EMF Pre-Assessed Equipment Configuration – Rotatable Beam Antennas for 50 MHz to 1.3 GHz

SCOPE

This Pre-Assessed Equipment Configuration guidance document (PAEC-2) forms part of the set of guidance provided by the RSGB on how radio amateurs can show that their station is compliant with the Ofcom UK amateur licence EMF condition [1] with respect to the ICNIRP 2020 guidelines [27].

It covers radio amateur stations using horizontally polarized rotatable antennas (typically Yagis) in the UK amateur bands from 50 MHz to 1.3 GHz inclusive.

It is intended for users who seek an alternative means to show compliance with fewer restrictions than achievable using the RSGB or Ofcom EMF Calculators that are intentionally biased to give conservative results.

It first establishes a minimum antenna height above which compliance is shown everywhere at ground level then, if needed, it specifies an EMF Exclusion Zone using a simplified or full approach to complete the compliance check.

For advanced level readers, the Annexes summarise the supporting research that used advanced computer modelling of thousands of equipment configurations. The resulting guidance is therefore based on detailed evidence and covers a wide range of amateur configurations.

Note that at the time of drafting, Ofcom were still finalising guidance with respect to frequencies below 110 MHz and this may lead to changes to the 50 MHz and 70 MHz guidance.

1 INTRODUCTION

Ofcom allows several alternative routes for radio amateurs to show that their station is compliant with the Ofcom UK amateur licence EMF condition [1] [28]. One of the simplest ways to check compliance is to use either the Ofcom [24] or the RSGB [25] EMF Calculators, but this involves a tradeoff: these simplified calculators may fail to show compliance in situations where a more accurate approach would succeed. Such situations may be quite common for UK amateur stations in built-up areas; hence the need for different and more accurate methods.

PAEC-2 applies the Pre-Assessed Equipment Configuration compliance route [28] to amateur VHF/UHF stations using directional beam antennas. It provides a more accurate approach to check compliance, based on establishing an EMF Exclusion Zone around your antenna, and then using it to identify locations where a person might be exposed above the general public EMF limits, if transmission were to take place while that person is present.

This report meets two different requirements. One is to document the PAEC-2 methodology in complete detail; the other is to offer step-by-step guides on how to apply the methodology in practice.

The Exclusion Zone concept is described in section 2. Section 3 describes how to perform a compliance check using the Exclusion Zone. Section 4 gives instructions on how to define the Exclusion Zone using a 'Simplified Approach' that should be sufficient for most amateur users, but at the expense of some restrictions in scope. Section 5 is the 'Full Version' that will provide a more accurate definition of the Exclusion Zone, at the expense of a little more effort on the part of the user.

For the more advanced reader, the extensive annexes summarise the technical background, the underpinning research, and provide additional guidance for less common equipment configurations. Examples are included throughout to help the reader understand how to apply the guidance.

For equipment configurations within its scope, PAEC-2 uses pre-assessed data from thousands of detailed computer models to define a clear and easily implemented EMF Exclusion Zone for any specific case. The more detailed modelling approach of PAEC-2 avoids much of the inbuilt conservatism of the Ofcom or the RSGB EMF calculators [24] [25], so the Exclusion Zones are generally smaller – sometimes much smaller – while at the same time being more accurate. The reasons why this is possible are outlined in Annex F.

Defining a smaller and more accurate Exclusion Zone can be highly valuable for amateur stations in built-up areas, where even differences of a few metres can determine whether operations are EMF compliant or not. This is especially true if unrestricted compliance can be demonstrated at ground level below and around the antenna, so the PAEC-2 methodology is designed to highlight and clarify this feature.

While this PAEC-2 document is intended for use in the UK, the research reported here has been performed in partnership with some members of the ARRL RF safety committee and so includes some US bands and power levels only relevant to US amateurs and US EMF regulations [12] [13].

It should be noted that the compliance basis for the Ofcom and RSGB (v1) calculators is ICNIRP 1998 [26] while the compliance basis for PAEC-2 is the ICNIRP 2020 [27] General Public (ICNIRP_GP) reference levels. Fortunately, the limits are very similar above 110 MHz (ICNIRP 2020 specifies additional local peak values to support the practical application of the whole-body average reference level).

For additional reading on EMF and avoidance of health effects, see [8], [9], [10] and other references in the bibliography at the end of the document.

2 EMF EXCLUSION ZONE

2.1 EMF Exclusion Zone concept

The aim of PAEC-2 is to show how to define the EMF Exclusion Zone around an antenna, for a given average RF power into the antenna and then to guide how to use the Exclusion Zone to show compliance with the Ofcom EMF licence condition. The EMF Exclusion Zone is defined as "**the region around the antenna within which a person might be exposed above the general public EMF limits, if transmission were to take place while that person is present**" (Ofcom [28]).

To ensure compliance, the licensee must therefore know where the boundaries of the Exclusion Zone are, relative to the antenna. To map out these boundaries, we compute EMFs at all locations around the antenna for the specified average power level. For each individual location, we then ask:

"If a person were to stand at this location while transmission is taking place, might they be exposed above the general public EMF limits?"

The answer defines whether the point in question is inside or outside of the Exclusion Zone; and so we map out the boundary of that zone in space.

The wording is important. "**While transmission is taking place**" comes from the definition above (Ofcom [28]). It acknowledges that, in the absence of any such person, no EMF exposure takes place; the situation is compliant by definition. It also places a responsibility upon the operator: either to confirm that no person "is or can be expected to be present"[1] within the Exclusion Zone; or else to cease or modify transmissions in order to achieve compliance.

The word **"stand"** is important because in PAEC-2 we always map EMF exposures by reference to **the specific point <u>upon</u> which a reference person is directly standing**. Normally this will be the local ground level or a floor level within a building, but the same definition also covers a person standing on a roof, on a ladder or even up a tree.

Having identified the person's foot-level as the reference point, we also consider the EMFs at points up to 1.8m higher,[2] because those values are needed to calculate the averaged whole-body exposure and the maximum local exposure as specified by ICNIRP (ICNIRP [27]). But after all that, it must be emphasized that those results are recorded against the reference point already defined: **the point <u>upon</u> which the person is directly standing**.

So, in even simpler terms, the boundaries of the Exclusion Zone are mapped out by repeatedly asking the question: **"Would it be OK for a person to stand upon this point?"** Unless the answer is an unqualified "Yes", that point must be within the EMF Exclusion Zone so the operator would need to take further action.

From a detailed mapping of the potential EMF exposure, we can then derive a much simpler set of dimensions for a practical Exclusion Zone.

[1] Ofcom provides extensive guidance on the meaning of that term, and suggest several acceptable means of confirmation (Ofcom [28]), (Ofcom [29])
[2] In discussions with the RSGB, Ofcom agreed a 1.8m tall reference person could be used in order that a compliance decision is possible for locations in the absence of a specific person.

2.2 PAEC-2 Exclusion Zone shape

Ofcom does not specify the shape of the Exclusion Zone. The main requirement is that the Exclusion Zone is well defined and appropriately managed.

For a beam antenna pointing in any one direction, the main beam is roughly cone-shaped, extending forwards and also above and below the plane of the antenna. Since it is assumed that the antenna will rotate through 360°, this cone then sweeps through a circular volume including all horizontal directions. This complex shape can be completely contained within a cylinder that then defines a simple, practical Exclusion Zone. The axis of the cylinder is always the pole on which the antenna is actually mounted.

Figure 1 shows the key dimensions needed to describe this shape and to apply it:

1. Height of antenna above horizontal reflecting surface (H_{ANT}) (see Annex G.4)
2. Radius of Exclusion Zone, the distance from the support pole to edge of the zone (R_{EZ})
3. Clearance height above ground to the lower edge of the Exclusion Zone (H_{CL})
4. For roof-mounted antennas and similar, it is also useful to know the distance below the antenna to the lower edge of the Exclusion Zone (D_{EZ}).

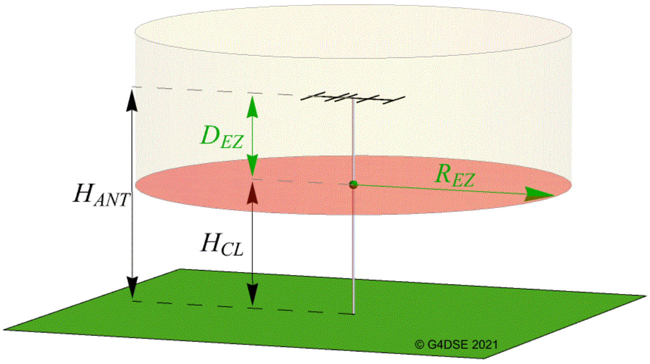

Figure 1–Representation of Exclusion Zone centred on the rotator pole. All locations are for points on which a person could stand.

The red disk in Figure 1 defines the base of the Exclusion Zone. To interpret this diagram, recall that the **boundaries of the Exclusion Zone are mapped as points at levels <u>upon</u> which a person could stand**, and that exposure of the rest of the body above that height has already been taken into account. **Do not include body height again in your own compliance check** – that would be double-counting.

Below the red disk, the 'vertical clearance height' H_{CL} includes all locations upon which it would be compliant to stand, either at ground level or on any kind of raised platform.

There is usually no need to define the upward extent of the Exclusion Zone. If needed, an approximation is that the Exclusion Zone extends up to H_{ANT} + (D_{EZ} - 0.9) metres (see 5.3).

3 SHOWING COMPLIANCE USING PAEC-2

This section describes the overall process of checking compliance. Sections 4 and 5 will provide more detail on defining your own specific Exclusion Zone.

3.1 Information needed to check compliance with EMF licence condition

To do a compliance check using PAEC-2, the following information is required:

- *Consistency with Pre-assessed Equipment Configuration* - For the PAEC-2 approach to be valid, you need to confirm the following:
  - your antenna is horizontally polarized (see G.3), is directed towards the horizon, and rotates 360 degrees about a vertical axis[3].
  - your antenna has a free-space forward gain ranging from a half-wave dipole with 2.15dBi to beams[4] with gains up to 17 dBi on 50 MHz and 70 MHz, 2.15dBi to 18.2dBi on 144 MHz, or 2.15dBi to 22.5dBi on 432 MHz and 1296 MHz.
- *Transmit power* –To evaluate the time-averaged power at the antenna, the RSGB calculator [25] takes you through entering transmit power, mode factor, transmit percent (within 6 min), and feeder losses. That is the power value to be used to establish the Exclusion Zone.
- *Band* – The PAEC database is partitioned according to the frequency band used. The precise frequency is not relevant for the compliance check.
- *Gain* – The free-space antenna gain expressed in dBi. Almost all antenna manufacturers and designers publish this data. Caution: at lower frequencies, manufacturers sometimes add a claimed "ground gain" of 6dB – the free-space gain is what is required here, so check against other antennas of similar boom length and subtract 6 dB if necessary.
- *Antenna height* (H_{ANT}) – To establish if the antenna is above a minimum required height, and also the evaluate the effect of ground, it is important to choose the correct value for H_{ANT}. Find the correct value of H_{ANT} from the following:
  a) For an antenna mounted on a ground-based mast or tower, or an antenna mounted above a sloping roof that does not need to be treated as a horizontal ground (see (b) below), the antenna height H_{ANT} is simply the vertical separation of the lowest antenna element with respect to ground.
  b) For an antenna mounted over a large flat roof, such as a communal or commercial building, the roof itself will need to be treated as a surrogate horizontal ground. H_{ANT} then becomes the vertical separation of the lowest antenna element to the flat roof surface. (Compliance checks on floors below the roof height will then be based on D_{EZ} – see Annex G.2, G.4.)
  c) For slightly sloping ground, consider the distance R_{EZ} from the centre of rotation in any direction that the ground rises and estimate the increase in ground height. H_{ANT} is then the vertical separation of the lowest antenna element to the highest ground level within the R_{EZ} (see Annex G.1, G.2).

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[3] A non-rotating antenna or an antenna with limited rotation is a different case, not considered in detail in PAEC-2. G.6 gives some ideas on how you might proceed.
[4] PAEC-2 does NOT apply to parabolic dishes, horns, and similar "aperture" antennas.

d) For vertically stacked arrays, or antennas such as quad-loops, H_{ANT} for the PAEC-2 compliance check is always measured to the lowest radiating part of the entire array – NOT the centre height (also see 5.3).

- *Antenna dimensions* – This information is only required when determining the Exclusion Zone using the full method. The physical size of an antenna affects the size of the Exclusion Zone. You will need reasonably accurate front element length, boom length, and the position of the rotator pole along the boom.

- *Locality plan/map* – If the antenna is located on or near buildings, then you will need to map the local area around the antenna showing any locations above ground level where people can be expected to be. The size of the area you may need to detail is determined after you have established the radius of the Exclusion Zone.

  Where necessary, you will need heights of any relevant locations (see 2.1), either above ground or their vertical distance below the antenna, as well as the horizontal distances from the antenna mast.

3.2 The compliance check process

Compliance with the Ofcom EMF licence condition is shown and recorded following a set of checks that together form the compliance check. Ofcom also requires that a record is kept showing how the licensee has shown compliance. In this section we outline how a compliance check can be completed using PAEC-2. The basic compliance check process is described first, and a more detailed flow chart is provided in Figure 2 that covers many more "what ifs?" by reference to relevant sections and annexes where more detailed guidance is available if needed.

You need first to collect the information as specified in section 3.1, which also confirms that your equipment configuration is consistent with the pre-assessed equipment configuration for PAEC-2.

You then should find the minimum height (H_{MIN}) for unconditional compliance at ground level. The simplest graph is Figure D.1, but for a less conservative (but still valid) value you may use Figure 3.

If you have an open site[5] with a mast more than 60m from any building or other place that anyone will stand above ground level and your antenna is mounted above the minimum height (H_{MIN}), you have shown compliance and don't need to do more than just retain a record of the compliance check – you're done!

If you don't have an open site or there are buildings within 60m of the antenna, then you will need to establish the Exclusion Zone. We recommend using the simplified approach (see section 4) that simply involves looking up the values for the Exclusion Zone defined in the series of Figure 3 plots.

Once you have established the Exclusion Zone, follow the guidance in section 3.3 to check compliance. If compliance is shown, then keep a record of the compliance check and you're done.

If you find that you have not yet shown compliance, then that means that you need to take some further action such as:

- It is clearly best to modify your station so that it complies without additional measures. In most cases, increasing the antenna height is probably the most effective measure to look at first.

- If you are prepared to reduce your transmit power, that will also be effective.

[5] If your antenna is above the recommended minimum height, then for the antenna gains covered by PAEC-2 and for maximum UK licence power, 60m is the greatest distance that might need to be considered.

- If the Exclusion Zone shown by the simplified approach is only marginally larger than would show compliance, you might also try using the full approach (section 5) for defining the Exclusion Zone in case that now shows compliance.

Finally, if there are still places within the smallest demonstrable Exclusion Zone where a person might be exposed above the general public EMF limits if transmission were to take place while that person is present, you will then need to define how you will prevent this from happening - either through stopping people accessing those locations when transmitting or by ensuring that you don't transmit if people are present. In whatever way you choose to achieve this, you will then need to keep a record of the compliance check and any measures necessary to comply.

As a general guide, if it is easy to show compliance, then your station is fine. If you have to work hard to show compliance, then this might suggest that you raise the antenna or take some other action to improve your station. If you really are constrained in what you physically can do, then of course it is valid to use an improved (more involved) approach to show compliance.

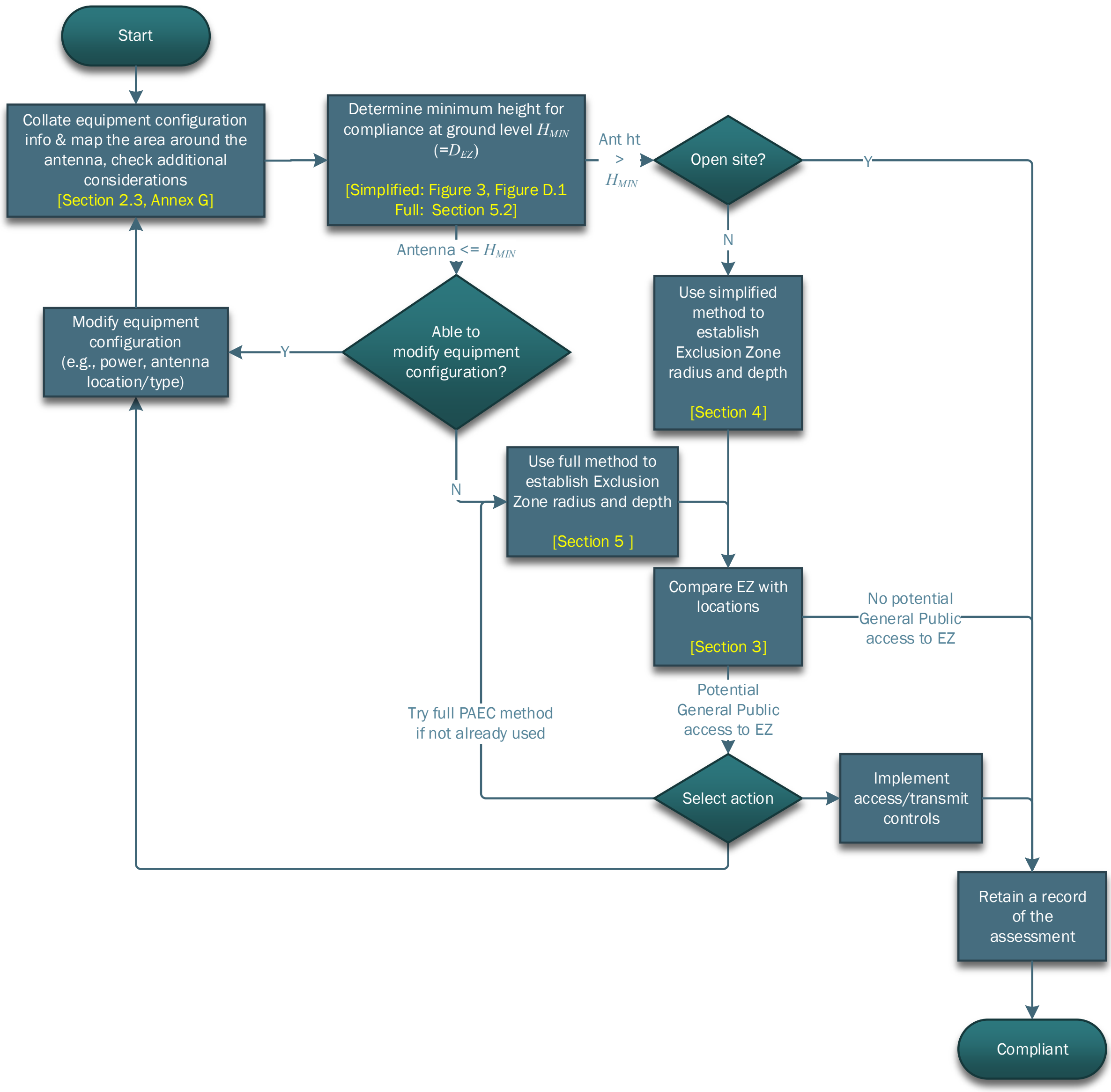


Figure 2–Compliance checking process

3.3 Compliance checking using the Exclusion Zone and plan of antenna locality

As stated in section 2.1, the key thing to check is where people can stand. The compliance interpretation using the Figure1 Exclusion Zone simply uses the following conditions/tests:

1. Any radial distance from the pole beyond R_{EZ} is always compliant, irrespective of height.
2. If the red disk in Figure 1 is above ground level, then compliance is automatic for all locations at ground level where persons could be standing.
3. If the red disk in Figure 1 intersects a building or rising ground within the radial distance R_{EZ}, any floor or ground levels below the disk will be compliant but the levels within the Exclusion Zone (i.e., within height H_{ANT} - D_{EZ} to H_{ANT} + D_{EZ} - 0.9 m and within R_{EZ} m from the pole) where a person might be standing as not been shown to be compliant.

Remember that the Exclusion Zone is with respect to points on the standing level. For example, if the antenna is at a height of (H_{MIN} + 1m) above ground, the Exclusion Zone under the antenna extends down from the antenna to just 1m above ground. However, compliance is still achieved for anyone standing at ground level.

Considering condition 3 listed above, the same reasoning applies to antennas mounted in a roof space or above a roof. If the distance down from the antenna to the relevant floor level below is greater than D_{EZ} then compliance is shown for that floor.

4 SIMPLIFIED APPROACH TO SPECIFY THE EXCLUSION ZONE

In this section, we use a simple look-up approach to determine the dimensions of the Exclusion Zone subject to some relatively minor restrictions and assumptions defined in Annex D. The Exclusion Zone specified with this approach will be a little bigger than strictly needed. (See Annex E for a study comparing Exclusion Zone sizes obtained using alternative methods).

The key restriction on applicability of the simplified approach is that it can only be used for horizontally-polarized antennas with their lowest radiating element mounted higher than the relevant minimum height H_{MIN}. This is where the red disk from Figure 1 is just above ground level so that compliance has already been proven for a person standing anywhere at ground level.

To find the Exclusion Zone dimensions (Figure 1), you need the frequency, forward gain, and average power at the antenna from section 3. Then:-

- Find the relevant Figure 3 for your band.
- Find the nearest power (labelled on each plot) plot *above* your average power then read off the value of D_{EZ} from the plot label and determine R_{EZ} for your antenna gain.
- The minimum antenna height (H_{MIN}) for this simplified approach is D_{EZ}. Check that the antenna height is above H_{MIN} (i.e., $H_{ANT} > H_{MIN}$ where $H_{MIN} = D_{EZ}$). If it is not, then unless you modify the equipment configuration (see section 3.2), this simplified approach is not valid.
- The radius of the Exclusion Zone is R_{EZ} measured horizontally from the centre of rotation, the pole vertical axis.
- The height of the Exclusion Zone extends down from the lowest antenna element by the distance D_{EZ} for the relevant band and power level (and up from the highest antenna element by D_{EZ} – 0.9m).

The Exclusion Zone dimensions are then available for use in the PAEC-2 compliance checking process (see section 3.2).

Example 4:1 144 MHz, 12 dBi antenna at a height of 8m with 90W average power

From Figure 3C the red 100W plot shows the D_{EZ} to be 4.3m. This means that the minimum antenna height for which this simplified approach may be used to show compliance at ground level is H_{MIN} = 4.3m. Since the actual height (H_{ANT}) of 8m is above this minimum value, the simplified approach is confirmed to be valid.

Therefore, the lowest part of the exclusion zone (H_{CL}) is 8m – 4.3m or 3.7m above ground. If the antenna is on a standalone mast, then compliance is shown for anywhere at ground level.

From Figure 3C track vertically up from 12dBi as far as the red 100W plot and then across to the vertical axis to read the Exclusion Zone radius R_{EZ} = 9.4m.

