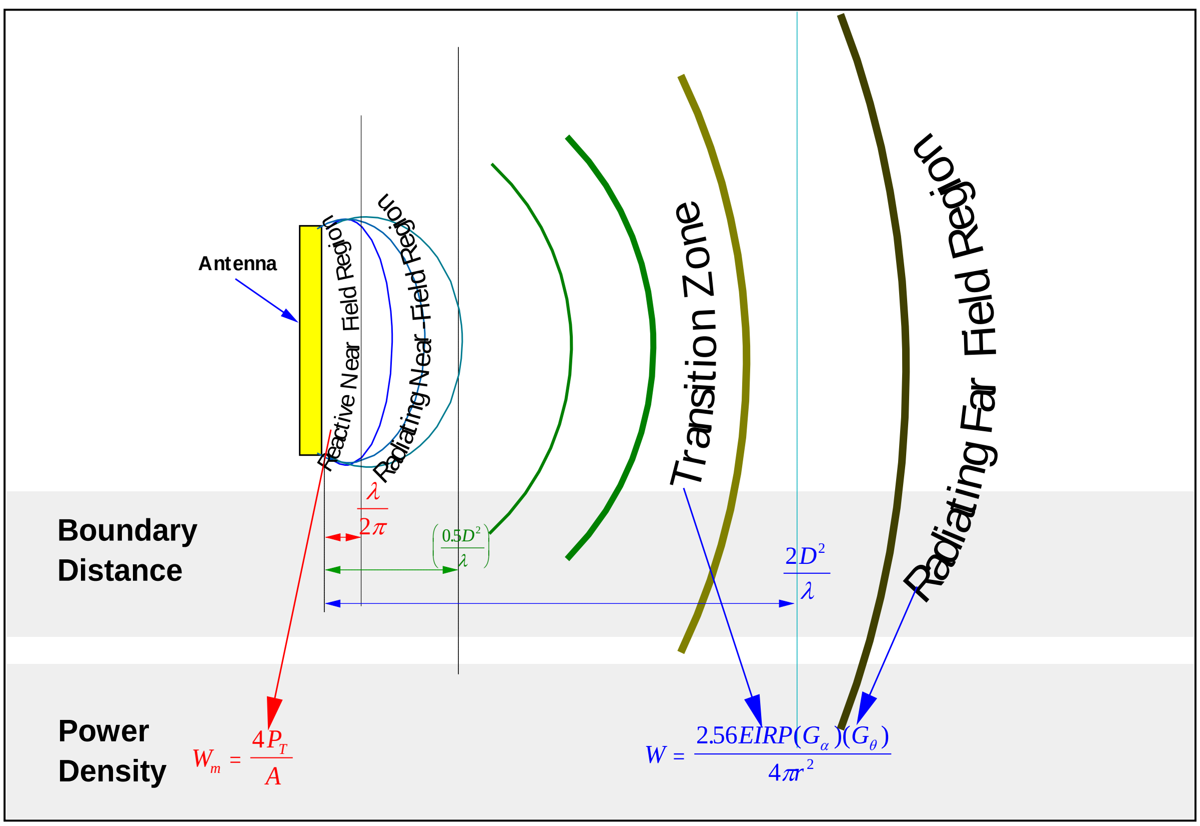

Figure A1 — General antenna field regions

Reactive near-field region – This is sometimes referred to as the evanescent (fading quickly) region and is the space immediately surrounding the antenna or leakage source, where the reactive (stored energy) components predominate and energy is stored in the field. In this region, the E and H fields are not orthogonal. Therefore, the impedance (Z) is not 377 ohms, but rather a complex impedance. However, the mathematical relationship of Z=E/H still applies. Z could be a small fraction of 377 ohms for a predominately magnetic field or many times 377 ohms for a predominately electric field. The region extends up to a distance of $\lambda/2\pi$ or 0.159 λ. For electrically small antennas (where, $D < \lambda$), the end of the reactive near-field region is also the boundary where the far-field region begins. In distance terms, it is: 1.6 m at 30 MHz, 32 cm at 150 MHz, 11 cm at 450 MHz, 5 cm at 875 MHz, and 2.5 cm at 1950 MHz.

Radiating near-field region – This is sometimes referred to as the Fresnel region. In this region, which starts at a distance from the antenna where the reactive near-field energy has diminished to an insignificant amount, the antenna gain and the angular distribution of the radiated field vary proportionally with the distance from the antenna. This is because the phase and amplitude relationships of the various waves arriving at the observation point from different areas of the antenna change with distance. For electrically large antennas ($D > \lambda$), this region extends from $\lambda/2\pi$ to $½D^2/\lambda$.