If the mast is more than 9.4m away from any place where a person may stand, then compliance has been shown.

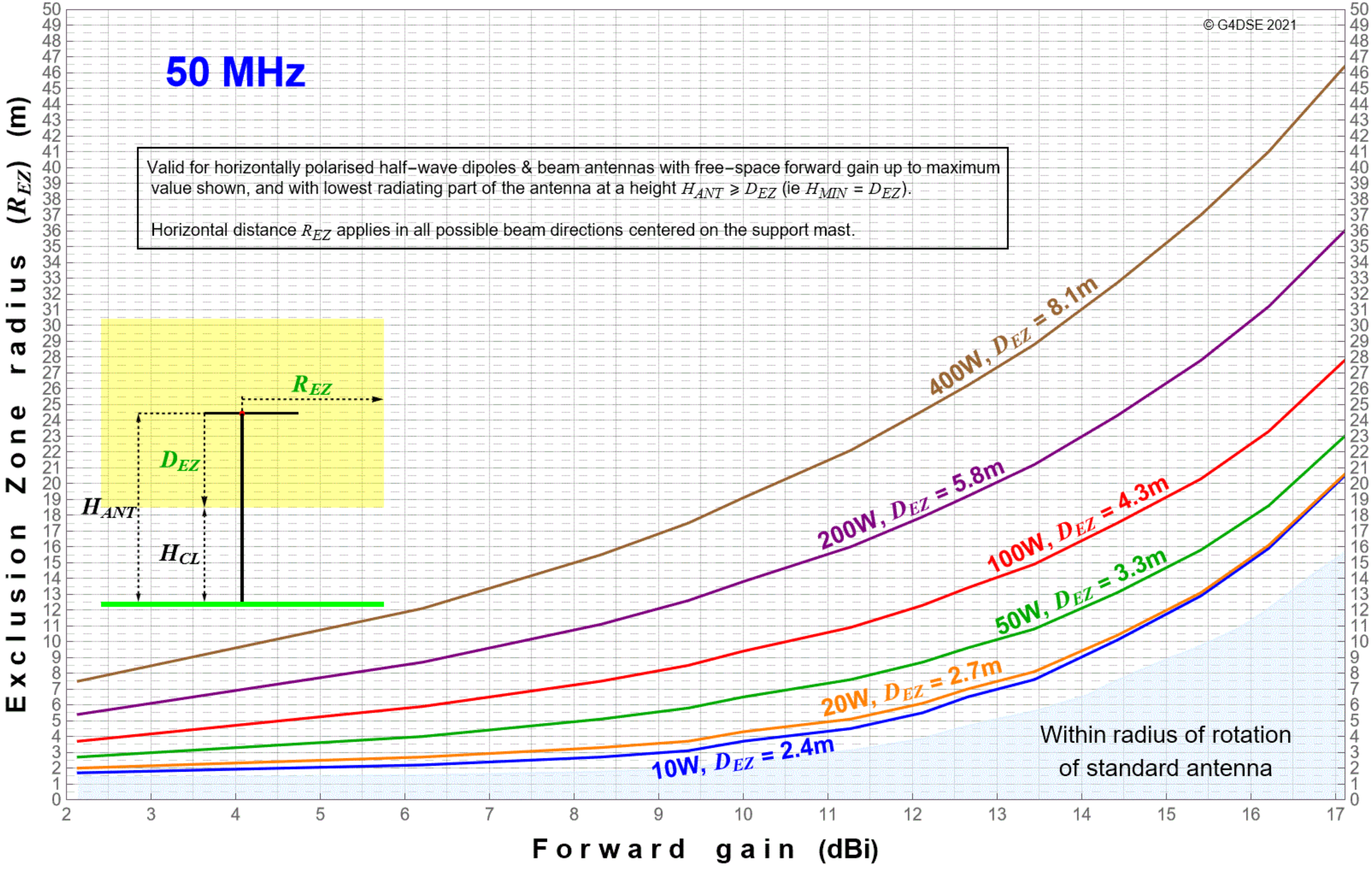


Figure 3A–Exclusion Zone for antennas mounted higher than $H_{MIN} = D_{EZ}$ (50 MHz)

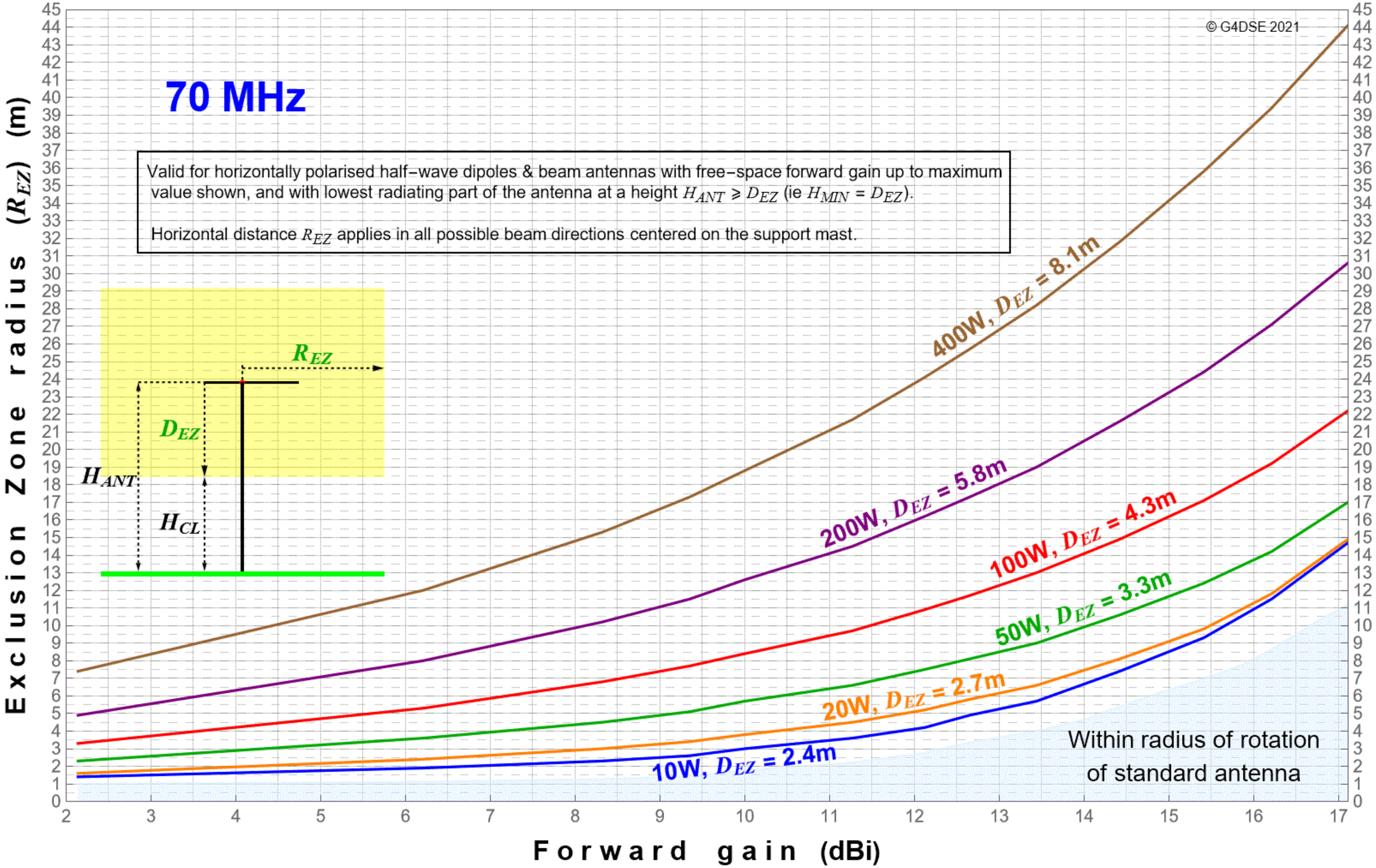


Figure 3B–Exclusion Zone for antennas mounted higher than $H_{MIN} = D_{EZ}$ (70 MHz)

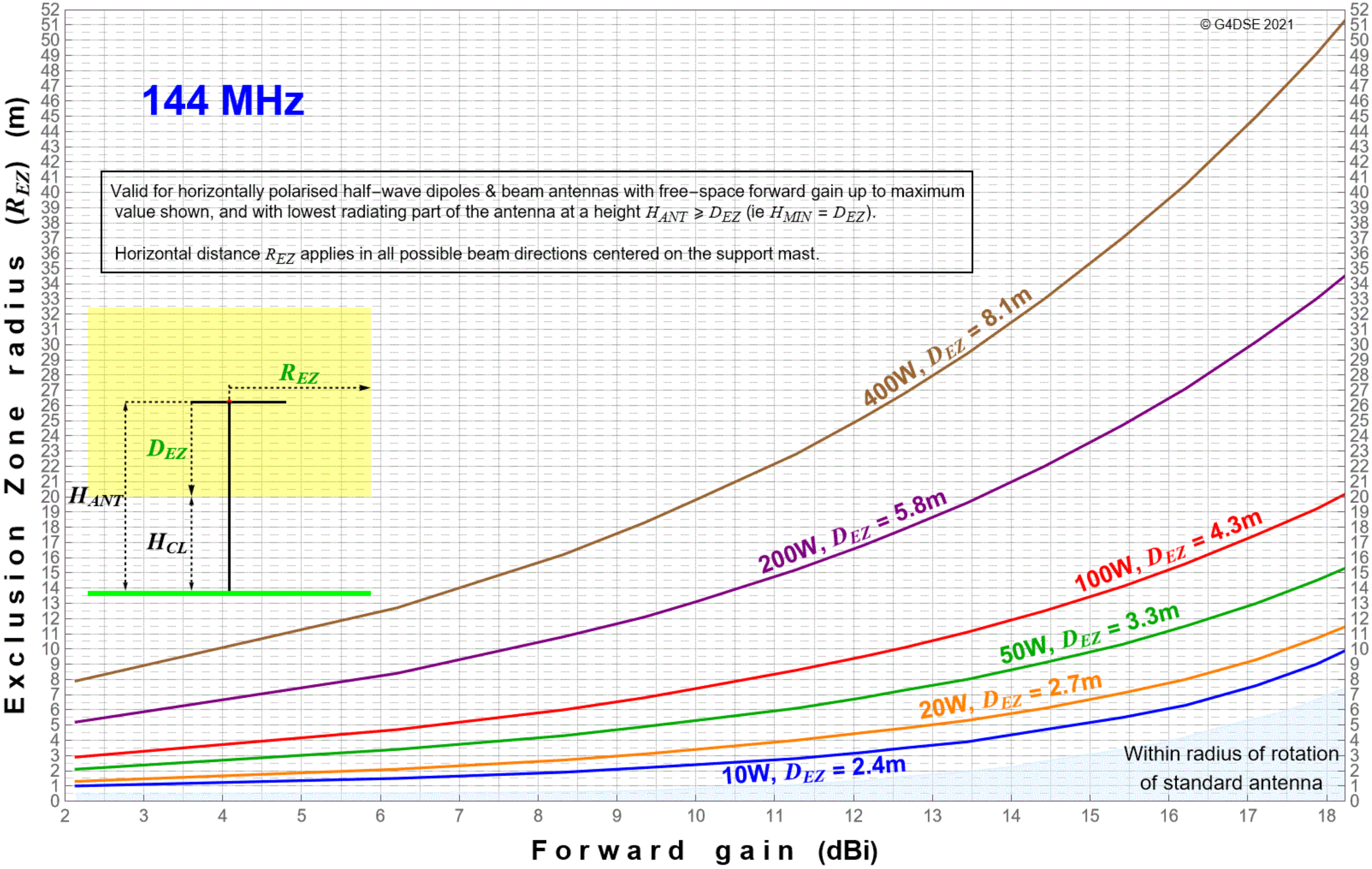


Figure 3C– Exclusion Zone for antennas mounted higher than $H_{MIN} = D_{EZ}$ (144 MHz)

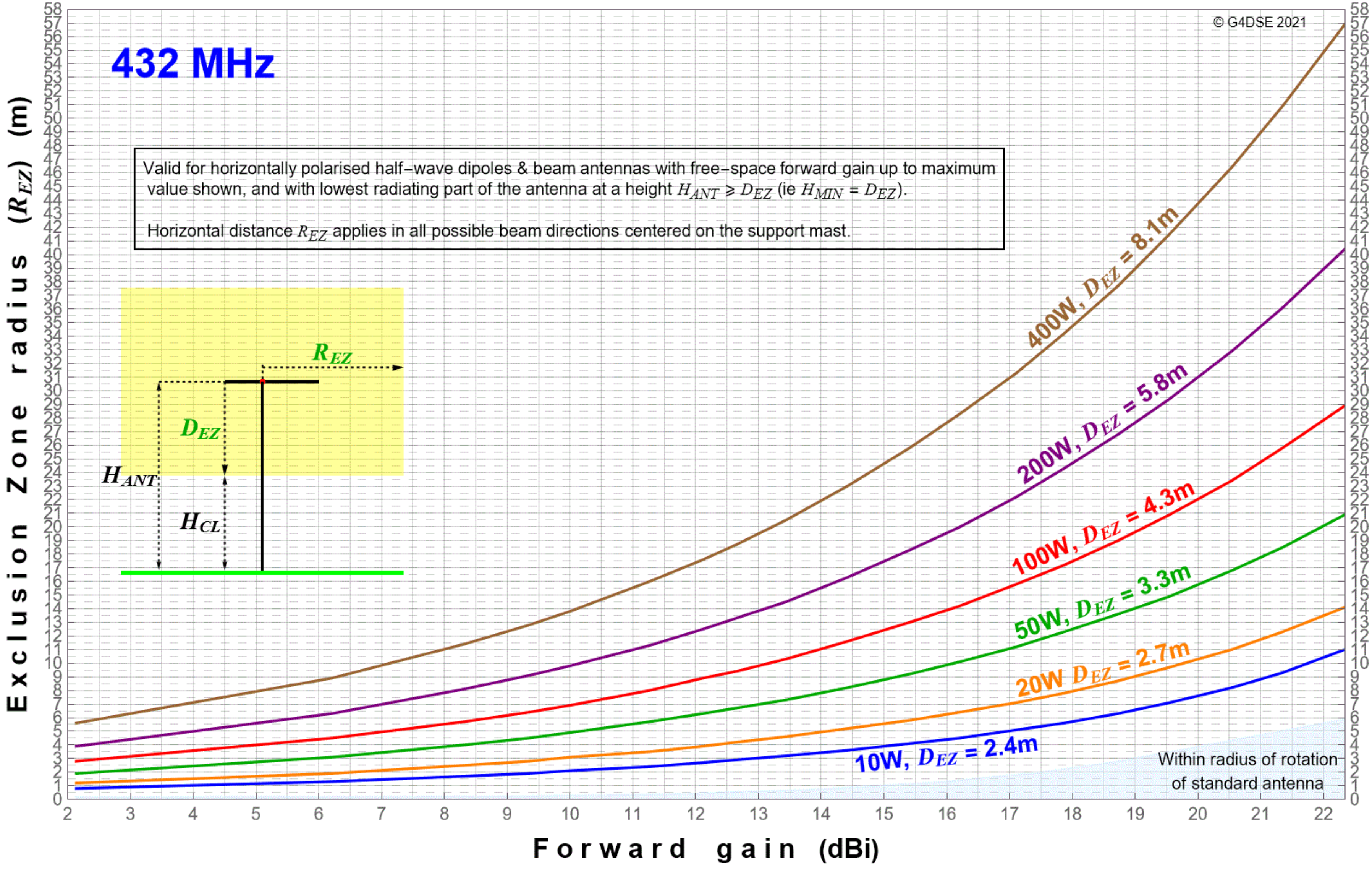


Figure 3D– Exclusion Zone for antennas mounted higher than $H_{MIN} = D_{EZ}$ (432 MHz)

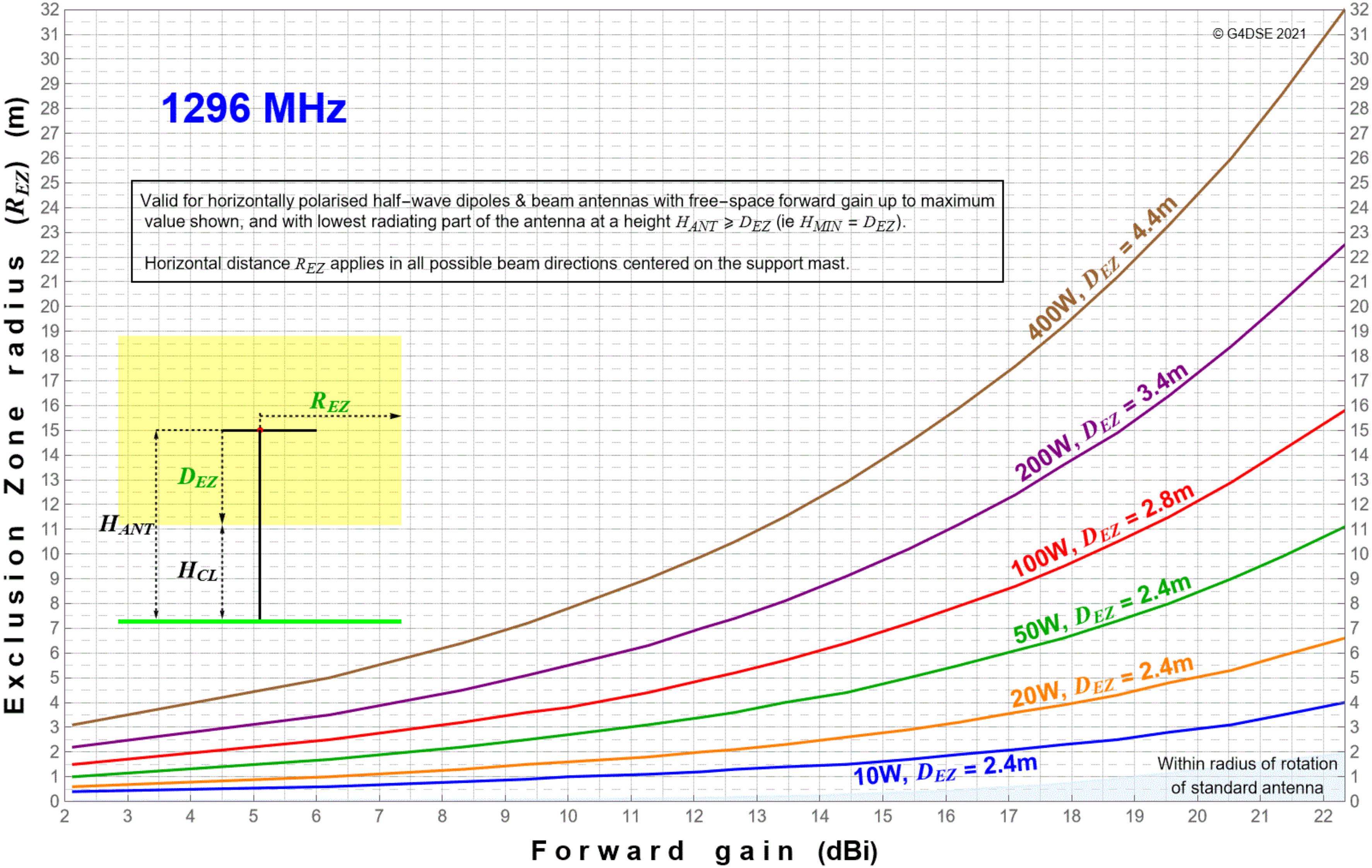


Figure 3E– Exclusion Zone for antennas mounted higher than $H_{MIN} = D_{EZ}$ (1296 MHz)

5 FULL APPROACH FOR THE DEFINITION OF THE EXCLUSION ZONE

In this section, we describe the step-by-step stages (using graphs derived from Annex C data) to define a minimum antenna height above which compliance is achieved at ground level. Then we describe how to implement an Exclusion Zone, including explanatory text with links to Annexes.

The differences between the full approach and the simplified approach (section 4) are that:

- for the minimum height the specific band data is used rather than the most conservative case, and,
- case-specific data is used to develop the Exclusion Zone radius – using the free space front compliance distance, the ground-influence factor, the position of the rotator pole along the boom, and the length of the front element.

These differences more closely align the full approach Exclusion Zone to the antenna being evaluated than the simplified approach, and as a result can deliver a smaller valid Exclusion Zone. (See Annex E for a comparison of Exclusion Zone sizes obtained using alternative approaches).

To find the Exclusion Zone dimensions (Figure 1) using the full approach, you need from section 3 the frequency, forward gain, average power at the antenna, the boom length, the position of the pole along the boom, and the length of the forward most element.

5.1 Approach overview

The minimum antenna height for compliance at ground level is determined and presented graphically based on over 4500 simulations as discussed in Annex C.

The Annex C modelling also shows that we can derive a factor to correct for the influence of ground on the forward compliance limit. This factor depends on the average transmit power, frequency band, antenna height, and gain of the antenna. Given the wide range of gains and antenna heights included in the Annex C data, a set of plots has been developed enabling a ground-influence factor to be determined for specific cases being compliance checked. For the antenna under evaluation, the free space forward compliance distance is then multiplied by this ground-influence factor.

Noting that that forward compliance distance should also apply forward from the ends of the element as well as the boom, and also that the centre of rotation may not be in the exact centre of the boom, a further correction is applied to give the radius of the Exclusion Zone.

Once the approach is understood, the key steps to getting the required Exclusion Zone dimensions are:-

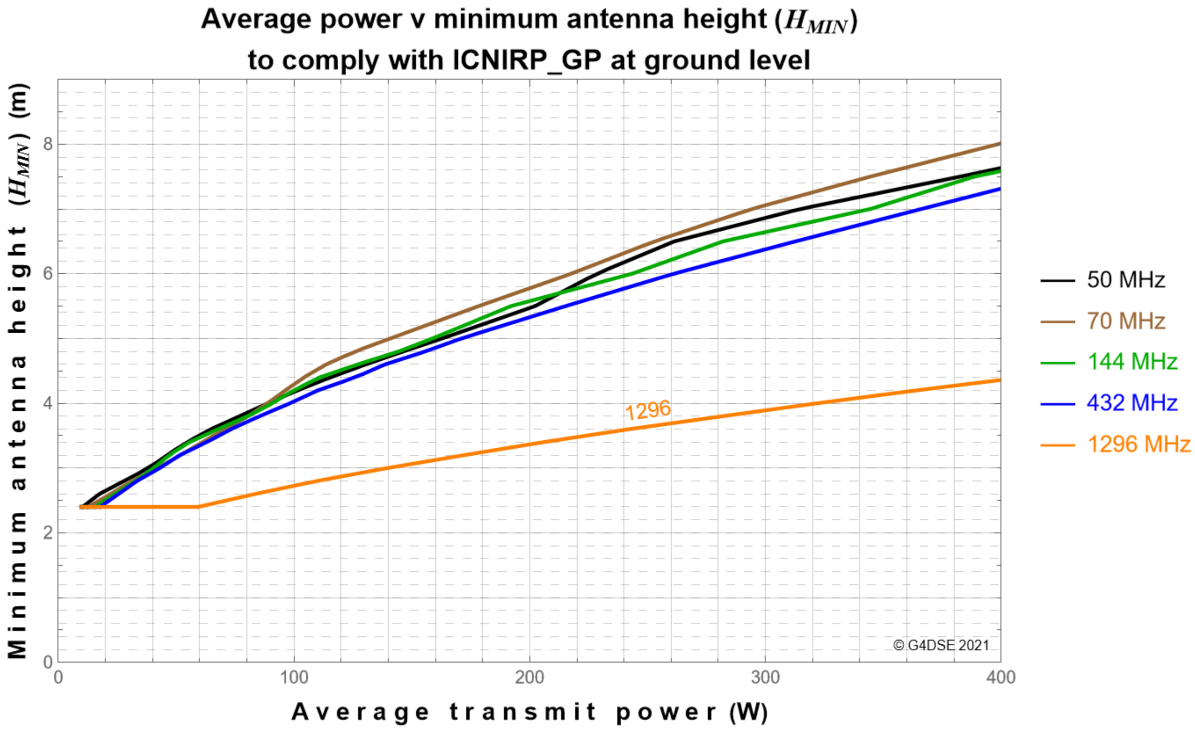
- Show compliance at ground level – Use Figure 4 in section 5.2
- Derive Exclusion Zone depth (D_{EZ}) in section 5.3
- Determine the free space forward compliance distance (R_{FS}) in section 5.4 using Figure 5
- Determine the ground-influence factor (F_G) in section 5.5 using Figure 6
- Determine the Exclusion Zone radius (R_{EZ}) using the earlier information and antenna dimensions according to section 5.6.

Several worked examples are included with these stages.

5.2 Showing compliance at ground level

A key determination is whether at ground level there is any location that needs to be subject to control measures such as access control or monitoring. Raising the antenna so that the exclusion zone is inaccessible is clearly a great result and worth aiming for if possible. Fortunately, the modelling [Annex C] has given us Figure 4 where all you need is the transmit power and antenna height. As explained in Annex C, each of the coloured limit lines in Figure 4 applies to any of the antennas on that particular band, within the scope of PAEC-2.

If your antenna is higher than the minimum height (H_{MIN}) in Figure 4 for the band and power being checked, that is sufficient to show compliance at ground level.



Band	H_{MIN} over 'Rich soil' for ICNIRP_GP					
	10W	20W	50W	100W	200W	400W
50 MHz	2.4	2.7	3.3	4.2	5.5	7.7
70 MHz	2.4	2.6	3.2	4.3	5.8	8.1
144 MHz	2.4	2.6	3.3	4.3	5.6	7.6
432 MHz	2.4	2.5	3.2	4.1	5.4	7.4
1296 MHz	2.4	2.4	2.4	2.8	3.4	4.4

Figure 4 – Minimum antenna height (H_{MIN}) to deliver ICNIRP-2020_GP compliance anywhere at ground level, for any of the applicable antennas.

Locating your antenna above the minimum specified height for your selected power is sufficient to show EMF compliance for a person standing anywhere at ground level.

If the antenna is higher than H_{MIN} and there are no buildings nearby (e.g., from Figure 3E, the largest value of R_{EZ} at 432 MHz is 60m for 400W), then nothing more is needed to show compliance.

Example 5:1 Your average power does not exceed 50W on any VHF/UHF band.

From Figure 4: if the lowest part of the antenna is at a height above 3.3m, then there is no EMF Exclusion Zone anywhere for persons standing at ground level.

Example 5:2 A six-over-six-element 144 MHz array is mounted with its lower antenna at 2.7m AGL and the upper antenna at 4m AGL. Your average power does not exceed 50W.

In this case, Figure 4 gives the minimum height as 3.3m. Since the lowest radiating part of the array is only at 2.7m AGL, EMF compliance has **not** been shown.

Your best action would be to raise the entire array by at least 1 m. Otherwise you would either need to decrease your average power to less than 20W, which would markedly affect your weak-signal communication range; or else establish and maintain an EMF Exclusion Zone at ground level.

Example 5:3 A 4 element cubical quad on 50 MHz is mounted with its boom at 4m AGL. The lowest radiating part of the antenna is at 3.2m. Your average power does not exceed 50W.

In this case, Figure 4 gives the minimum height as 3.3m. Since the LOWEST part of the antenna is only at 3.2m AGL, compliance has **not** been shown.

If you wish to use 50W, either raise the antenna so that the lowest point is higher than 3.3m AGL, or else establish and maintain an EMF Exclusion Zone at ground level.

5.3 Vertical clearance height (H_{CL}) and vertical distance (D_{EZ})

Figure 1 shows the meaning of the Exclusion Zone height and distance variables discussed in this section.

Even if compliance at ground level has been shown (see 5.2), if there are locations accessible to the general public above ground level and within the radius of the Exclusion Zone (R_{EZ}), it is then necessary to consider the vertical clearance (H_{CL}) to determine if these accessible areas are in fact within the Exclusion Zone.

For antennas directly above a building (or close by) compliance might be better expressed in terms of D_{EZ}, the vertical clearance *below* the antenna down to the relevant floor level (see Annex G).

The modelling discussed in the Annexes has shown that the ground reflection factor can increase the exposure close to ground. Since Figure 4 gives a minimum clearance height against ground, this will be conservative when considering antennas higher than that minimum height.

The minimum compliant antenna height (H_{ANT}) determined from Figure 4 is H_{MIN}. Then, for the antenna at height H_{ANT}, the lower extent of the Exclusion Zone can be found by:

$$H_{CL} = H_{ANT} - H_{MIN} \text{ and } D_{EZ} = H_{MIN}$$

For the rare cases where the upper extent of the Exclusion Zone is also of importance, this value is taken to be $H_{UANT} + D_{EZ} - 0.9$ m. (H_{UANT} means the height of the highest antenna element to account for stacked and looped arrays). The offset of 0.9m is estimated from the 1.8m height of the standard person. Considering that the maximum exposure occurs when the main beam points to the middle of the body, the offset is understood to be approximately half of that height.

Example 5:4 50 MHz, 10dBi antenna at a height of 8m with 40W average power

From Figure 4 graph H_{MIN} is 3.m.

Therefore, the lowest part of the exclusion zone (H_{CL}) is 8m – 3m or 5m above ground. If the antenna is on a standalone mast, then compliance is shown for anywhere at ground level.

If the antenna is mounted on a roof, it might be of more interest to consider the vertical separation from the antenna to the top floor foot level. In that case we need D_{EZ} which is less than or equal to H_{MIN}, i.e., 3m. Therefore, if the antenna is 3m above the walking level of the top floor, then compliance has been shown for that case.

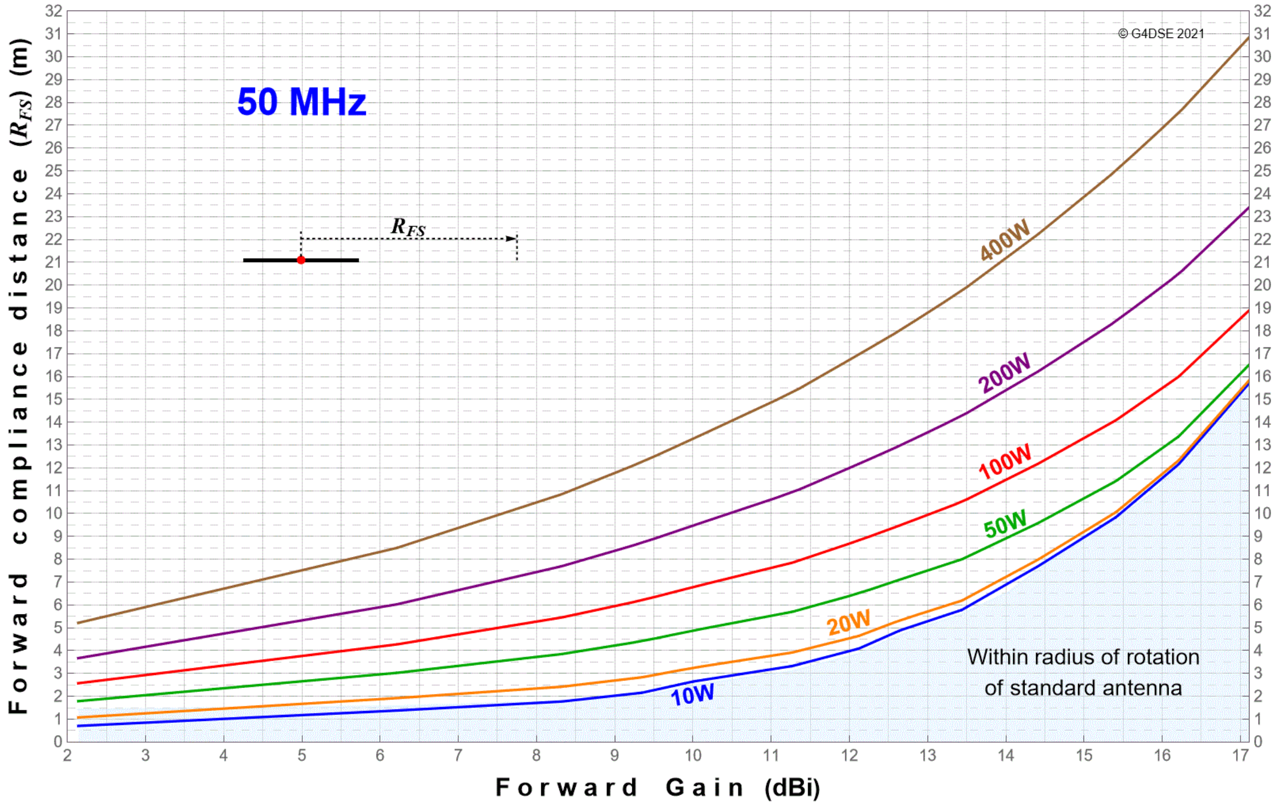
5.4 Free space forward compliance distance (R_{FS})

In free space, without any influence from ground reflections, the EMF exposure at a large distance from the front of the antenna will be closely related to the EIRP. At smaller separations, the exposure can be different due to the variation of the incident field strength over the surface of the exposed person, and also the change in effective gain close to the antenna where the full antenna pattern has not yet emerged.

To evaluate all of these effects, a set of compliance checks were performed using NEC-4.2 under free-space conditions and the processing described in Annex C. The resulting plots of free space forward compliance distances versus antenna gain for different power levels are shown in Figure 5 for each band.

The free space forward compliance distance expressed here is the horizontal distance from the vertical line passing through the centre of the boom, out along the main beam to the vertical line that intersects the furthest location that is just compliant with the most limiting ICNIRP reference level (Figure C.3). Note that for the lower bands, the modelled forward compliance distance for lower power levels falls within the length of the boom or the turning radius for the antenna being checked (section 4). This explains some apparently unusual free space forward compliance distances where there is little or no difference between adjacent low power levels. In such cases, compliance is governed mostly by keeping a minimum distance from the antenna to avoid touch hazards.

The free-space forward compliance distance determined from Figure 5 is then used with the ground-influence factor F_G from Figure 6, and some physical dimensions of the antenna to establish the overall radius of the Exclusion Zone (see 5.6).



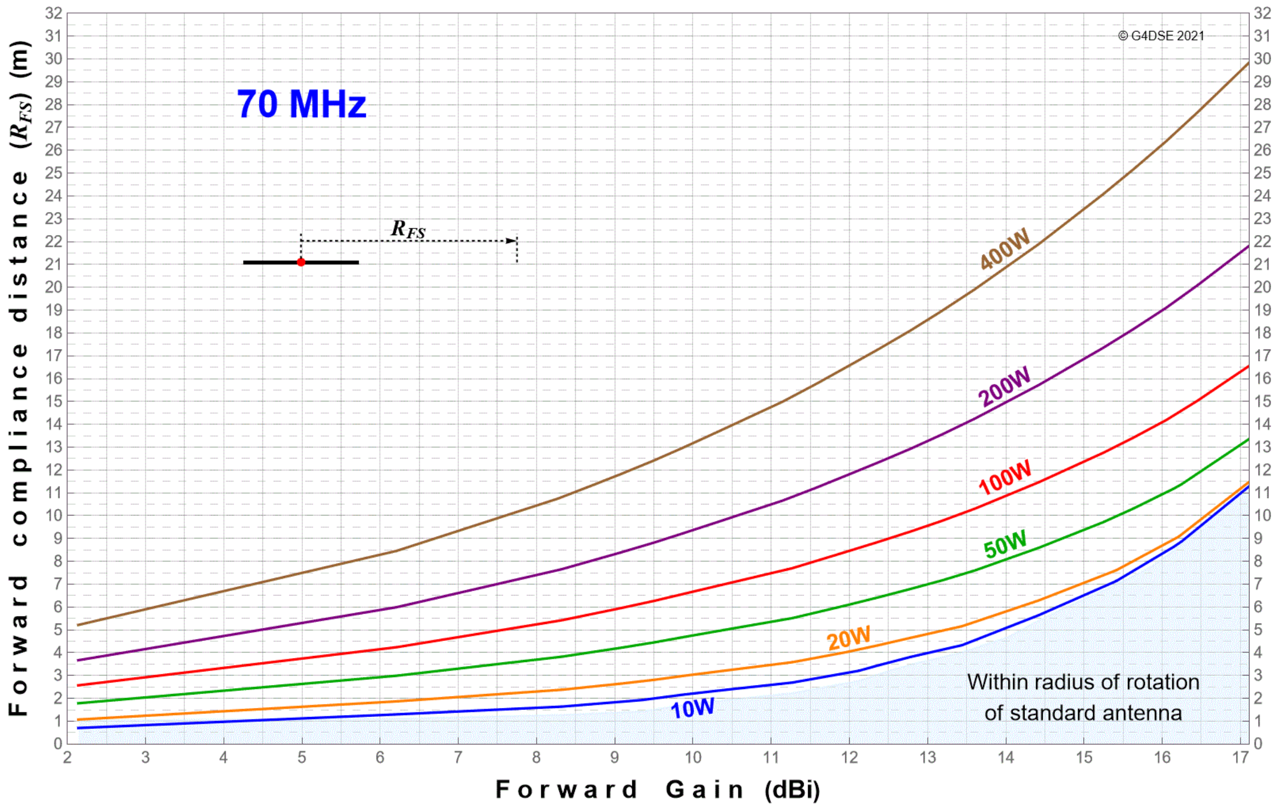


Figure 5A, 5B–Distance forward from boom centre for ICNIRP_GP compliance (R_{FS}) versus forward gain (free space, all reference antennas, 50 MHz and 70 MHz)

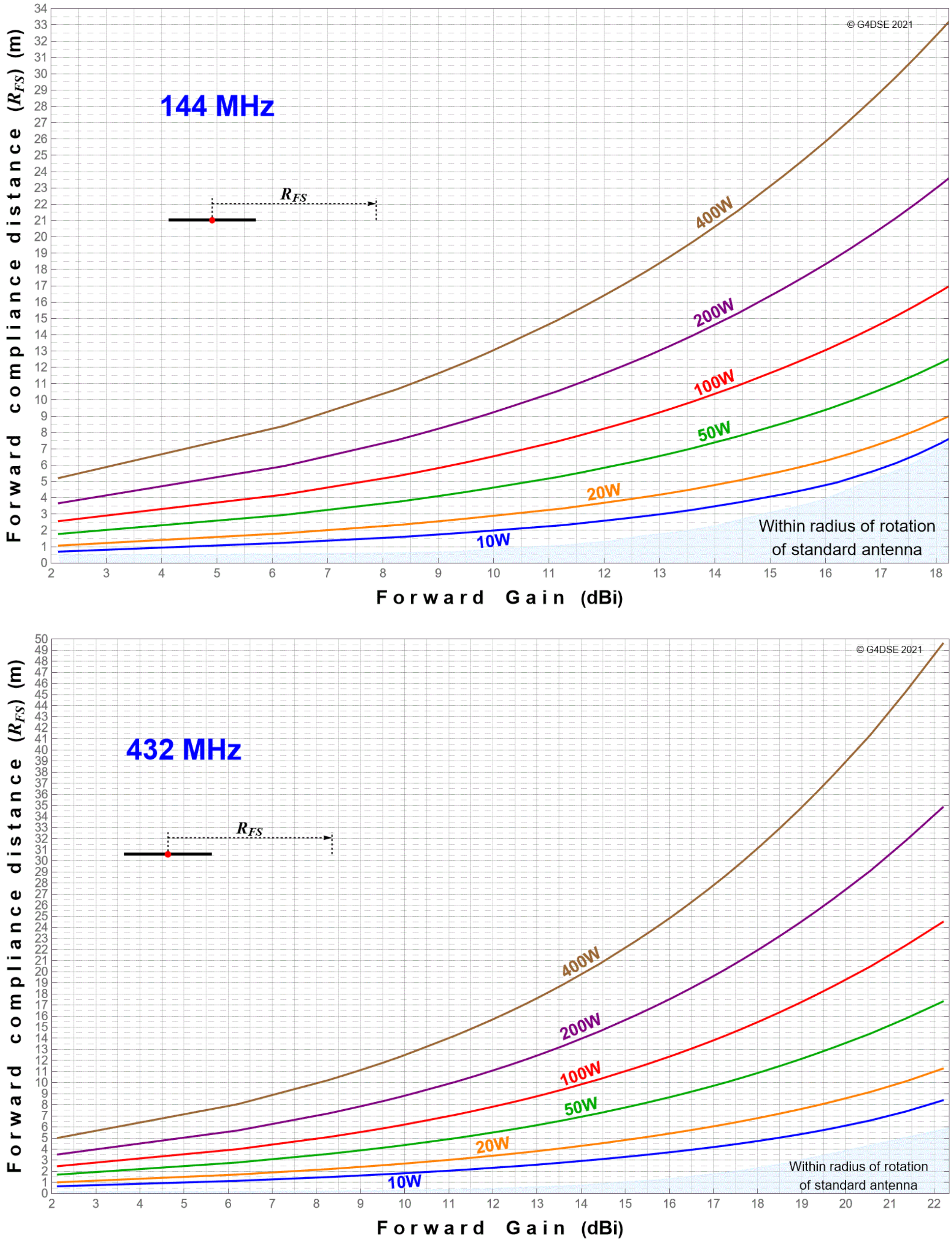


Figure 5C, 5D–Distance forward from boom centre for ICNIRP_GP compliance (R_{FS}) versus forward gain (free space, all reference antennas, 144 MHz and 432 MHz)

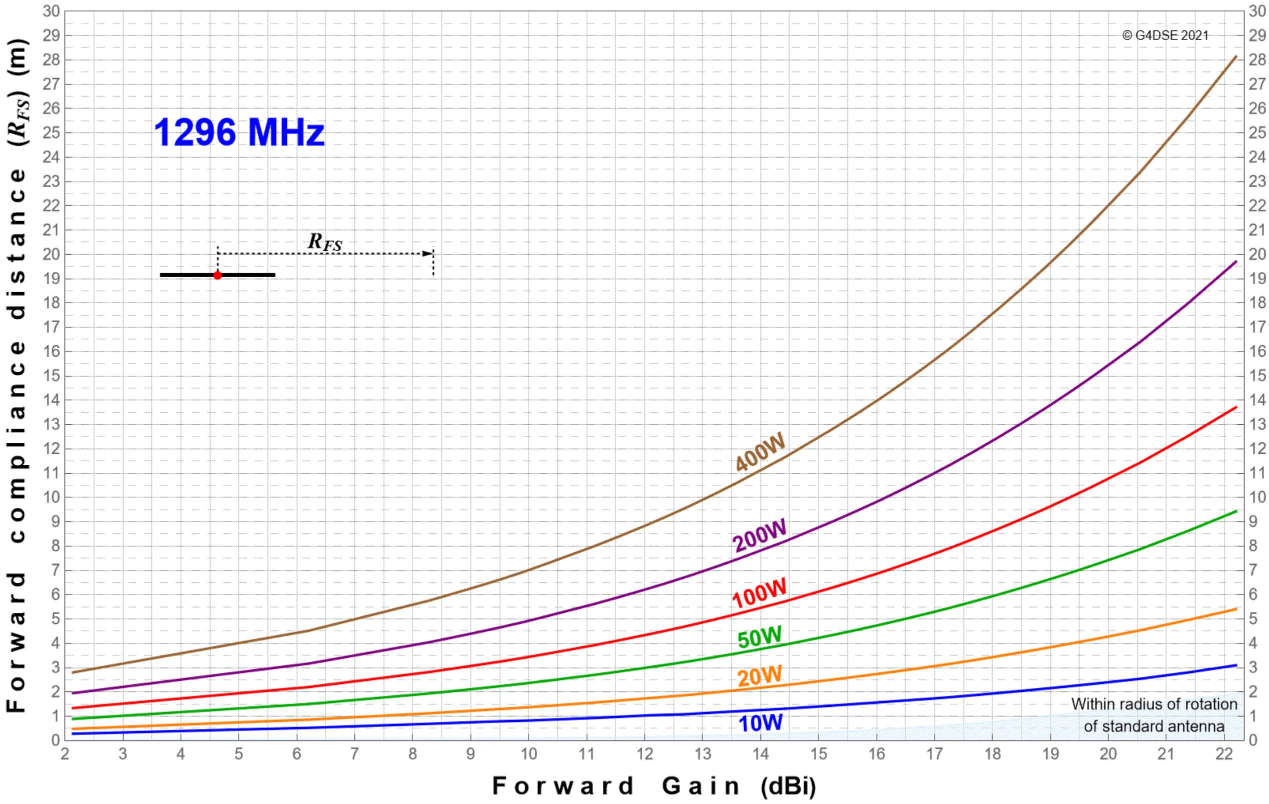


Figure 5E–Distance forward from boom centre for ICNIRP_GP compliance (R_{FS}) versus forward gain (free space, all reference antennas, 1296 MHz)

Example 5:5: For a 2m antenna with 12dBi gain and 90W average transmit power, what is the free-space forward compliance distance for ICNIRP compliance?

The relevant chart is Figure 5C, and the nearest data above 90W is the red curve for 100W. Find the 12dBi point on the gain axis and trace upward to intersect the red 100W curve. From the intersection point, move left onto the Y axis and read off 8.3m. This is the free-space forward compliance distance (R_{FS}) with respect to the boom centre point. Section 5.6 shows how this is used to establish the radius of the Exclusion Zone.

Example 5:6: For a 6m antenna with 10dBi gain and 40W average power, what is the free-space forward compliance distance for ICNIRP compliance?