Transition zone (intermediate-field region) – For an antenna that is electrically small compared to the wavelength in question, the transition zone is considered to exist at distances anywhere between 0.1 wavelength and 1.0 wavelength from the antenna, essentially between the radiating near-field and the far-field regions. This region is comprised of a combination of the characteristics found in both the near-field and the far-field regions, but the far-field characteristics are becoming more evident moving outwards. The E and H fields are almost orthogonal (Z is almost 377 ohms). This region extends from $½D^2/\lambda$ to $2D^2/\lambda$ and, for the purpose of SC6, is assumed to be the region in which the far-field starts.

Far-field region (Fraunhofer region) – This region is also referred to as the Fraunhofer region. This region is sufficiently far from the source that the phase and amplitude relationships of the waves stemming from different areas of the antenna do not change appreciably with distance. The antenna gain and angular pattern are independent of distance, and the power density is inversely proportional to the square of the distance from the source. Although the transition from the reactive near-field region is a gradual one, in antenna design and engineering, the far-field region is commonly assumed to begin at a distance of approximately $2D^2/\lambda$ for electrically large antennas and extends to infinity (“D” being the largest linear aperture dimension and λ the wavelength at the frequency of interest). The E and H fields are orthogonal and Z=E/H=377 ohms. This region extends from $2D^2/\lambda$ to infinity, but the SC6 guideline recommends that it generally be taken as $½D^2/\lambda$ to infinity because it considers the transition region and the far-field region to be one.

Establishing the Antenna Boundary Regions

For electrically small antennas, the near-field/far-field boundary is given as:

$$\textit{Wavelength}\ \lambda = \frac{c}{f}$$

$$\textit{Near-Field (Reactive)/Far-Field} = \frac{\lambda}{2\pi}$$

Where: *f* is the operating frequency (MHz),
λ is the wavelength (m), and
c is the speed of light (m/s).

For electrically large antennas, the near-field/far-field boundary is given as:

$$\textit{Near-Field (Reactive)/Near-Field (Radiating)} = \frac{\lambda}{2\pi}$$

$$\textit{Near-Field (Radiating)} = \textit{Far-Field} = \frac{0.5D^2}{\lambda}$$

Example:

Antenna Type:	Broadband Dipole Array
Antenna Length (D):	1.22 m
Operating Frequency:	875 MHz

$$\textit{Wavelength}\ \lambda = \frac{c}{f} = \frac{3x10^8}{875x10^6} = 0.34\,\text{m}$$

$$\textit{Near-Field (Reactive)} = \frac{\lambda}{2\pi} = \frac{0.34}{2\pi} = 0.05 \text{ m (or 5 cm)}$$

$$\textit{Near-Field (Radiating)/Far Field} = \frac{0.5D^2}{\lambda} = \frac{0.5(1.22)^2}{0.34} = 2.17 \text{ m}$$

This is considered a large antenna, since D > λ.

Power Density Analysis

Power density predictions are made in both the near-field and the far-field regions of an antenna. The region where the prediction is being made will determine the type of prediction model used. Like field measurements, prediction in the near-field is a complicated undertaking and depends on the type of antenna. However, in the far-field region, the free-space model used is independent of the type of antenna. For multiple antenna/multiple frequency sites, it may not always be possible to determine where those regions lie. A situation could exist where, although the point of interest may be in the far-field of one antenna, it could also be in the near-field of another antenna at that same site, making the power density prediction difficult and complicated as the number of antennas increases.

In the near-field region, it is very difficult to determine the true power density. The reactive near-field (stored) energy decays very rapidly with distance and is completely decayed at a distance of several wavelengths from the antenna surface, as this region extends only up to $\lambda/2\pi$ (0.159λ). Therefore, the worst-case scenario is assumed (for land mobile (LM) and microwave (MW) application):

$$W = 4\frac{P_T}{A}$$

Where: W is the power density (W/m^2),
P_T is the transmitter power delivered to the antenna (W), and
A is the physical aperture area of the antenna (m).

Power density prediction in the radiating near-field region is possible using several established engineering models. However, the models chosen depend on the type of antenna being evaluated.