The relevant chart is Figure 5A, and the nearest data above 40W is the green curve for 50W. For a gain of 10 dBi on the X axis, the free space forward compliance distance (R_{FS}) is 5m. Section 5.6 shows how this is used to establish the radius of the Exclusion Zone.

5.5 Establishing the ground-influence factor (F_G)

5.5.1 What you need to do

For several transmit power levels Figure 6 plots the ratio of the forward compliance distance for Rich soil ground to forward compliance distance for Free Space conditions for a range of antennas and antenna heights. This ratio quantifies the effect of ground on the forward compliance distance. We call this the ground-influence factor (F_G) that needs to be applied to the free-space forward compliance distance to find the forward compliance distance over Rich soil ground for the ICNIRP general public reference levels for horizontally-polarized antennas.

Figure 6 is a collection of charts derived from the extensive advanced modelling data. The ground-influence factor F_G is shown by the colours on each antenna average power plot of antenna gain (dBi) and antenna height (m). An F_G value of 1 would correspond with free space (no correction necessary) but for a level of conservatism, the minimum F_G is set to 1.1.

To define F_G, the ground reflection correction factor for your antenna – or alternatively, to confirm that ground reflection is unimportant – follow the steps below.

1. Identify the operating band, the average transmit power, the free-space antenna gain (dBi) and the antenna height above ground level (metres).
2. Find the Figure 6 chart that corresponds to your frequency band, and then select the plot labelled with the next value of power above your averaged power.
3. Read vertically from the antenna gain axis, and across from the antenna height axis, and note the colour shading at the intersection point.
4. The colour code on the key at the bottom of each Figure will tell you the value of F_G.

Example 5:7: For a 144 MHz antenna with 12dBi gain and 90W average transmit power, what values of F_G are required (a) if the antenna is at 3m AGL, and (b) if it is raised to 5m AGL?

The 144 MHz chart is Figure 6C. The plot with the nearest power value above 90W is labelled 100W.

(a) For 12 dBi on the antenna gain axis, and 3m on the antenna height axis, the intersection point falls within the orange shading. The sidebar show that this represents F_G value 1.5.

(b) Looking at 5m on the antenna height axis, the value of F_G has now moved into the grey area representing F_G = 1.1

Conclusion: raising the antenna from 3m to 5m AGL has reduced the radius of the forward compliance zone to 73% of its previous value. This will be accompanied by an improvement in communication range and reduced risks of RF interference, so it is obviously well worth doing if at all possible.

5.5.2 How the ground-influence factor relates to the Ofcom calculator method

At a basic level, the PAEC-2 and Ofcom calculator approaches are actually very similar. The Ofcom calculator [24] determines its compliance distance R based on the free space compliance distance multiplied by a fixed factor of $(1+|\Gamma|)$ with the value of Γ "gamma" set to 0.6 ("gamma" is the factor indicating the fraction of the electric field strength that is reflected by the ground). Therefore, the Ofcom calculator in effect assumes a fixed ground-influence factor of 1.6, and applies it in all directions, and at all heights above ground. Annex C shows why this is a simplification on real life.

The PAEC-2 approach uses the results from extensive simulations to determine a more accurate value of the ground-influence factor for specific equipment configurations, valid for the forward compliance distance, horizontal polarization, and ICNIRP 2020 General Public limits. By limiting the applicability, PAEC-2 is able to specify a different ground influence factor value according to the antenna and transmit power being compliance checked.

Note that the "gamma" value relates to specular reflection from flat ground and specifically relates to the fraction of the incident ray that is reflected. For rough ground, the fraction reflected in a coherent manner is lower than for specular reflection. Therefore, our simplifying assumption of specular flat ground is conservative. Also note that the use of ground influence factor in PAEC-2 and also by Ofcom is specifically about the effect of the ground reflection on the compliance distance which is different from the effect on far-field signal strength evaluated at a point and the far-field vertical radiation pattern.

Both the PAEC-2 and Ofcom ground-influence factors extend the front compliance distance with respect to the distance determined in free space. An F_G of 1.6 in Figure 6 therefore corresponds with the fixed factor included in the Ofcom calculator [24]. The shading colour indicates the value of F_G. All values up to and including 1.5 (orange shading) show situations where the Ofcom EMF calculator is overestimating the radius of the EMF Exclusion Zone. This is completely in accord with the stated aim of the Ofcom calculator to produce conservative results.

However, the Figure 6 charts also shows some areas (shaded red/dark red) where the Ofcom factor underestimates the forward compliance distance. These areas require a specific combination of three conditions: low antenna height, high antenna gain, and high RF power. In those situations, we strongly recommend the use of PAEC-2 to determine the Exclusion Zone…or better still "don't do it" – raise the antenna!

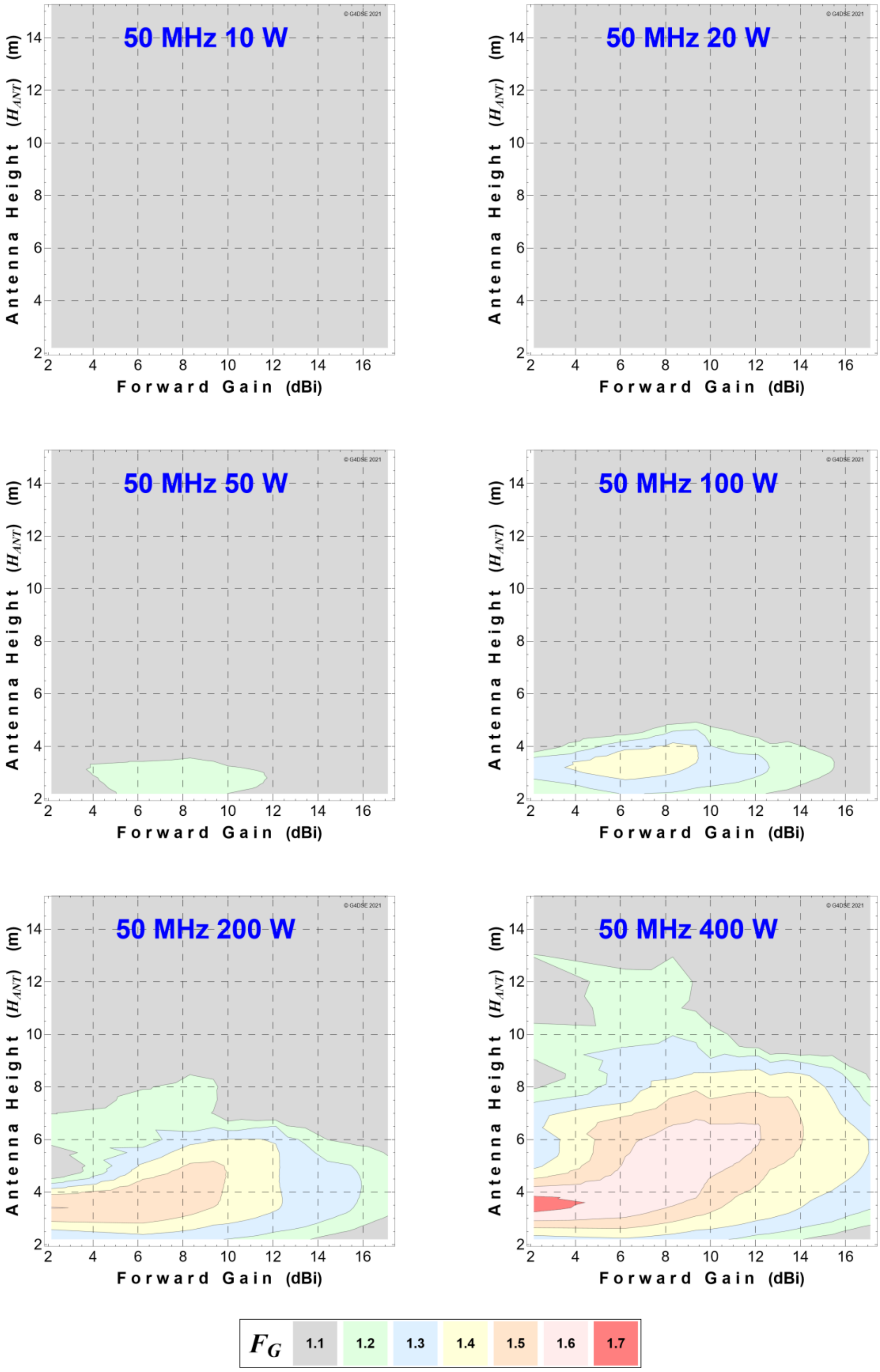


Figure 6A–Ground-influence factor (F_G) to be applied to free-space forward compliance distance – 50 MHz (only for horizontal polarization and ICNIRP2020 General Public limits)

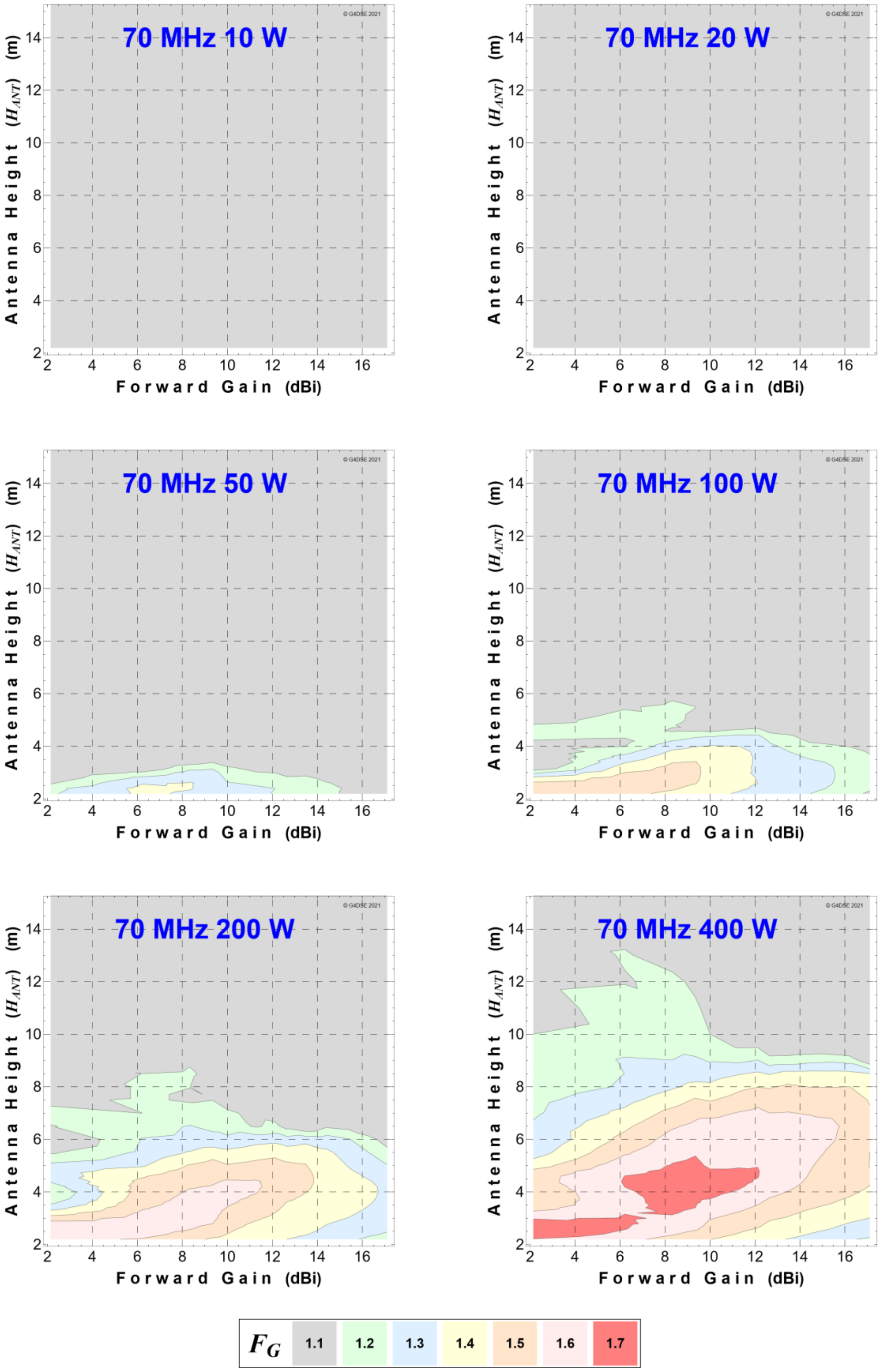


Figure 6B–Ground-influence factor (F_G) to be applied to free-space forward compliance distance – 70 MHz (only for horizontal polarization and ICNIRP2020 General Public limits)

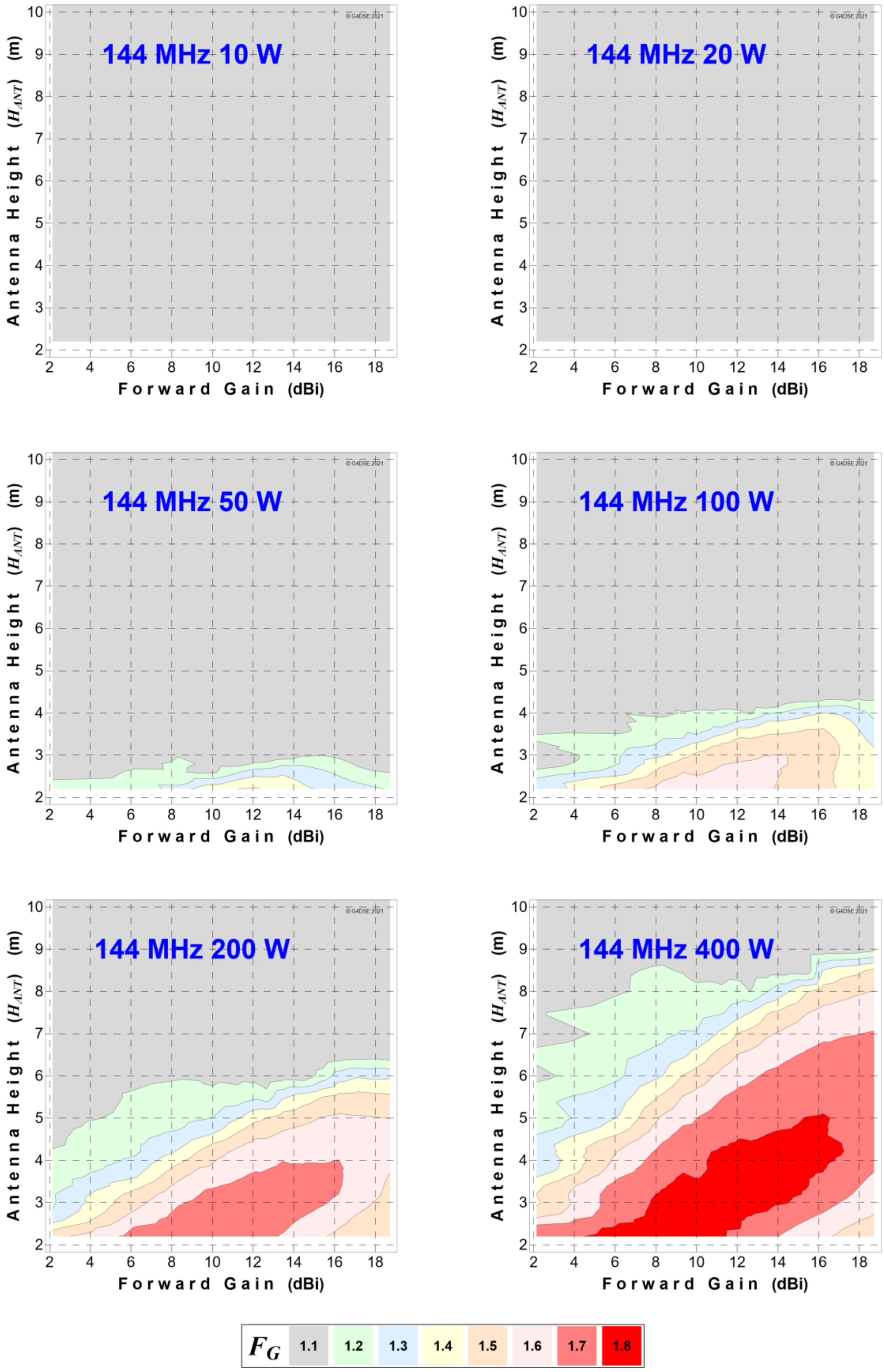


Figure 6C–Ground-influence factor (F_G) to be applied to free-space forward compliance distance –144 MHz (only for horizontal polarization and ICNIRP2020 General Public limits)

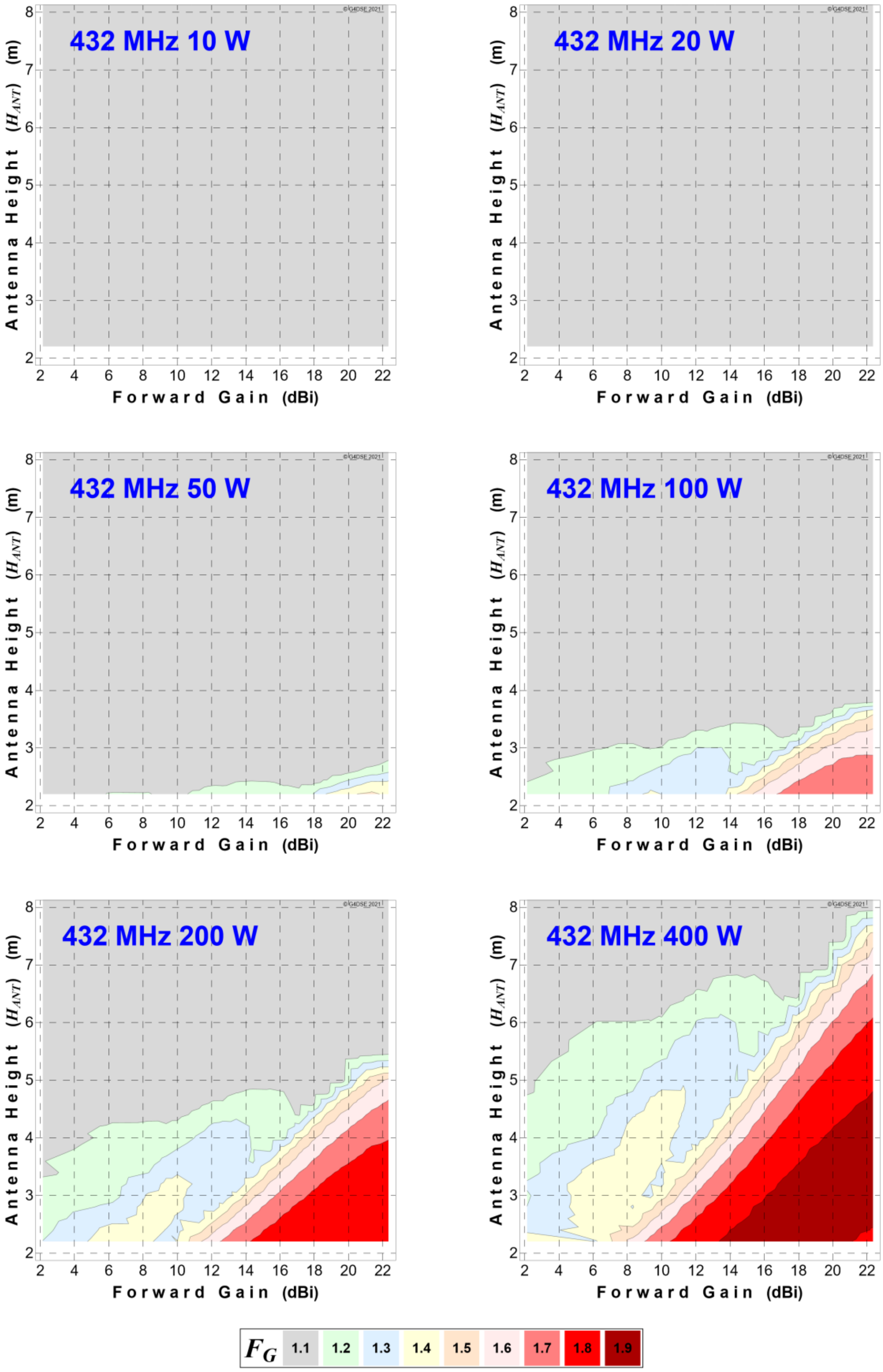


Figure 6D—Ground-influence factor (F_G) to be applied to free-space forward compliance distance – 432 MHz (only for horizontal polarization and ICNIRP2020 General Public limits)

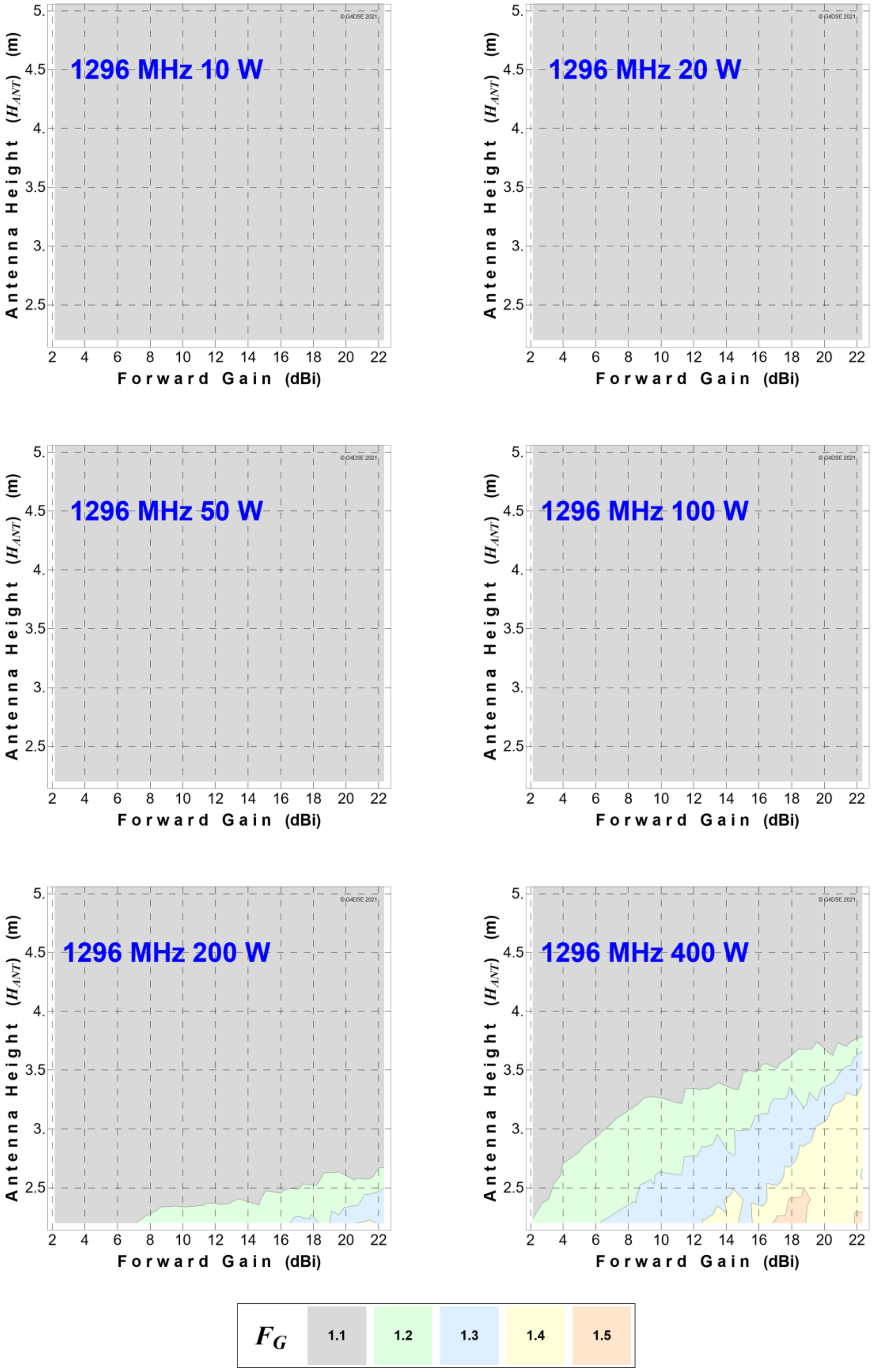


Figure 6E—Ground-influence factor (F_G) to be applied to free-space forward compliance distance – 1296 MHz (only for horizontal polarization and ICNIRP2020 General Public limits)

5.6 Establishing the Exclusion Zone radius (R_{EZ})

If there is a potentially occupied building nearby with a floor at or below the clearance height (H_{CL}), then the exclusion zone radius (R_{EZ}) (see Figure 1) should be determined.

To be conservative, when determining R_{EZ}, the separation achieved from the front end of the boom to the forward compliance distance (R_{FS}) should be maintained in the forward direction from the front director element tips. Also, it should be considered that the rotator pole may not be exactly in the middle of the boom length. The Exclusion Zone radius is established after first determining the following parameters:

1. Free space forward compliance distance (R_{FS}) - From the average power and gain information, use Figure 5 for the relevant band to determine the free-space forward compliance distance (R_{FS}).
2. Ground-influence factor (F_G) – From the frequency band, average power, antenna height and antenna gain use Figure 6 to find the ground-influence factor (F_G).
3. Distance between the rotator pole and the mid-point of the boom (α) (+ve for pole closer to reflector, -ve for pole closer to director) - from manufacturer data, design data or measurements.
4. Length of director (L_D) – From manufacturer's data, design data, measurements or else assume a quarter wavelength.

To calculate the exclusion zone radius (R_{EZ}) centred on the rotator pole:

$$R_{EZ} = \sqrt{(R_{FS} \times F_G + \alpha)^2 + (\frac{L_D}{2})^2}$$

Where:

R_{EZ} is the horizontal radius of the Exclusion Zone measured from the axis of the rotator pole (see Figure 1)

R_{FS} is the free space forward compliance distance (see Figure 5 and Figure C.4)

F_G is the ground-influence factor (see Figure 6)

α is the distance from the pole to the mid-point of the boom (+ve for pole closer to reflector, -ve for pole closer to director)

L_D is the length of the director

For moderate powers and the higher bands covered by this document, the correction to 'R_{FS} times F_G' as the compliance distance is likely to be small. For 50 MHz and 70 MHz and antennas with few elements, correcting for α and L_D can make a significant difference.

While this all may seem a bit complicated, it should be noted that this process:

- Gives an Exclusion Zone boundary that is referenced from the pole at the centre of rotation for the antenna making it an easy check at ground level with a tape measure.
- Accounts for the free-space forward compliance distance R_{FS} being expressed with respect to the centre of the boom and in the forward direction.
- Uses a realistic ground-influence factor considering that the ground affects the forward compliance distance differently according to power, height, and antenna gain.

5.7 Example exclusion zone calculations

In many cases it will be possible to show compliance without completing all of the steps described in section 4 and section 5. As soon as there is sufficient basis to show compliance, there is no obligation to calculate further. However, for the sake of illustration, the examples in this section will calculate the exclusion zone parameters R_{EZ}, D_{EZ}, and H_{CL}.

Example 5:8 – 50 MHz dipole at 8m, 100W average power, Gain = 2.14dBi

First establish if compliance is achieved at ground level:

From Figure 4, H_{MIN} is 4.2m. Since the antenna H_{ANT} is above this height, compliance is achieved on the ground. The bottom of the exclusion zone is at $H_{CL} = H_{ANT} - H_{MIN} = 3.8$m AGL.

Now establish the radius of the exclusion zone:

Free space forward compliance distance (R_{FS}) from Figure 5A, 50 MHz red 100W plot at 2.15dBi, R_{FS} = 2.5m

Ground-influence factor (F_G) from Figure 6A, 50 MHz, 100W at 8m is grey, F_G = 1.1

Dipole element length = 2.83m, Boom length = 0, $\alpha = 0$.

$$R_{EZ} = \sqrt{(R_{FS} \times F_G + \alpha)^2 + (\frac{L_D}{2})^2} = \sqrt{(2.5 \times 1.1 + 0)^2 + (\frac{2.83}{2})^2} \simeq 3.1\text{m}$$

Therefore, the Exclusion Zone starts 3.8m above ground and has a radius of 3.1m centred on the support pole.

Example 5:9 – 144 MHz 8 element Yagi at 8m, 100W average power, Gain = 12.65dBi

Front director element length = 0.9m, pole is 0.1m towards reflector from the boom midpoint

First establish if compliance is achieved at ground level:

From Figure 4, H_{MIN} is 4.3m. Since the antenna H_{ANT} is above this height, compliance is achieved on the ground. The bottom of the exclusion zone is at $H_{CL} = H_{ANT} - H_{MIN} = 3.7$m AGL.

Now find the radius of the exclusion zone:

Free space forward compliance distance (R_{FS}) from Figure 5C, 144 MHz red 100W plot at 12.7dBi, R_{FS} = 9m

Ground-influence factor (F_G) from Figure 6C, 144 MHz, 100W at 8m height is grey, F_G = 1.1

$$R_{EZ} = \sqrt{(R_{FS} \times F_G + \alpha)^2 + (\frac{L_D}{2})^2} = \sqrt{(9 \times 1.1 + 0.1)^2 + (\frac{0.9}{2})^2} \simeq 10\text{m}$$

Therefore, the exclusion zone starts above 3.7m and has a radius of 10m centred on the support pole.

Example 5:10 – Same antenna and power as Example 5:3 but now on a short portable mast at 3m AGL.

First establish if compliance is achieved at ground level:

From Figure 4, H_{MIN} is 4.3m. Since the antenna H_{ANT} is *below* this height, compliance is not achieved on the ground and the Exclusion Zone includes the ground out to the radius of the Exclusion Zone also at ground level.

Now find the radius of the Exclusion Zone:

Free space forward compliance distance (R_{FS}) from Figure 5, 144 MHz red 100W plot at 12.7dBi, R_{FS} = 9m (same as previous example since this is just free space)

Ground-influence factor (F_G) from Figure 6C, 144 MHz, 100W at 3m is orange, F_G = 1.5

$$R_{EZ} = \sqrt{(R_{FS} \times F_G + \alpha)^2 + (\frac{L_D}{2})^2} = \sqrt{(9 \times 1.5 + 0.1)^2 + (\frac{0.9}{2})^2} \simeq 13.5\text{m}$$

Therefore, the Exclusion Zone has a radius of 13.5m centred on the support pole at ground level.

ANNEX A - FROM ANTENNA MODELLING TO EXPOSURE MODELLING

Licensed amateurs should already be familiar with the basic concepts of antenna gain and radiation patterns. Many amateurs will also have some experience of antenna modelling. But those are only the first steps along the much longer road towards estimating human EMF exposure and compliance with the relevant ICNIRP limits.

This annex describes each of the steps along that new road.

A.1 Antenna modelling

In amateur radio, antenna modelling is about designing antennas and optimizing their performance for long distance communication – at least hundreds of wavelengths, and quite possibly millions or more. EMF exposure modelling is different: it is about determining the electromagnetic field strengths in areas close to the antenna and then processing those field strengths to compare with the ICNIRP reference levels for human exposure.[6]

While the same EM simulation tools can be used in both cases to estimate the field strengths, the constraints on where the fields should be evaluated and how they should be interpreted are different between the two applications.

In this annex we outline the steps that lead from traditional antenna modelling to evaluating the maximum power that can be radiated from the antenna while still complying with the relevant ICNIRP exposure limits for members of the general public nearby. Alternatively, the same methods can be used to evaluate what changes might be needed in the antenna configuration in order to achieve compliance at a given power level.

For the more technically adventurous, separate documentation is under preparation to provide even more detail on the techniques involved. Topics include comparisons between different versions of the industry-standard Numerical Electromagnetics Code, NEC-4.2 [3] and NEC-5 [4] [5], determining appropriate segmentation guidelines, and detailed interpretation of NEC files; interpretation of ICNIRP 2020 exposure limits; and how to relate NEC results to those limits.

Although antenna modelling tools are generally available, many of them free, this report required several thousand individual NEC runs followed by extensive post-processing. Specialist software had to be developed to automate these processes and analyse the gigabytes of resulting data.

A.2 Free-space antenna modelling

We begin with radiation patterns in free space, which should be familiar to most amateurs.

Figure A.1 shows the horizontal and vertical radiation patterns of our example Yagi in free space, computed using NEC-4.2 [3]. The antenna itself is horizontally polarized. The red pattern is in the horizontal plane (looking downwards on the antenna) and clearly shows the forward lobe that contains most of the radiated RF energy. There are minor sidelobes, and a rearward lobe that is suppressed by about 14dB relative to the forward lobe.

The blue pattern is in the vertical plane, looking sideways at the antenna. Clearly this vertical pattern has much larger downward- and upward-facing minor lobes – and in general, this will be true in

[6] ICNIRP reference levels are described as “guidelines”, compliance is now a mandatory part of the UK amateur radio licence conditions so they can equally be described as “limits”.

almost all directions. The two major exceptions are in the forward and rearward directions, where the vertical and horizontal patterns coincide.

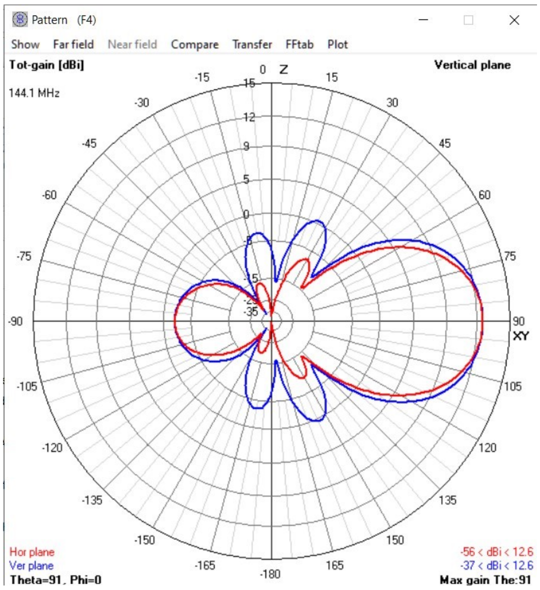


Figure A.1–Far-field horizontal and vertical patterns of the example 8-element Yagi in free space

A.3 Effects of ground reflection

The field strength seen at a point is the result of the addition of "rays" coming directly from the antenna (i.e., line-of-sight) and via major reflecting surfaces – most commonly the ground. While the ground may not be smooth, a common simplification is to consider it to be so, and this enables the estimation of the effect on observed field strength of the ground beneath us. Rough ground will tend to disperse the energy falling on it, making the effect on compliance less marked than for the more idealised case actually modelled.

The next step is to combine the direct and reflected components. Figure A.2 is the vertical-plane pattern of the same Yagi, now at 8 m above level ground that is characterised as 'Rich Soil' with good RF reflecting properties. As usual, the radiation pattern is in the direction of maximum forward gain – but the presence of reflecting ground makes the vertical pattern very different from the free-space pattern in Figure A.1. (The horizontal pattern scarcely changes at all and need not be considered further.) It is important to understand that this pattern includes the contribution of the direct line-of-sight path and the reflection from the ground.

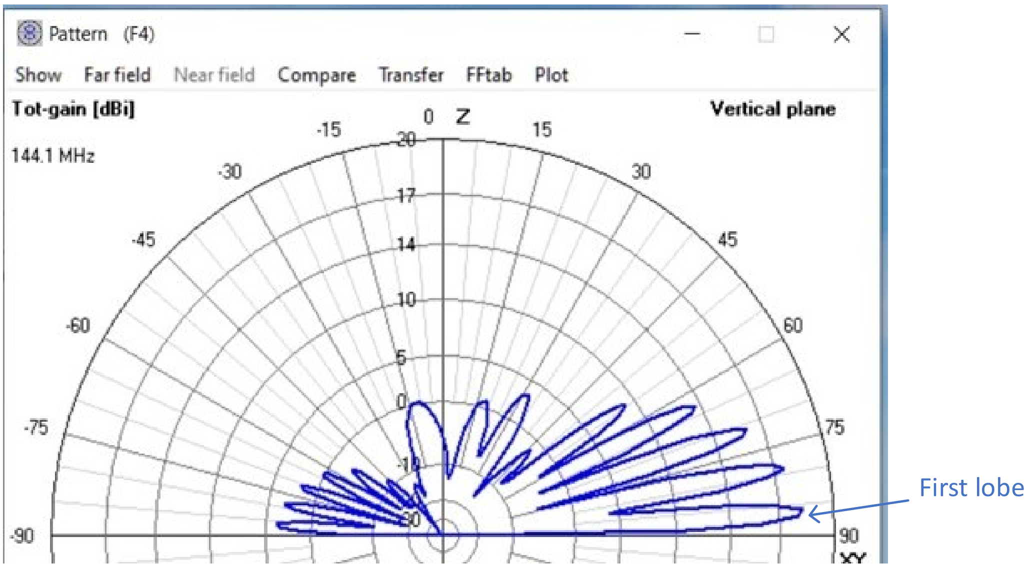


Figure A.2–Far-field vertical pattern of the example 8-element Yagi, 8 m above level ground.

Downward-directed radiation from all the individual elements of the Yagi has been reflected from ground and joins with the direct rays to create a complex radiation pattern. At greater distances this resolves into several lobes separated by deep nulls, as shown in Figure A.2. With real ground there is always a deep null at an elevation angle of exactly 0deg for horizontally polarized antennas, followed by the first lobe which is the one that we regularly use for terrestrial communication. Above the first lobe is a deep null, followed at higher angles by a repeating pattern of lobes and nulls. To simulate the far-field pattern in Figure A.2, the ground out to the reflection point is in effect part of the antenna system so in this case we mean in the far field of the antenna and ground combined – so the Figure A.2 pattern is only resolved far away from the antenna – perhaps hundreds of metres.

Generally speaking, the maximum values of estimated field strengths close to ground will increase with ground conductivity; but the actual ground conductivity is almost never known, so for EMF calculations it is wise to assume a high-but-realistic value. For the PAEC-2 NEC simulations, the assumed ground conditions are 'Rich Soil' ($\varepsilon_r = 20$, $\sigma = 0.0303$) and the NEC software also assume smooth and level ground which will tend to over-estimate the field strengths. In summary, the effects of ground reflection determined in these PAECs are most unlikely to be exceeded in practice. Ofcom has clarified [17] that compliance should be based on the best estimate of the EMF levels. By erring our analyses towards overestimation, it makes it easier to justify applying the results to a wide range of antennas and locations.

Up to this point, we have been describing conventional antenna modelling which is primarily concerned with long-distance communication. In other words, we have been modelling the radiation pattern in the far field of the antenna and ignoring any close-in differences that might occur in the near field. Also, we have not needed to consider the RF power level, because far-field patterns of beam antennas are always computed relative to the gain in the direction of maximum radiation.

For EMF compliance checks, those assumptions now have to change.

At amateur power levels, the exclusion zones will often be somewhere in the 'near field',[7] very much closer to the antenna, and the dimensions of these exclusion zones will increase or decrease according to the RF power level. Instead of relative polar diagrams we also need to see detailed maps of the E and H fields at user-defined points surrounding the antenna.

Most antenna modelling software based on the NEC code has the ability to produce this detailed data (this is usually labelled "near field"). Some software also has the ability to create graphics, typically 2D slices from the 3D radiation pattern, with contour shading to show the computed field strengths.

The graphics processing used for the PAECs takes this much further, as described below.

A.4 X-Z maps of field strength

Figure A.3 shows the next step along the road to an exposure assessment: a contour map of electric field strength around the actual location of the Yagi. In Figure A.3 we are looking sideways at the Yagi, which is 8m above ground level (the Z axis), with the centre point of the boom, (black bar) found at X=0. The X axis is the distance in front of or behind the Yagi in the conventional forward/reverse beam directions.

This style of presentation is known as an "X-Z slice" of the full 3D radiation pattern. Unless stated otherwise, this slice is taken along the direction of maximum field strength.

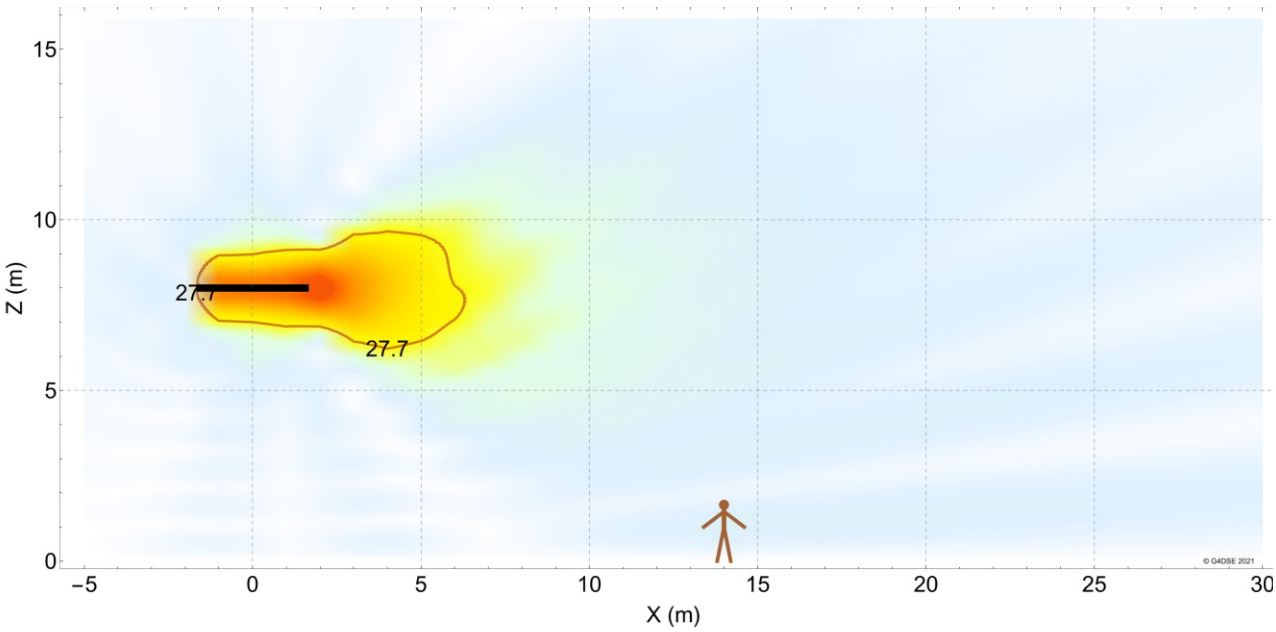


Figure A.3–E-field pattern of the example 8-element 144 MHz Yagi, 8 m above ground, at an RF power level of 50W

This X-Z plot is colour-shaded according to the electric field strength for the assumed RF power of 50W. The contour line shows the boundary where the field strength is at the electric field strength reference level defined by ICNIRP which in this case is for an E-field strength of 28 V/m for the general public exposure limit. Note that this plot just shows the field strength at points in space; it

[7] The PAEC reports only use the term "near field" in the most general sense, mostly to mean "not the far field". PAECs do not use the descriptive labels that are sometimes applied to various sub-regions of the near field (e.g., "reactive near field", radiative near field" or "transition region"). The NEC software used for EMF computation has no use for these labels; it calculates the actual field at any given location, based purely on the physics.

does NOT show either the average field strength over the height of the body or the maximum field strength over the height of the body that are the actual ICNIRP reference levels for exposure assessment. However, in this case, if the field strength at a location is less than the spatial average reference level (see A.5.1), then the spatial average limit must be met at that point. In this example, all locations that might exceed the spatial average reference level are well above head height indicating that this configuration is compliant with the Ofcom license condition. Having made the calculation at 50W, note that it means that this configuration is also compliant at every lower level of RF power.

Figure A.4 shows a less clear-cut situation, the same antenna configuration but at an average RF power level of 400W. Here the limiting E-field contour is approaching ground level, roughly where the main lobe of the antenna spreads out to reach the ground. At the short wavelengths of the VHF and UHF bands, addition of incident and reflected waves can cause rapid variations of field strength over the height of the body. Where compliance is constrained by the field strength averaged over the whole body [7], these local variations mean that a simple plot of field strength does not always tell us whether a particular location is compliant or not. If the average field is below the limit, then compliance is still achieved even if there are some locations where the maximum level exceeds the ICNIRP whole-body limit. Conversely, if any of these locations exceed the ICNIRP local limit, even if the average is below the spatial-average limit, then the situation would be non-compliant. That is why, to do a full exposure assessment against ICNIRP, both the spatial-maximum and spatial-average field strengths need to be determined and compared with the local and whole-body ICNIRP limits respectively. To achieve this, further data processing is needed, as shown below.