In the transition and far-field regions, the plane wave/free-space power density formula is commonly used. However, as per an FCC recommendation, a **modified free-space power density formula** is used to account for ground wave reflection. At the reception point, 2 m above the ground or rooftop level, the equivalent E-field includes both the direct and the reflected E-fields. The reflected portion of the E-field is taken as 60% of the direct E-field as per the FCC recommendation (reflection is not considered from objects surrounding the reception point, e.g. adjacent buildings).

$$\textit{Power Density } W = \frac{E_T^2}{Z}$$

At the reception point

$$E_t = E_{Direct} + E_{Reflected} = E_{Direct} + \Gamma E_{Direct} = E + 0.6E = 1.6E$$

$$W_M = \frac{(1.6E)^2}{120\pi} = \frac{1.6^2\left(\frac{\sqrt{30EIRP}}{r}\right)^2}{120\pi} = \frac{2.56\left(\frac{30EIRP}{r^2}\right)}{120\pi} = \frac{2.56EIRP}{4\pi r^2}$$

Where: W is the power density (W/m^2),
W_M is the modified free-space power density (W/m^2),
E_{Direct} is the direct electric field (V/m),
E_T is the total electric field (V/m),
Z is the free-space impedance (ohms), and
Γ is the reflection coefficient.

In addition to the changes to the free-space power density formula to account for ground wave reflection, a further modification is done to account for both the vertical and horizontal antenna patterns. The normalized numerical vertical and horizontal gains are introduced relative to the observation point as outlined in Figure A2.

Free-Space Formula *Modified Free-Space Formula*

$$W = \frac{P_T G}{4\pi r^2} = \frac{EIRP}{4\pi r^2} \qquad W_M = \frac{2.56 P_T G}{4\pi r^2} = \frac{2.56 EIRP}{4\pi r^2} = \frac{2.56 EIRP_{\max} G_v(\beta) G_h(\theta)}{4\pi r^2}$$

Where: W is the free-space power density (W/m^2),
W_M is the modified free-space power density (W/m^2),
P_T is the transmitter power fed into the antenna (W),
G is the numeric gain of the antenna with respect to an isotropic source,
EIRP is the effective isotropic radiated power from the antenna (W),
$EIRP_{max}$ is the effective isotropic radiated power with the maximum antenna gain (W),
β is the vertical angle of interest or the vertical discrimination angle (see Figure A2 below),
β is equal to (α – mechanical tilt – electrical tilt) where α is the vertical depression angle (°) (see Figure A2),
θ is the horizontal discrimination angle from the antenna main beam (°) (see Figure A2),
$G_v(\beta)$ is the normalized numerical vertical antenna gain for the angle of interest ($0 \leq G_v(\beta) \leq 1$),
$G_h(\theta)$ is the normalized numerical horizontal antenna gain ($0 \leq G_h(\theta) \leq 1$), and
r is the distance from the centre of radiation of the antenna to the test point (m).

Both β and θ are used to determine the vertical and horizontal gain reductions to be applied to $EIRP_{max}$ respectively.

Notes: In reference to Section 3.2 of the main document (TN-261) and using Figure A2 as a reference,

(i) the cosine approximation of the normalized numerical vertical antenna gain $G_v(\beta)$ can be generalized with the introduction of applied tilts as follows:

$G_v(\beta) = \cos(\alpha - \text{Mechanical tilt} - \text{Electrical tilt})$ where 30 MHz ≤ frequency ≤ 54 MHz
$G_v(\beta) = \cos^3(\alpha - \text{Mechanical tilt} - \text{Electrical tilt})$ where 54 MHz < frequency

(ii) $G_h(\theta)$ is equal to one (1) given that the horizontal antenna pattern is considered omnidirectional.