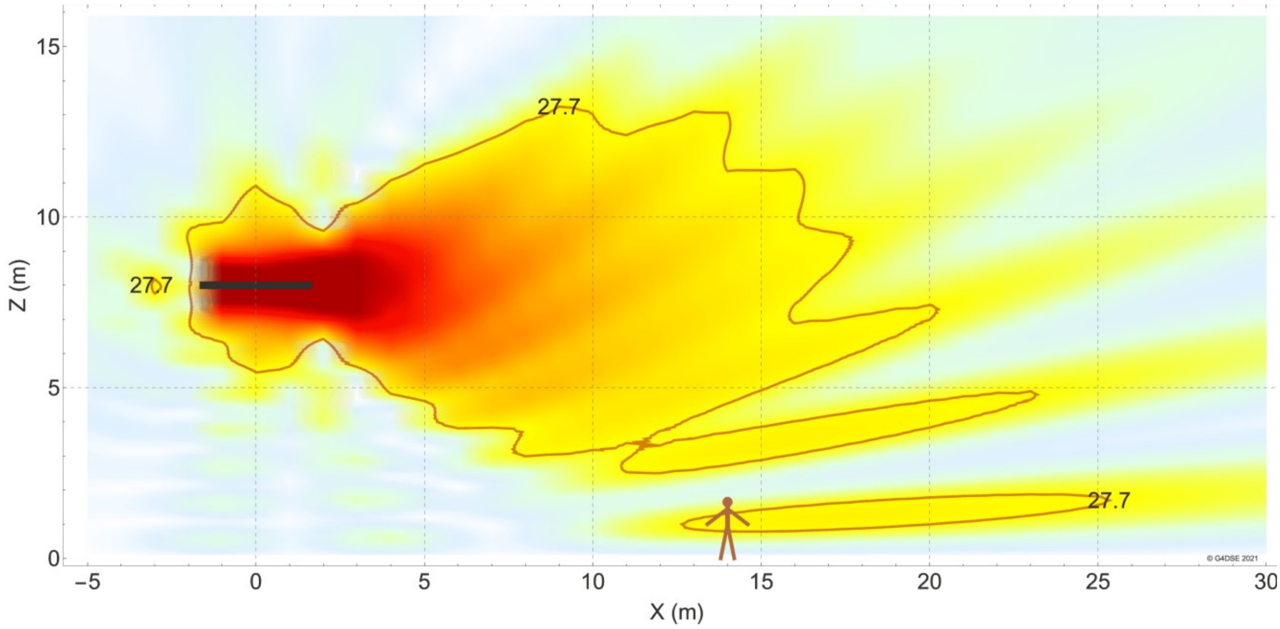


Figure A.4–E-field pattern of the example 8-element 144 MHz Yagi, 8 m above ground, at an RF power level of 400W

A.5 Convert field strength plots to show exposure limits

While EMF modelling tools compute field strength values for specific points in space, exposure is about establishing a processed value that considers the set of points in space representing the potential location of a person. This section describes how to develop field strength plots into plots more aligned to the ICNIRP reference levels.

A.5.1 Initial processing

Figure A.5 illustrates the processing to determine two key values, the averaged[8] field strength and the maximum field strength at sampled points over the height of a person.

This shows that to just get a single “point” for comparison with the ICNIRP limits, you need to consider the field strength sampled at multiple points in space. Also imagine that, instead of being interested in the compliance precisely at 0m, i.e., standing on the ground, we wished to consider the situation of the person standing on top of a 0.3m high box. In that case, the sampling needed would be from 0.4m to 2.1m. While this is a different assessed position, many individual sample points are used in both cases. This is a key difference between having a field strength computed at a single point and what is needed to get a value that can be compared with the ICNIRP limits. A modelled field value at any single point in space may be considered in multiple potential positions of a person and may therefore be associated with a number of assessed exposure values. The key thing to understand is that exposure assessment refers to the whole body and is recorded in this PAEC at the position of the foot. As shown in Figure A.5, an exposure value determined for a point at 0m height therefore represents the exposure value for a whole person standing on that point.

In these PAECs, the “standard” human body is 1.8m tall (as agreed by Ofcom in discussion with RSGB) and is standing on level ground. Averaging is achieved by considering field strengths at a range of heights up to 1.8m.

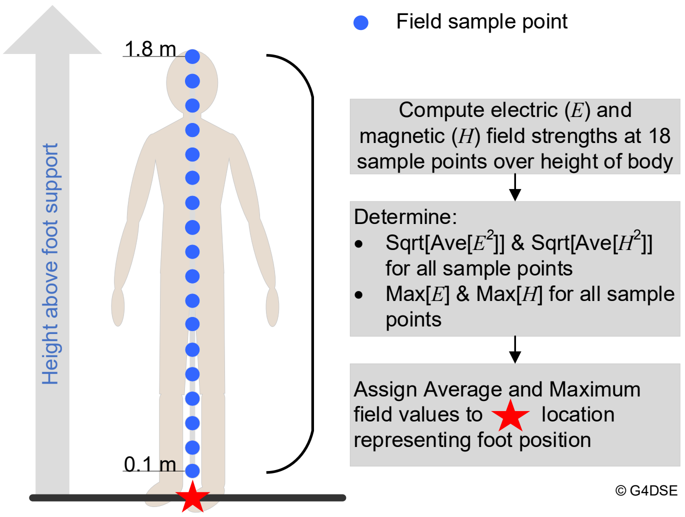


Figure A.5–How several field strength samples over the height of the body are processed to find the average and maximum electric and magnetic field strength values consistent with ICNIRP reference level definitions

The sample separation used for 50 MHz to 432 MHz is 0.1m, which gives a good distribution of points over the height of the body. For the shorter wavelengths of 1296 MHz and above, the

[8] ICNIRP actually specifies the average of the field strength-squared values since exposure is based on power and power is proportionate to the field strength squared.

separation is reduced to 0.025m, and the number of samples increased accordingly so that interference effects due to ground reflection are adequately sampled.

To compare with the ICNIRP exposure limits, the field strength sample values first need to be processed, initially normalizing them to 1W radiated power[9]. The following are computed:-

- Maximum over height of body – for the set of points from lowest sample to 1.8m sample, find the highest E and highest H observed and associate that with the position of the foot.
- Average over height of body – for the set of points from lowest sample to 1.8m sample, take the average of the root sum squared of all the E (and H) values and associate that with the position of the foot.

A.5.2 Plots of limit compliant power

Once we have the set of spatial-maximum and spatial-average field strengths for a nominal 1W radiated power at any "foot" point on the X-Z plane, it is then possible to find the ratio of the associated exposure limit to the computed field strengths. Since power is proportionate to the square of the field strength, the ratio squared gives the radiated power that would just result in the exposure limit at the foot position of interest. For the set of applicable ICNIRP exposure limits (Max E, Max H, Average E, Average H), the lowest such power at any given foot position is the limiting power value that the modelling can show compliance. By applying this processing, we therefore get a plot that gives the spatial distribution of where compliance is achieved, i.e., where a person may stand and remain exposed in compliance with ICNIRP_GP for any desired average transmit power.

The NEC results are processed to find the spatially-averaged and maximum E and H values over the 1.8m height of a potential exposed person for a nominal 1W actual radiated power. These values are compared with the local and whole-body E and H reference levels and the minimum compliant power determined. Figure A.6 presents the maximum compliant powers for the same example as Figure A.3 and Figure A.4 .

The averaging has two effects. One is a general smoothing-out of the compliance pattern. The other effect is a vertical shift because the value of Z now shows the height above ground of the subject's **feet**. In Figure A.6 the person is now depicted as the red star showing their foot position according to Figure A.5.

The advantages of the presentation in Figure A.6 over the basic field strength plots are:

- It addresses the real topic: **exposure of persons present.**
- It directly shows the limit power for exposure compliance at any given location, on or above ground.
- It covers all potential transmit powers in a single plot.

[9] In NEC-based modelling programs, the specified level of RF power actually delivered to the antenna is reported, regardless of the actual feed point impedance. This avoids the need to manage the RF impedance matching externally.

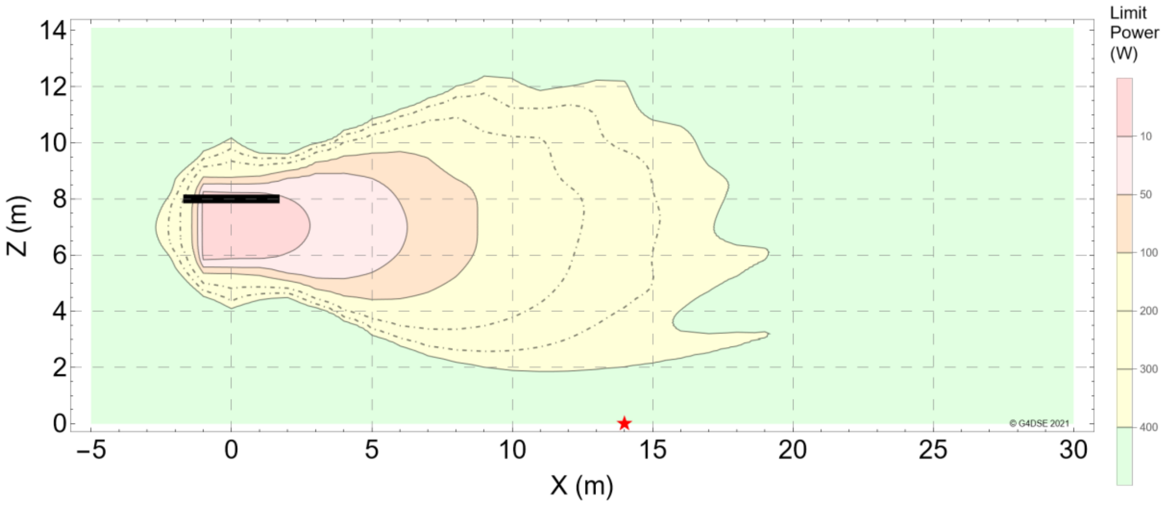


Figure A.6–Maximum transmit power for compliance with exposure limit for 8-element 144 MHz Yagi, 8 m above ground (same as Figure A.3 and Figure A.4)

Figure A.6 can now be used to define the size and shape of the EMF Exclusion Zone, for any given power level. At 400W average power (the UK power limit) this example confirms:

1. Compliance (green background) for any person standing at ground level, at any location within or beyond this plot. **This allows operation from directly beneath the antenna and avoids any need to micro-manage the ground level Exclusion Zone.**
2. Extra vertical clearance is also available at all locations, a minimum of 1.9m at forward distances of 10-15m, but even greater in most locations.
3. The forward boundary of the Exclusion Zone is a complex shape, but any point beyond 19m will be compliant regardless of height above ground level.
4. If members of the general public can access locations above ground level that are within the forward compliance boundary (e.g., a building or very sharply rising ground) this situation **will** need more active management – more details in section 3).

At lower power levels, the EMF Exclusion Zone reduces in size, drawing closer to the antenna itself. Figure A.6 also shows the smaller exclusion zones for RF power levels of 200W, 100W, 50W, 25W and 10W. Together, these contours cover the maximum permitted output power at all three levels of the UK amateur licence (400W, 50W and 10W), along with additional values to help with interpolation.

At power levels of 10W or below, the minimum antenna height is no longer determined by EMF compliance, but by the need to prevent anyone touching the bare metal of the antenna.

On all VHF-UHF bands, the minimum recommended antenna height is 2.4m.

Increasing the antenna height is always recommended. This will increase the communication range and minimize local RF interference problems on both transmit and receive.

ANNEX B DEFINING 'REPRESENTATIVE' ANTENNA MODELS

B.1 The need for antenna models

Antenna modelling is the preferred process for showing EMF compliance since it is possible to test "what if?" cases before investing time and effort in construction. Annex G.5 discusses why accurate measurements suitable for EMF exposure assessment is more difficult than many at first imagine.

Annex A described the process by which one given configuration of antenna, height and RF power can be subjected to an EMF exposure assessment. But to develop a set of generalized PAEC guidelines covering the entire range of practical configurations, the entire process of Annex A needs to be repeated across the entire range of practical configurations.

This Annex describes the generic beam antenna designs that were developed to support the entire range of simulations. Annex C will list the calculations that have been done, and section 5 shows how the huge mass of resulting data was converted into usable evidence-based guidelines.

B.2 A consistent family of Yagis

The Yagi is a common type of VHF-UHF beam antenna, and to meet the needs of exposure assessment it can be used represent the range of gains and main directive properties of other beam configurations as well. The aim here is to create a range of Yagis that is typical of mainstream design, forms a 'family' that gives consistent performance across the entire range of boom lengths and numbers of elements, and can be readily modelled using the NEC-4.2 [3] computer code.

Modelling of Yagi antennas for EMF exposure assessment is not to be confused with modelling for optimization of on-air performance. The latter requires far higher accuracy because it is concerned with detailed optimization for forward gain, suppression of minor sidelobes to minimize co-channel interference and noise pickup, good feed point impedance matching, tolerance to changes in the environment – and not least, practical construction without losing those computer-optimized properties. Many of these aspects are less relevant for EMF exposure assessments, so it is not necessary to model the real-life antenna to the same degree of accuracy.

The main consideration for these purposes is to calculate forward gain within ±1dB, along with the linked effect on the beamwidth of the major lobe.

With all of that in mind, the selected family of Yagi designs was based on the DL6WU Yagis [14], which are particularly noted for their dependable performance and have contributed 'design DNA' to almost all modern computer-optimised VHF-UHF Yagis. A notable feature of the DL6WU Yagis is that they can be extended from 10 elements to at least 100 elements without any major deviation from the expected smooth increase in gain with boom length. Further work for this PAEC has shown that performance for EMF exposure assessment purposes is also adequately representative for shorter Yagis, down to 4 elements.

These features make the DL6WU Yagis ideal for bulk computations as it is only necessary to create one master file of dimensions for a 100-element design. It is then possible to create any other design for the same frequency, but with a shorter boom length and fewer elements, simply by shortening this same master file. For a different frequency, a new master file is created simply by re-scaling all of the antenna dimensions to the new wavelength.

To complement the existing set of DL6WU-derived antennas from 100 elements down to 4, separate individual designs were added for Yagis of 3 and 2 elements, and finally a half-wave dipole. The 3-element design was taken from a published source [22] and is representative of its type. The 2-element Yagi is an optimized design from the *ARRL Antenna Book* [23].

B.3 Selecting examples to be modelled

For this exercise it is not necessary to consider any aspects of mechanical design. Regardless of physical practicality, the element diameter in the master file can simply be scaled to a new frequency along with all the other dimensions, so the electrical resonance of each Yagi element will always be correct.

From our NEC verification investigations, an element diameter of 0.001 wavelengths was found to give a stable feed impedance with different segmentations so that diameter was chosen as the basis for the design. The individual element lengths and spacings were taken from the VK1OD design tool [18] which is traceable to the original DL6WU design data that had been verified in an anechoic chamber. Individual designs up to 100 elements synthesized and the gain determined. Segmentation was investigated and a scheme chosen where both NEC-4.2 [3] and NEC-5 [4] give comparable results. These two EM simulators have significant fundamental differences, so the good agreement gives extra confidence in the results of either code as advised in [5].

Element materials in the Yagi models are assumed to be perfectly conducting. This slightly increases the predicted field strengths compared with any practical case where there are ohmic losses, and also means that the small element diameter does not affect the field strengths.

B.4 Comparison with VE7BQH data

A particularly useful source of Yagi performance data is the collection of models developed by Lionel Edwards, VE7BQH, and a large group of collaborators [15]. Figure B.1 shows the VE7BQH data for Yagis of boom lengths from 0.75λ to 20λ, plotted in terms of free-space forward gain (dBi) versus boom length (λ), with the equivalent PAEC-2 data (DL6WU Yagis) for comparison.

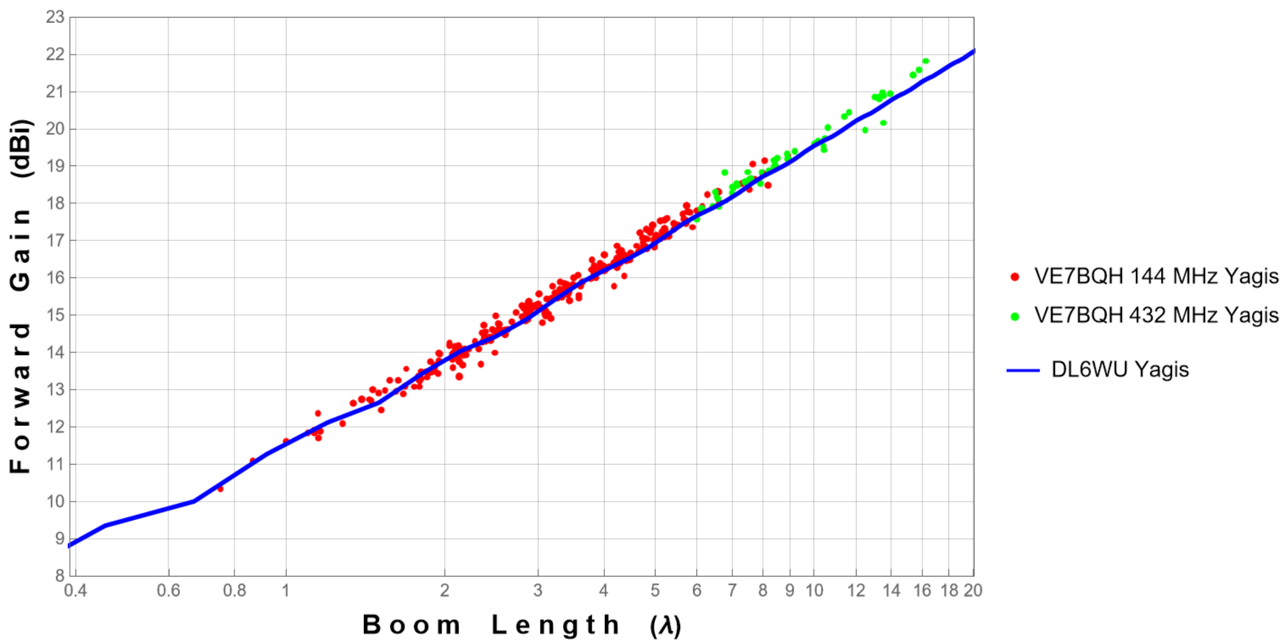


Figure B.1–VE7BQH antenna data versus PAEC-2 model data, boom lengths 0.4λ to 20λ.

The data illustrate the expected trend of forward gain versus boom length. The DL6WU-derived Yagis of 4 elements and upward create a remarkably self-consistent curve. The data points from the VE7BQH collection come from a wide range of real-life antennas that are not related to one another, but they all cluster about the DL6WU-derived trendline within typically ±0.5 dB (the few exceptions above the trendline are mostly antennas that have been intensively optimized for forward gain).

Small Yagis are not heavily represented in the VE7BQH data because the project was originally about larger antennas for moonbounce. However, the data for the 2- and 3-element reference Yagis are consistent with other modelling results. Not plotted in Figure B.1 is the half-wave dipole, with a 'boom length' of zero and a gain of 2.15dBi.

ANNEX C MODELLED DATA AND ANALYSIS OF KEY COMPLIANCE PARAMETERS

C.1 General approach

This Annex presents a summary of the main NEC modelling runs, followed by detailed descriptions of how the data has been interpreted. The aim is to develop a rationale for a widely applicable exposure assessment that provides a simple description of any EMF Exclusion Zone that might be necessary to comply with the Ofcom EMF requirements. Since this work is in collaboration with the ARRL in the USA, the 220 MHz and 902 MHz US amateur bands are included.

Section C.2 itemises the computer modelling, which totals more than 4000 individual NEC runs.

Sections C.4 and C.5 report on the analysis of the resulting 250 GB of data used to clarify the key parameter values used in section 5 to define the EMF Exclusion Zone.

Patterns of data emerge that are not limited to a specific antenna type, and not always limited to any specific frequency bands. These findings allow smaller but more accurate Exclusion Zones to be defined than could be achieved using the Ofcom or RSGB EMF calculator methodology [24], [25].

A major breakthrough is a simple way to decide when no Exclusion Zone is needed for persons standing anywhere at ground level for a given transmit power, provided that the height of the antenna exceeds a minimum value that will usually be quite modest.

C.2 Data runs

Having established how to use NEC data to perform exposure assessments in Annex A, multiple runs were completed using the reference Yagi family described in Annex B. Table C.1 summarises the entire exposure assessment dataset.

Table C.1–Exposure assessment dataset

Band (MHz)	Standard Yagi # Elements	Antenna heights	Number of NEC runs	Resolution
50	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 18	2.2->5m, 0.2m steps 5.5->10m, 0.5m steps 11-> 20m,1m steps 22->36m, 2m steps	559 – Rich Soil ground	X = 0.1m Z = 0.1m
		36m	13 – Free space	
70	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 18	2.2->5m, 0.2m steps 5.5->10m, 0.5m steps 11-> 20m,1m steps	455 – Rich Soil ground	
		26m	13 – Free space	
144	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 18, 21, 25	2.2->5m, 0.2m steps 5.5->10m, 0.5m steps 11-> 20m,1m steps	525 – Rich Soil ground	
		20m	15 – Free space	
222	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 18, 21, 25	2.2->5m, 0.2m steps 5.5->10m, 0.5m steps 11-> 20m,1m steps	525 – Rich Soil ground	
		20m	15 – Free space	
432	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 18, 21, 25, 30, 38, 46, 59	2.2->5m, 0.2m steps 5.5->10m, 0.5m steps 11-> 20m,1m steps	665 – Rich Soil ground 665 – Perfect ground	
		20m	19 – Free space	
902	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 18, 21, 25, 30, 38, 46, 59	2.2->5m, 0.2m steps 5.5->10m, 0.5m steps 11-> 15m,1m steps	570 – Rich Soil ground	X=0.1m Z=0.05m
		15m	19 – Free space	
1296	1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13, 15, 18, 21, 25, 30, 38, 46, 59	2.2->5m, 0.2m steps 5.5->10m, 0.5m steps 11-> 15m,1m steps	570 – Rich Soil ground	X=0.1m Z=0.025m
		15m	19 – Free space	
Note: The US 222 MHz and 902 MHz bands are included since the data set is able to be used both by the RSGB in the UK and the ARRL in the USA. Analysing all the data gives a better overview of the physical dependencies.				

Each data run consists of an X-Z slice along the main beam out to the compliant distances for the Ofcom and the FCC exposure limits, and up to or above the height of the antenna. The limit compliant powers (General Public and Occupational) are found for each data point representing the foot position of a 1.8m tall standard person.

For this work, special routines were developed using *Mathematica* [2] to drive NEC-4.2 in a batch mode, to process the NEC .TXT files, and then to create the various plots for this PAEC-2.

From Table 2, this involved more than 4600 individual NEC runs. These generated more than 250 GB of output files; detailed hard evidence as opposed to traditional simplifications.

C.3 Achieving compliance anywhere at ground level

There are huge practical benefits if compliance can be achieved at all points at ground level. It allows operation directly below the antenna, close to the foot of the mast, with no need to alter operating procedures or apply access controls for anyone else at ground level.

The straightforward way to achieve this is to raise the antenna above a certain minimum height. We then set out to mine the gigabytes to figure out which factors are important. The key factor is the RF power level.

For each of the thousands of modelling runs, we established the minimum power level at which compliance was just demonstrated, for a person standing on level ground. This process was repeated for every 0.1m step along the X axis of each plot like Figure A.6. All of those steps were then repeated for every combination of frequency band, antenna type (number of elements) and antenna height as described in Table C.1.

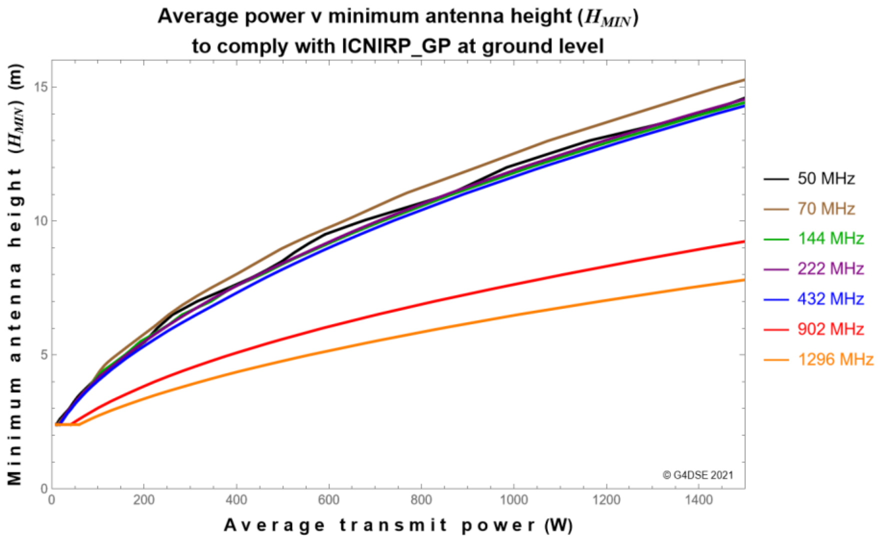
Having got the compliance data, for antennas ranging from dipoles to high-gain arrays, and for positions ranging from directly under the antenna to beyond the compliance distance for the highest power investigated, and this set of data repeated for incremental antenna heights from 2.2m to above 10m, we then determined for each antenna height the power level that would be just compliant at ground level from all antennas and for all distances from the antenna. Then once again at each antenna height, we determined the *lowest* transmit power for which compliance was shown *anywhere at ground level* and from *any of the wide range of antennas*.

The actual minimum compliant power level for any individual antenna at any specific location is highly variable. We observed that for low powers, the near-in cases are most important and so low-gain antennas with wide vertical beamwidths are the critical case. For higher powers, it is possible that a person may be in the edge of the main beam when standing further from the antenna and this may then become the critical case. By covering the range of antennas, we have addressed such extremes and the cases in between to find the worst case.

By doing this, we determined the worst-case relationship between antenna height and maximum transmit power that would still result in compliance *anywhere at ground level for any antenna*. For any arbitrary antenna, the actual maximum compliant power at an arbitrary position on the ground may be significantly higher or may be close to the worst case. On the other hand, the practical effect on the required mast height will often be less significant.

These data are plotted in Figure C.1. The horizontal axis is now the transmitter power, and the vertical axis is the lowest antenna height at which unrestricted ground-level compliance can be proven for the wide range of beam antennas. The coloured lines are the data for each band, and it can clearly be seen that the lines for all the bands from 50 MHz to 432 MHz are all bunched together. Within this frequency range, frequency has little or no practical effect on the conservative minimum antenna height.

This is mainly because ICNIRP has defined exactly the same limits for field strength for all frequencies between 30 MHz and 400 MHz, covering the range of wavelengths where energy absorption could be increased by whole-body resonances. The ICNIRP limit for 432 MHz is slightly more relaxed, so the blue line for that band is slightly below all the others. The limits for 902 MHz (USA) and 1296 MHz are higher still, which moves the limit curves for those bands even further downward.



Band	H_{MIN} over 'Rich soil' for ICNIRP_GP						
	10W	20W	50W	100W	200W	400W	1500W
50 MHz	2.5	2.7	3.3	4.2	5.5	7.7	14.6
70 MHz	2.4	2.6	3.2	4.3	5.8	8.1	15.3
144 MHz	2.4	2.6	3.3	4.3	5.6	7.6	14.5
222 MHz	2.4	2.5	3.3	4.2	5.5	7.6	14.6
432 MHz	2.4	2.5	3.2	4.1	5.4	7.4	14.3
902 MHz	2.4	2.4	2.5	3.1	3.9	5.1	9.3
1296 MHz	2.4	2.4	2.4	2.8	3.4	4.4	7.9

Figure C.1 – Minimum antenna height (H_{MIN}) to deliver ICNIRP-2020_GP compliance anywhere at ground level, for any of the applicable antennas. (Includes US bands and power levels.)

Figure C.1 is based on the reference antenna family, and the ground conditions for “Rich soil”. Figure 4 in the main text is a “close up” of Figure C.1 for the UK licence power range.

More checks were performed to confirm if these data are transferable to other antenna types and other ground conditions.

To check on antennas with higher gain for a given boom length, Justin Johnson G0KSC kindly supplied data for three of his highly optimised Yagi designs [16]. These have higher gains and cleaner patterns than the Annex B reference antennas of the same boom length. Compliance checks were made using these examples and it was found that applying the height limits in Figure C.1 still resulted in EMF compliance for persons standing anywhere at ground level.

Examples of stacked arrays (vertical stacking) were similarly checked. In this case the ‘minimum antenna height’ is that of the lowest boom in the array stack, and once again the Figure C.1 guidance remained conservative.

Finally, some examples were computed using the NEC option of “Perfect ground”. At power levels up to 400W the minimum antenna heights remain unaffected, with only marginal increases at higher power levels.

Figure C.1 therefore is a good basis to address the limitation in the Ofcom EMF calculator [24], which does not consider the actual radiation pattern when determining its “compliance distance".

The outcome of these PAEC computations is that locating your antenna above the minimum specified height for your selected power is sufficient to show EMF compliance for a person standing anywhere at ground level.

C.4 Forward compliance distance

When determining the "compliance distance", the Ofcom EMF Calculator [24] and the RSGB Calculator [25] both account for ground reflection by calculating the field strength in free space, independent of direction, and then multiplying all results by a factor of 1.6. In order to be simple and conservative, these calculators ignore the spatial averaging defined by ICNIRP (Figure A.5) and do not consider whether the ground reflection factor is correct for any given exposure location or is even needed at all. This section describes how PAEC-2 improves on those simple assumptions when establishing the forward compliance distance used to define the radius of the PAEC-2 Exclusion Zone.

C.4.1 How ground reflections affect observed field strength

When radio waves meet a change in the propagation medium such as an air/ground boundary, some of their energy is absorbed in the medium and some is reflected. For antennas located above ground, part of that energy follows a direct path from the antenna to a point of interest and part follows a reflection path bouncing off the ground. At the point of interest, the observed field strength is the combination of these two rays. Vector addition of those two rays at any point can result in either an increase or a decrease in the resultant field strength, and over a larger area this creates an interference pattern with regions above and below an average field strength.

While that is an idealised model, it offers a means to provide a limiting maximum field strength value for the more complex real-world conditions with uneven ground and other reflecting surfaces in the environment.

Another feature of ground reflection is that it depends on the distance from the antenna to the target location, and their respective heights above ground. For some locations, the reflected field strength will be negligible compared with the field strength of the direct ray. In Figure C.2, the reflected ray from a point close to the antenna will have to travel a much longer distance compared with the direct ray, so the direct ray will dominate. There is then no justification to apply a ground reflection factor.

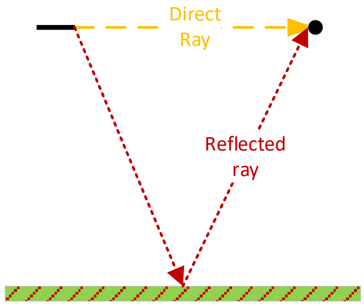


Figure C.2 – Target location close to antenna, where the direct ray dominates

At the longer distances shown in Figure C.3, the angle of incidence between the reflected ray and ground is very shallow, so the direct and reflected paths are of similar length. The value of the ground reflection can then make a substantial difference to the combined field strength. Beyond moderate distances from the antenna, the reflections actually reduce the combined field strength very close to the ground, while still increasing the field strength at some heights above ground.

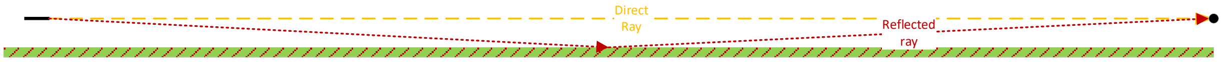


Figure C.3–Point of interest where ground reflection is significant

This discussion is just an interesting qualitative observation that needs to be quantified before it can be used in an exposure estimation or evaluation of compliance limit distances.

As already noted, for compliance checks we are almost entirely interested in identifying the boundary points where the exposure estimation is just barely compliant with the exposure limit. Generally, low transmit power will result in a small forward compliance distance, so at reasonable antenna heights above ground that will mean the Figure C.2 condition applies; in other words, ground reflection does not materially affect the forward compliance distance. However, as the power is increased, the compliance distance also increases, and then the Figure C.3 condition begins to apply, and the ground reflection factor can significantly affect the forward compliance distance (and for higher EIRPs giving greater forward compliance distance, the position of the maximum froward compliance distance can be raised some way above ground).

From the results of exhaustive exposure modelling (see Table C.1), we can explore the maximum extent of the forward compliance distances for a range of antennas for different frequency bands, at a range of heights above ground, and for different transmit powers. The NEC-4.2 [3] code uses advanced methods to calculate the interactions of EM fields with ground, which gives a much more accurate basis to establish where ground reflections are, or are not, relevant to the forward compliance distance.

C.4.2 Determine conditions where ground reflection is / is not relevant

In section C.4.1, we explained why we might expect there to be a difference between the forward compliant distance for low and high antennas and for different transmit powers. To illustrate these effects, Figure C.4 shows three compliance limit plots for the same 11 element 144 MHz Yagi, all modelled using NEC-4.2 [3]. Similar to Figure A.6, the contours show the maximum transmit power that would just be compliant with ICNIRP limits at the indicated boundaries.

The centre of the boom is located at X=0, marked with the blue vertical line. The yellow vertical lines show the maximum extent of the 400W compliance contour for the three different cases modelled: antenna in free space, 10m above “Rich soil” ground, and 5m above “Rich soil” ground.

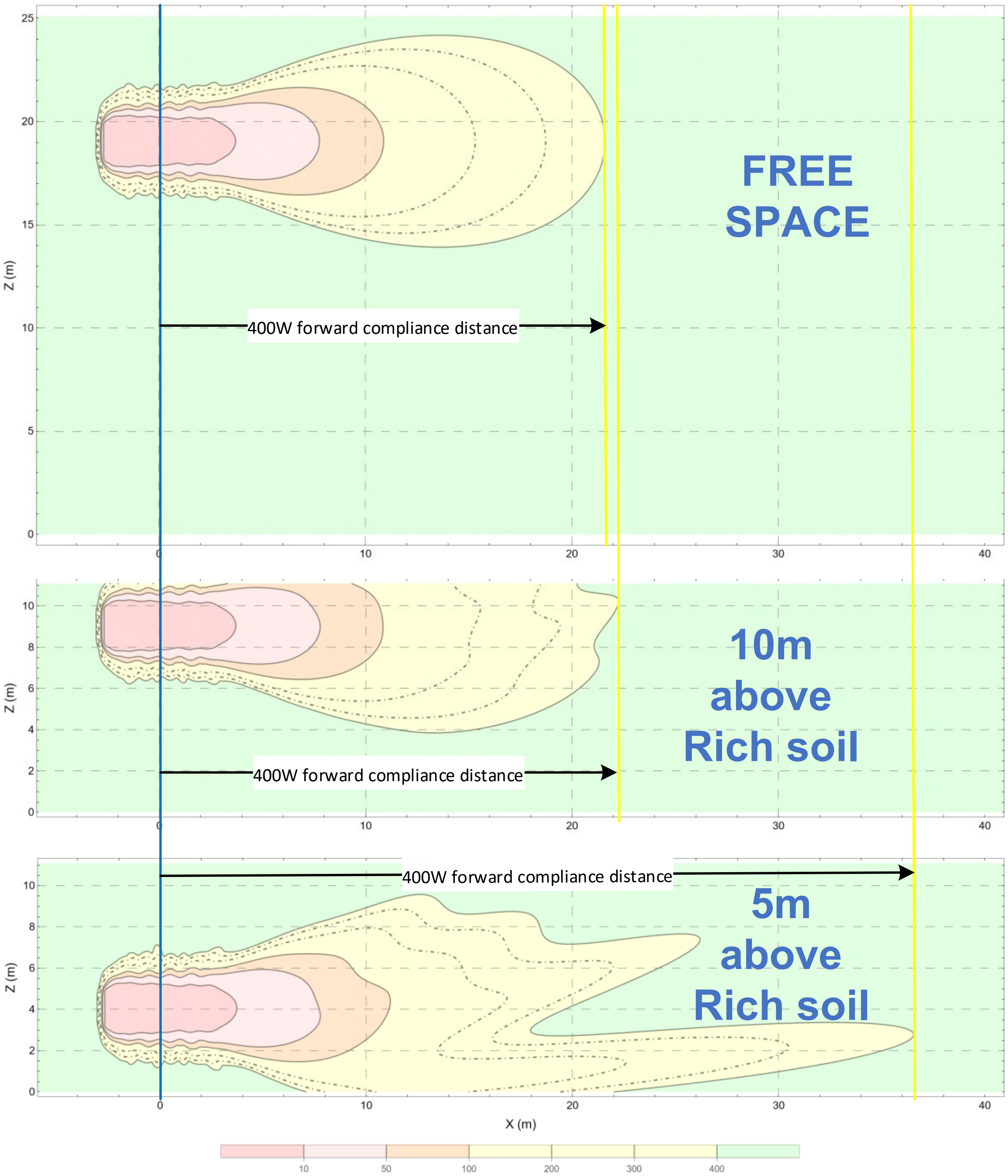


Figure C.4–Limit power contours for 11 element 144 MHz antenna modelled in three different environments. The yellow vertical lines show the maximum extent of the forward compliance distance at 400W average power.

The effects predicted in Figures C.2 and C.3 are therefore confirmed. At an antenna height of 10m AGL, the forward compliance distance is scarcely different from free space, confirming that ground interactions are minimal. But when the antenna is lowered to only 5m above ground, the interaction is noticeable; not only does the 400W compliance contour touch the ground over a significant distance, but also the reflected ray considerably increases the forward compliance distance as per the case in Figure C.3. However, at power levels of 100W or less, the smaller forward compliance distances do not change with height or ground type showing that the ground reflection has less and less effect on compliance as per the case in Figure C.2.

Continuing with the same idea and the same antenna, we now analyse the same data for a wider range of antenna heights and an expanded range of RF power levels. For Figure C.5 we explore for each transmit power how the maximum forward compliance distance changes with different antenna heights. The substantially vertical portions of each curve show where the forward compliance distance is largely independent of antenna height showing that ground reflections are not important in these cases. The rightward-pointing bulges at lower antenna heights and/or higher power levels show where ground effects are combining to push the forward compliance distance further away from the antenna. (For a direct comparison between Figure C.5 and Figure C.4, look at Figure C.5 brown 400W line. At the antenna height of 10m the forward compliance distance is 23m in both plots; and at a height of 5m, both plots show how the forward compliance distance is pushed out to 37m.)

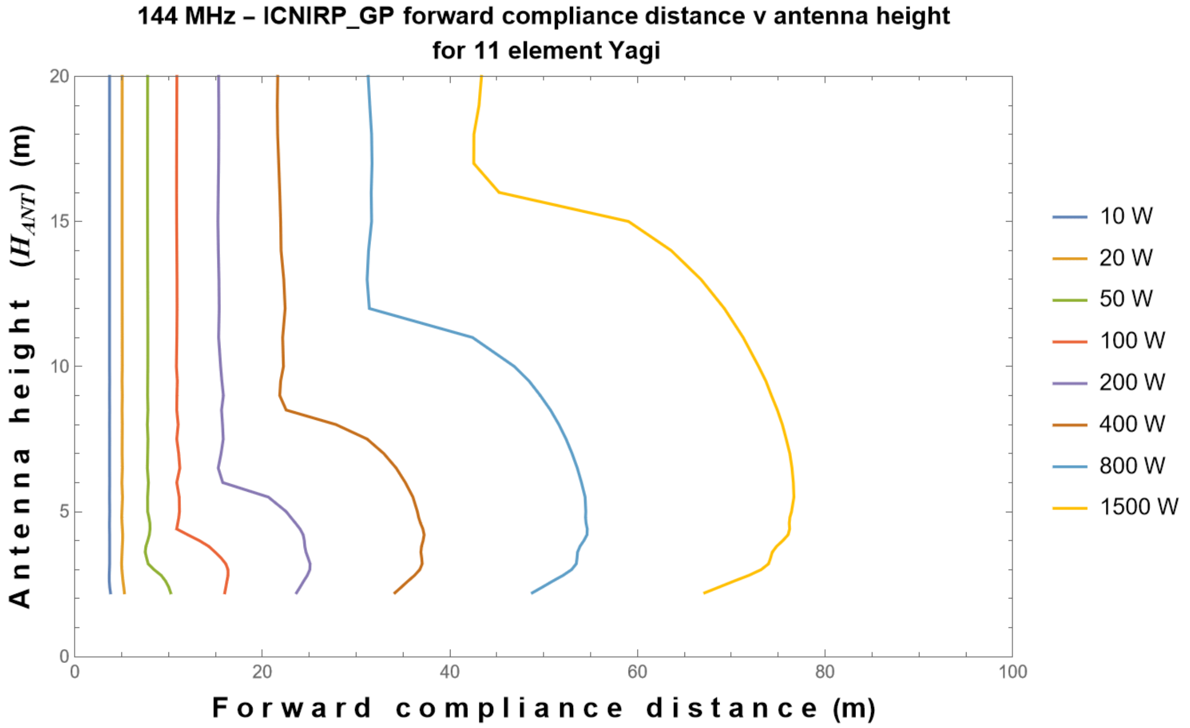


Figure C5–Forward compliance distance v antenna height for different transmit powers

For each transmit power down to 50W, there is a clear threshold or breakpoint in the antenna height, above which the ground reflections no longer significantly affect the forward compliance distance and the predicted field strengths become identical to the free-space case. For the lowest powers (10 W and 20 W) the forward compliance distance is so short that ground reflections are unimportant at any antenna height, down to our self-imposed minimum of 2.4m.

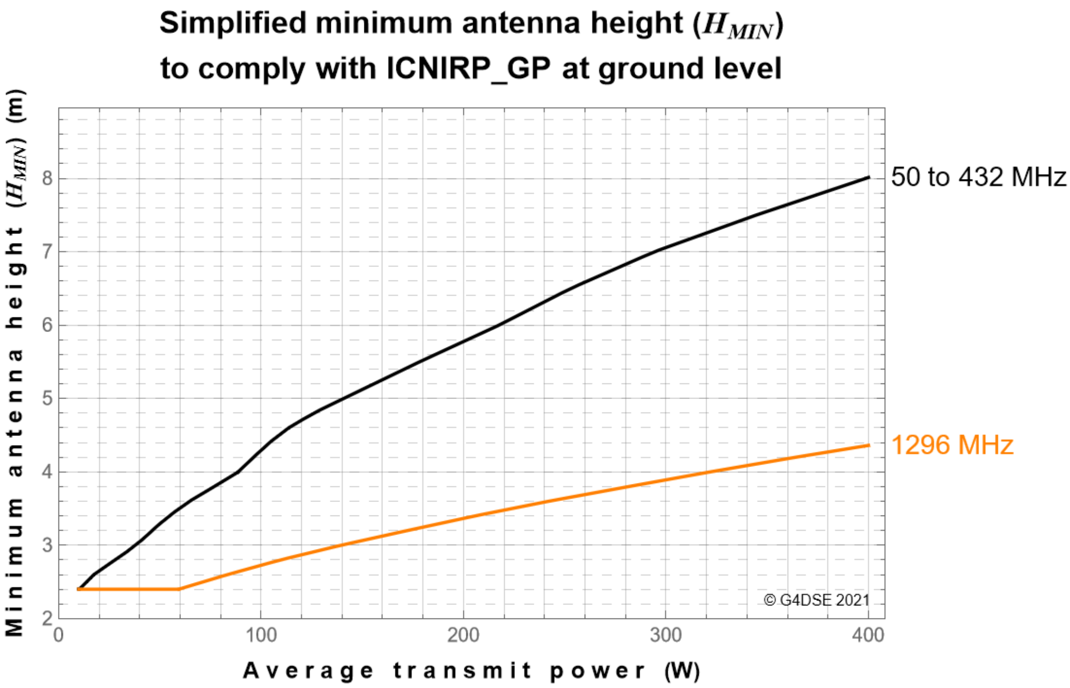
Key observation - As the antenna height AGL increases, the ground reflection's effect on the forward compliance distance becomes less significant and above a certain height it ceases to be important.

ANNEX D SIMPLIFICATIONS USED IN SECTION 4

This document includes complex graphics that offer the opportunity for people to dig a little deeper into their EMF compliance check if they are interested or absolutely need to. For the majority of amateurs, it is expected that as long as they can show compliance with the Ofcom EMF license condition, they would much prefer as simple a method as feasible. In this Annex, we define applicability restrictions and conservative simplifications in order to define the simplified Exclusion Zone as described in section 4.

D.1 Simplifying minimum height for ground compliance

It can be seen from Figure C.1 that there really is little difference in the minimum heights for the bands from 50 MHz to 432 MHz inclusive. Therefore, we can define a single worst-case curve that can be used for all of these bands see Figure D.1.



Band	H_{MIN} over 'Rich soil' for ICNIRP_GP					
	10W	20W	50W	100W	200W	400W
50 to 432 MHz	2.4	2.7	3.3	4.3	5.8	8.1
1296 MHz	2.4	2.4	2.4	2.8	3.4	4.4

Figure D.1—Minimum compliant-anywhere-on-ground antenna height for ICNIRP General Public (GP) (H_{MIN}) for a range of powers UK bands and powers – Simplified version

Use H_{MIN} as the value for D_{EZ} to determine the lowest extent of the Exclusion Zone for antenna heights above H_{MIN}

D.2 Simple guidance for the determination of the radius of the exclusion zone (R_{EZ})

In section 5 we describe how to determine a ground-influence factor and free space forward compliance zone and then how to use these with some key antenna dimensions to establish the radius of the exclusion zone centred on the rotator pole. Here, we will apply just a few restrictions to develop a simple look-up plot to get you straight to R_{EZ}.