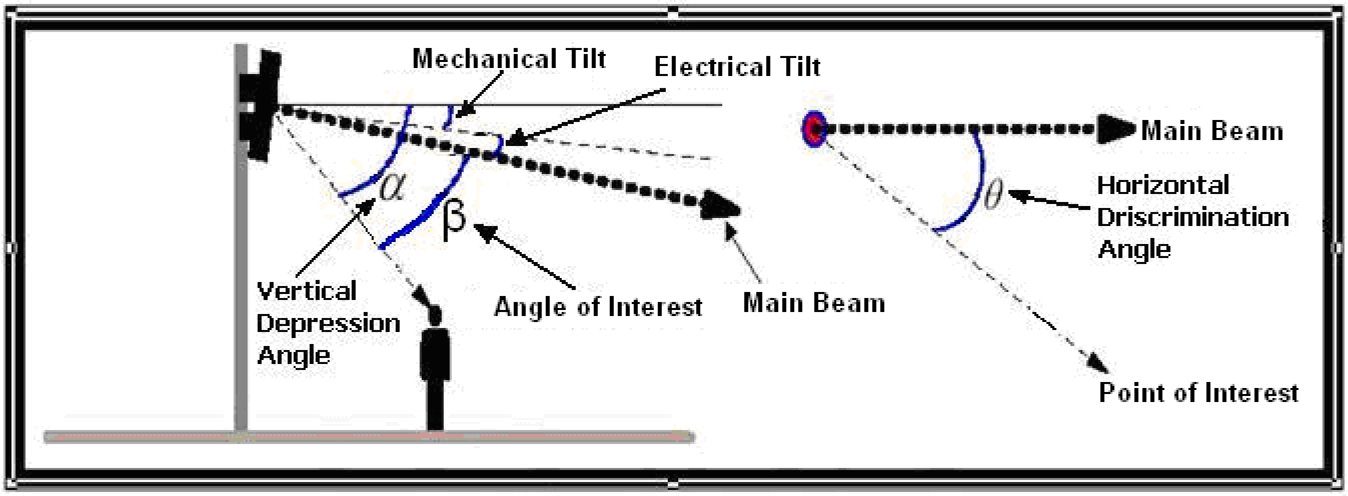

Figure A2 — Considering the horizontal and vertical discrimination angles with applied antenna tilts

There are numerous sources of error encountered when predicting field strength. One source is the transmitting antenna installation. This source of error is generated by the limited accuracy in the horizontal azimuth (for directional antennas) and in the mechanical tilt when the antenna is installed. The telecommunications industry estimates the level of accuracy to be in the order of approximately ±3° for the azimuth and about ±1° for the mechanical tilt. Essentially, this means that the angle to the point of interest for both the vertical (α) and horizontal (θ) angles may be either less than or greater than the calculated angle. It is important to consider these factors when predicting power density levels. To safeguard against this, a conservative approach of using both the horizontal and vertical envelope antenna patterns should be considered.

General Considerations

It is important to collect as much information as possible about the antenna installation being studied. Analyze the technical parameters of each transmit antenna, taking into consideration the antenna heights above ground and rooftop level, antenna type(s), mechanical tilt, electrical tilt, gains and radiation patterns (both horizontal and vertical), frequency range and transmit power fed to the antenna (or transmitter power and line losses).

Calculations

Calculations are generally done at 2 m above ground or rooftop level. For rooftop sites, look for the worst-case scenario to use as a test point by analyzing the rooftop layout diagram.

Steps to Consider

1. Define the near-field/far-field boundary for the antenna(s) being studied.
2. Determine if the test point lies in the near-field or far-field for each antenna.
3. If test point is in near-field, use appropriate model.
4. If test point is in far-field, use free-space formula (with cosine or antenna pattern) + 60% reflection (for electric field) at 2 m above ground or rooftop level only.
5. Determine the horizontal and vertical angles to the test point.

6. Factor in the electrical and mechanical tilt of the antenna.
7. Using the antenna pattern, estimate the normalized numerical H and V gains.
8. Factor in the field installation accuracy of antennas (in the horizontal plane ±3°, in the vertical plane ±1°).
9. Repeat the previous procedures for each TX antenna for a multiple-antenna site.
10. Calculate power density for each TX antenna at the test point.
11. Normalize the power density of each TX antenna at the test point, using SC6 limits with respect to the operating frequencies (for Uncontrolled Environment or Controlled Environment).
12. Sum the normalized power density values from all sources at the test point.
13. Repeat the procedure for several test points by moving the test point horizontally (in the main beam) away from the antenna under test.
14. Identify the hot spots, i.e. where the normalized power density = 0.5 or > 0.5 (in terms of percentage, = 50% or >50%). Those zones should be subject to further measurements or mitigation measures (see Step 3 of Section 3.0 of the main document, TN-261).

$$N_{SC6\%} = 100 \cdot \sum_{i=1}^{n} \left(\frac{W_i}{W_{SC6\_limit}} \right), \text{ with } W_i = \sum_{j=1}^{m} W_{j,i}$$

$$N_{SC6\%} = 100 \cdot \sum_{i=1}^{n} \left(\frac{E_i}{E_{SC6\_limit}} \right)^2, \text{ with } E_i = \sqrt{\sum_{j=1}^{m} E_{j,i}^2}$$

$$N_{SC6\%} = 100 \cdot \sum_{i=1}^{n} \left(\frac{H_i}{H_{SC6\_limit}} \right)^2, \text{ with } H_i = \sqrt{\sum_{j=1}^{m} H_{j,i}^2} \text{ and}$$

Where:
n is the total number of frequency components present at the test point
m is the total number of antennas
$W_{j,i}$, $E_{j,i}$ and $H_{j,i}$ are respectively the power density, the electric field and the magnetic field at the test point due to antenna *j* at the frequency component *i*.