1. Constrain that the antenna is at or above the height H_{MIN} from Figure D.1 for the selected power.
2. Determine from Figure 6 the highest ground-influence factor (over all gains) for that frequency and power (see Table 2), (e.g., from Figure D.1, 50 MHz, 100W corresponds to a minimum height of 4.3m, then from Figure 6, 50 MHz@100W the 4.3m height gives a maximum F_G of 1.3 listed in Table 2).
3. Use the boom length from the standard antenna family for the associated gains.(we have seen that the standard antenna boom lengths are longer than more optimised antennas and so this is conservative).
4. Use a quarter wavelength as the length of the first director. (The frontmost director is likely to be shorter than a free-space quarter wavelength so this is conservative)

Table 2–Ground-influence factor (F_G) for antenna at or above H_{MIN}

Band	**Simplified F_G for antenna $H_{ANT} \geq H_{MIN}$ (see Figure 6)**					
	10W	20W	50W	100W	200W	400W
50	1.1	1.1	1.2	1.3	1.4	1.4
70	1.1	1.1	1.1	1.2	1.3	1.4
144	1.1	1.1	1.1	1.1	1.4	1.4
432	1.1	1.1	1.1	1.1	1.1	1.1
1296	1.1	1.1	1.1	1.1	1.1	1.1

Using these constraints, we then define a new family of curves similar to Figure 5 but this time for real ground and corrected to give R_{EZ} directly (see Figure 3), the horizontal distance with respect to the rotator pole and D_{EZ}.

ANNEX E COMPARING COMPLIANCE CHECK APPROACHES

E.1 Outline of study

As a result of the work to develop PAEC-2, there are now alternative ways that can be used by UK radio amateurs to analyse V/UHF stations using beam antennas:

a) Using the RSGB calculator based on the Ofcom algorithm
b) Using the PAEC-2 "simplified" approach
c) Using the PAEC-2 "full" approach

In addition, there is the full advanced technique with NEC-4.2 and the G4DSE Mathematica [2] post analysis scripts as used to perform the modelling upon which PAEC-2 is based.

In this study, a test case is defined that has not previously been analysed in the course of the PAEC-2 development. This is then subjected to each of these assessment approaches and the difference in the findings compared. The study investigates the size and shape of the Exclusion Zone rather than a full compliance check.

This annex provides data on the likely benefits of applying more rigorous assessments as compared with the increased approach complexity.

E.2 Key parameters

For this comparison study the parameters used are shown in Table E.1:

Table E.1–Parameters used in comparison study

Description (unit)	Value	Comment
Frequency (MHz)	144.2	
Average power at antenna (W)	40	Takes into consideration mode, usage, feeder loss
Yagi - Number of elements	10	"Reference" DL6WU set
Gain (dBi)	14.0	
Boom length (m)	4.46	
Front director length (m)	0.89	
Pole offset from centre (%)	5	Centre of rotation, 2 m from the reflector, $\alpha = 0.05 * 4.46 = 0.23$
Antenna height AGL (m)	8.0	
Physical radius of rotation (m)	2.5	

E.3 Exclusion zone – determined using Ofcom algorithm (RSGB calculator)[10]

This comparison uses the Ofcom interpretation of Compliance Distance (CD) to determine the minimum distance from any part of the antenna to any part of the body. To compare with the PAEC-2 Exclusion Zone, we establish the Zone containing the levels on which the reference person may stand to be more than CD away from the antenna. The CD is obtained using the RSGB calculator without any assumptions on vertical directivity.

[10] Calculator version emf-calculator-v0.1.2-rsgb 10a.xlsx, downloaded 2021-08-13

Entering the Table E.1 parameters into the RSGB calculator [25] gives:

Compliance Distance (CD) = 10.2m (from the antenna)

Vertical separation = 6.2m,

Horizontal separation = 8.0m: This is the distance on the ground from the physical radius swept by the antenna considering the boom length, final director length and offset of the pole from the centre of the boom.

To enable comparison with the PAEC-2 and advanced modelling results, these results are developed into an Exclusion Zone.

Figure E.1 shows the Exclusion Zone determined, using the RSGB calculator and the Ofcom interpretation of the Compliance Distance, with respect of the standing level of exposed persons. Since the RSGB/Ofcom paradigm is based on “no part of the body”, the Exclusion Zone extends the lower part of the “no part of the body” perimeter towards the ground by the “standard height” of 1.8 m.

The radius of the zone on the ground is the RSGB horizontal separation + radius of rotation of the antenna i.e., 8 + 2.5 = 10.5m. At and 1.8m below antenna height, the maximum radius is the compliance distance + radius of rotation of the antenna = 12.7m.

For comparison with the nomenclature in PAEC-2, the Ofcom D_{EZ} is the compliance distance or 10.2m – which is less than the antenna height resulting in the Exclusion Zone extending to ground level.

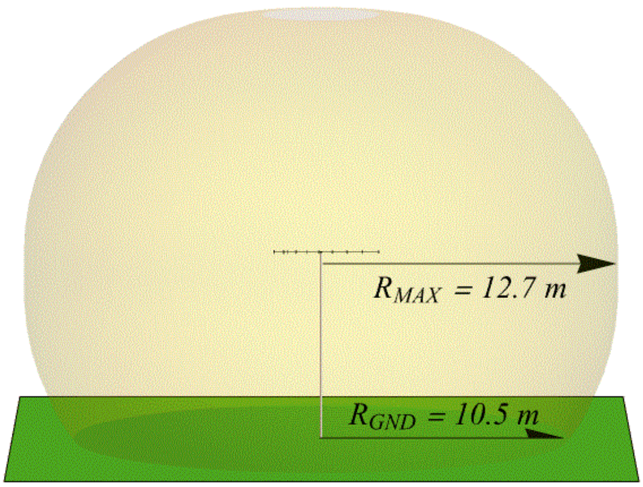


Figure E.1–Ofcom-based exclusion zone based on Compliance Distance and foot position for standard 1.8 m tall person

E.4 Exclusion zone – determined using PAEC-2 “simplified” approach (Section 4)

For the PAEC-2 simplified approach (section 4), the key parameters are:

Frequency Band = 144 MHz, Antenna gain = 14 dBi, Average power = 40 W, Antenna height = 8 m.

For 144 MHz we look at Figure 3 and note that the 50 W plot is the nearest available above the desired power.

From that 50 W plot we see the H_{MIN} is 3.3m and note that this is less than the 8 m evaluation height, so compliance is demonstrated at ground level. Further, we can also use the 3.3 m figure to define the lowest extent of the exclusion zone H_{CL} = 8 – 3.3 = 4.7 m. i.e., the exclusion zone is 3.3 m below the antenna height and 4.7m AGL.

Reading across from the 50 W plot at the 14 dBi gain point, we get an R_{EZ} of 8.7 m.

Figure E.2 shows the PAEC-2 simple exclusion zone in scale with the antenna.

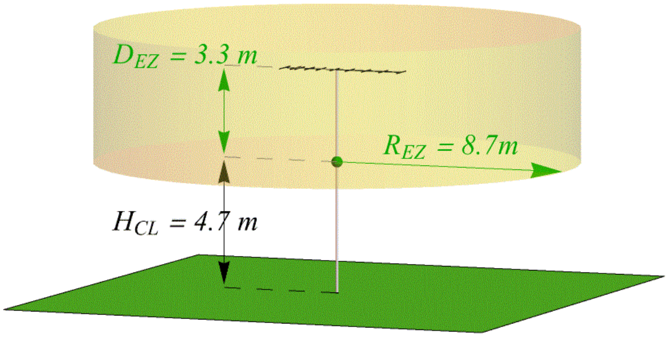


Figure E.2–PAEC-2 "Simple" exclusion zone based on foot position for standard 1.8 m tall person

E.5 Exclusion zone – determined using PAEC-2 "full" approach (section 5)

For the PAEC-2 full approach (section 5), the key parameters are: Frequency Band = 144 MHz, Antenna gain = 14 dBi, Average power = 40 W, Antenna height = 8 m, boom length = 4.46 m, front director length = 0.296 m, Rotator pole at 2 m from the reflector end of boom.

From Figure 4, Green 144 MHz plot, 40W gives H_{MIN} of 3m, (D_{EZ} = H_{MIN})

From Figure 5, 144 MHz, Green 50 W at 14dBi gives R_{FS} = 7.4m

From Figure 6, 144 MHz, 50W at 14 dBi and 8m gives F_G = 1.1

Distance between the rotator pole and the mid-point of the boom α = (4.46/2)-2=0.23m

Length of director: L_D = *0.296* m

$$R_{EZ} = \sqrt{(R_{FS} \times F_G + \alpha)^2 + (\frac{L_D}{2})^2} = \sqrt{(7.4 \times 1.1 + 0.23)^2 + (\frac{0.296}{2})^2} = 8.4 \text{ m}$$

Figure E.3 shows the PAEC-2 Full exclusion zone in scale with the antenna.

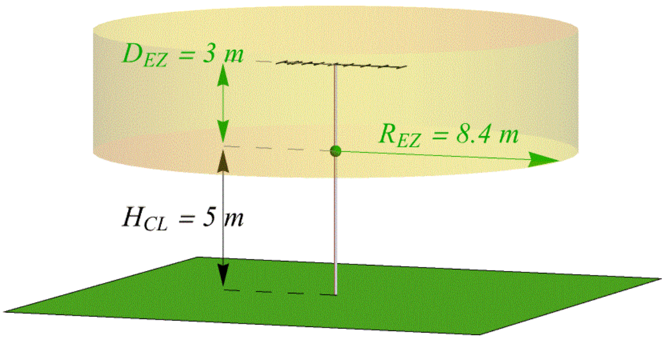


Figure E.3–PAEC-2 "Full" exclusion zone based on foot position for standard 1.8 m tall person

E.6 Exclusion zone – determined using advanced modelling

Applying the same modelling as used in Annex C to the 10-element reference Yagi, Figure B.4 gives the limit power for compliance plot.

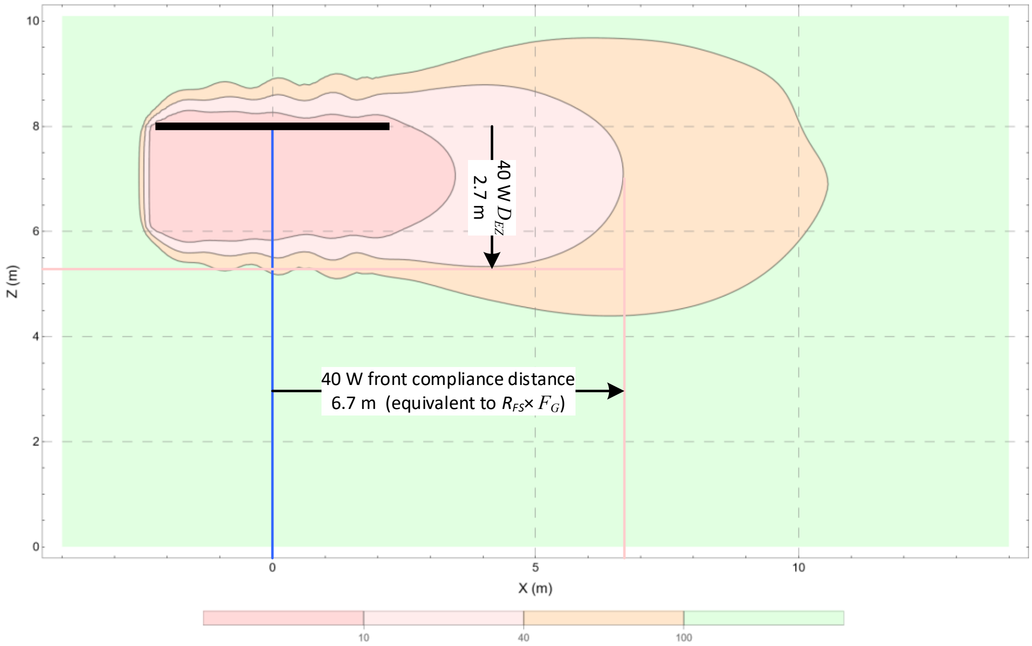


Figure E.4–Plot of limit power for compliance for test antenna

To determine R_{EZ}, we still need to do a correction for the pole offset from the boom centre and the length of the final director. Since the forward compliance distance includes the ground influence factor for this specific case:

$$R_{EZ} = \sqrt{(R_{FS} \times F_G + \alpha)^2 + (\frac{L_D}{2})^2} = \sqrt{(6.7 + 0.23)^2 + (\frac{0.296}{2})^2} = 6.9 \text{ m}$$

From inspection of Figure E.4, D_{EZ} = 2.7 m.

Figure E.5 shows the advanced modelling exclusion zone in scale with the antenna.

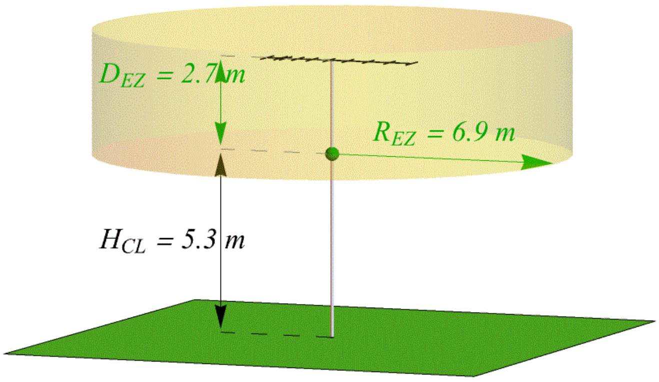


Figure E.5–Advanced modelling Exclusion Zone based on foot position for standard 1.8 m tall person

E.7 Discussion

Table E.2 compares key aspects of the Exclusion Zones determined using the four alternative methods described in this annex.

Table E.2–Comparison of Exclusion Zones

Compliance basis	**Zone determination basis**	**Maximum exclusion zone radius (m)**	**Exclusion zone radius at ground level (m)**	**Ground clearance height (H_{CL}) (m)**	**Clearance below antenna (D_{EZ}) (m)**
ICNIRP 1998	Ofcom (RSGB)	12.7	10.5	N/A	10.2
ICNIRP 2020	PAEC-2 Simplified	8.7	N/A	4.7	3.3
	PAEC-2 Full	8.4	N/A	5	3.0
	Advanced (NEC-4.2 and post processing)	6.9	N/A	5.3	2.7

Each approach is able to demonstrate compliance with the respective compliance basis, but each has a different level of overestimate. If you just use the default offered by Ofcom, and the resulting Exclusion Zone does not affect how you wish to operate, then there is no need do anything else.

By using PAEC-2, it is possible to show compliance for smaller Exclusion Zones. It should still be noted that these are still larger than can be shown using the very complicated advanced method. A key thing to note therefore is that even though PAEC-2 can show compliance for a significantly smaller Exclusion Zone than the Ofcom algorithm, PAEC-2 still remains conservative.

Taking the advanced method as the "reference", what are the trade-offs for the simpler approaches, in terms of increased freedom of action vs effort involved?

1. With beam antennas, there is a dramatic difference between the shape and size of an Exclusion Zone based on the Ofcom calculator and the much smaller Exclusion Zone based on PAEC-2. Conclusion: for beam antennas applying PAEC-2 will always be worthwhile.
2. The big win from PAEC-2 is verified compliance everywhere at ground level. Again, that's always worth the effort.

3. Only then do we get to the differences between simplified and full PAEC-2 approaches. The difference in H_{CL} and R_{EZ} compliance demonstrations will often be too small to matter, so only use the “full” PAEC-2 approach if compliance is very tight and there are no other practical options like increasing antenna height.
4. So how much does overestimation of R_{EZ} by both of the PAEC approaches really matter? (In the example here that means 8.4m or 8.7m compared with the “reference” value of 6.9m.)

   In most cases, probably “not much”. Primarily, if you already have ground-level clearance, R_{EZ} doesn’t matter at all unless there are elevated, inhabited buildings/structures or sharply rising ground within that radius. Even then, the differences between PAEC-2 estimates and the “reference” value only affect the narrow annulus between 6.9m and 8.x m.

ANNEX F WHY DIFFERENT COMPLIANCE CHECK METHODS CAN RESULT IN DIFFERENT RESULTS

This annex considers why compliance checks using PAEC-2 can be less restrictive than when using the Ofcom [24] and RSGB [25] calculators – but all are valid. To understand why, we need to consider their underlying methods and the ICNIRP exposure limits.

The Ofcom/RSGB calculators use an algorithm that evaluates the power density at a distance in the main beam to the front of the antenna assuming initially the antenna is in free space i.e., unaffected by ground reflections. This power density is then subject to a fixed multiplication factor to account for ground reflections. The modified power density value for a single point is then compared directly with the ICNIRP 1998 General Public reference level. The distance at which the computed power density corresponds with the reference level is the "compliance distance". Ofcom then states this distance means the nearest approach of any part of the body to any part of the antenna.

The calculators are likely to be conservative because:

- An explicit aim of the methodology is that it shall not result in excessive exposure and apply to pretty well all antennas.
- They do not explicitly consider the directivity of the antenna.
- They calculate the power density and compare it with 1998 ICNIRP limit that is *"intended to be spatially averaged values over the entire body of the exposed individual"* (see p509 [26]). The field will vary significantly over the height of a person standing on the ground.
- They use a fixed ground-influence factor (based on a reflection coefficient of 0.6) to account for the presence of ground.
- They use far-field evaluation methods to calculate the power density in places close to the antenna where the far-field radiation pattern has not fully developed.
- When defining the Exclusion Zone boundary, the antenna and body dimensions are not accounted for in the compliance distance value.

If another compliance check method takes these aspects into account more accurately than the calculators, then the results can be expected to be less restrictive. For example, for the defined range of antenna types and cases, the PAEC-2 method:

- Takes the directivity into consideration using data from a wide range of antennas.
- Uses results from advanced EMF modelling that is more accurate close to an antenna or ground. Establishing a more targeted ground-influence factor that in most cases is smaller than the default used by the calculators.
- Determines the values of the spatial average and the spatial peak of both electric and magnetic field strengths and compares each with the respective ICNIRP 2020 General Public reference level (see [27]). The ICNIRP 2020 Table 6 local exposure values are used to interpret accurately fields that vary significantly over the height of the person if they exceed the ICNIRP 2020 Table 5 whole body average levels.
- PAEC-2 directly establishes an Exclusion Zone boundary based on the antenna height and distance from the rotator pole having fully accounted for the antenna and body dimensions.

ANNEX G ADDITIONAL CONSIDERATIONS

In the preparation of PAEC-2, many thousands of simulations have been performed using NEC-4.2 [3] supported by specially developed processing software using Wolfram Mathematica [2]. This has enabled both simple and more advanced compliance guidance to be developed to use those simulations. However, it is impossible to cover all situations and it is perhaps not obvious how many commonly found situations might use PAEC-2. This Annex at least starts to fill some of these gaps.

G.1 Sloping ground

The simulations reported here all assume that the antenna is pointing parallel to the ground. This is a common situation when considering the region from the base of the antenna support out as far as the compliance distance. However, if the ground rises significantly in the direction that the antenna is pointing, then inevitably the fields at ground level will be higher than the flat ground situation.

You can take the rise in ground height from the support mast in the uphill direction (as far as the Exclusion Zone boundary) as approximately equivalent to lowering the antenna by that amount and use the methods in this report on that basis. This is justified since for slightly upward sloping ground, the angle of incidence to the ground for the reflected ray is steeper than for the corresponding flat ground case. For horizontally polarized rays, the reflected energy is reduced for the steeper-incidence angles. Having less reflected field reduces the ground-influence factor and hence should reduce exposure. Therefore, treating sloping ground as a lowering of the antenna height should be a conservative simplification.

However, this has not been robustly evaluated and needs further study to show the level of conservatism.

G.2 Building attenuation

Since radio amateurs are generally located in residential areas, it is common for their antennas to be in close proximity to, or mounted on or even in, occupied buildings. It might be thought that there will be some attenuation of the EMFs as they enter buildings and as such this might offer a further factor to help claiming compliance.

While the reader may wish to investigate the professional literature in this area (e.g., [19], [20], [21]) the position is that the attenuation depends critically on the specific building construction, the presence of windows, and alignment/proximity of the exposed area to EMF sources. Further, the attenuation varies with frequency and probably field polarisation. As such, it is not feasible to offer in this PAEC-2 a general guidance to apply an attenuation factor for EMF compliance purposes.

The advice therefore is to assume that there is no attenuation, and that any such attenuation is considered as another factor offering some conservative bias.

G.3 Vertical / slant polarized beams

Where the field at a point of interest is heavily influenced by reflections, it is likely that there will be a difference between horizontal and vertical polarisation cases since ground reflection is different for the two polarisations. Therefore, the ground reflection factors determined in section 5 do NOT apply other than to horizontally polarized antennas. PAEC-2 should therefore only be used for horizontally polarized antennas.

Further work might be possible to fill this gap if there is a significant demand.

G.4 Roof and building mounted antennas

Antennas are often mounted on buildings on the roof or in the roof space above occupied floors. Doing a detailed evaluation of the field strength in complex or specific configurations is outside the scope of this PAEC-2. However, by applying conservative thinking, a compliance check can be made that will address most reasonable antenna installations.

For a compliance check within the building, assume that there is no building material between the antenna and the accessible places. Explore out as far as R_{EZ} and find the height of any walkway or foot level of potentially occupied floor. If the vertical separation is greater than H_{MIN}, then compliance can be claimed.

For extended flat roofs such as on commercial/education buildings or communal dwellings, the roof surface acts as a surrogate ground (see C.4.1). Therefore, for compliance checks on or above the flat-roof height, the constraints on H_{MIN} apply with respect to height above the flat roof surface.

For a small flat roof such as on single-dwellings or extensions, the point of reflection is too close to the antenna (see C.4.1) to affect materially the compliance check and so H_{MIN} applies with respect to the ground.

Example 7.5:1 144 MHz, 50W average power (taking into consideration mode and use factors and feeder loss) mounted 1.5m above the ridge of the roof. The roof ridge is 2m above the loft floor and this is 2.5m above the top floor standing level. This means that the antenna is 3.5m above the loft space and 6m above the top floor level. With an H_{MIN} of 3.3m, compliance is shown – even without determining the radius of the exclusion zone.

G.5 EMF measurements

This PAEC-2 shows that EMF modelling can be complicated to get confidence in the results. The same is also true for EMF exposure measurement. The technical standards referenced by Ofcom in their guidance [17] (e.g., [11]) are not intended for radio amateurs. They offer good guidance but are intended for professional users, the documents are priced accordingly, and require use of professional grade test equipment and practices. The upshot is, doing a measurement is not difficult, the challenging part is establishing the results' uncertainty and interpreting the values for a reliable and traceable compliance check. For free information on professional EMF measurement and calculations, you can get IEEE C95.3:2021 [6] – all 240 pages are available free in digital format by registering with the IEEE (no membership needed or other commitments).

G.6 Fixed or limited rotation beams

This PAEC-2 has assumed that the beam is fully rotated through 360 degrees. This gives a circular Exclusion Zone to cover all possible beam directions as the antenna is swept through all compass directions. There may be cases where beams are fixed or have a mechanically limited range of directions. If the full R_{EZ} does not cause a problem, then just accept that the Exclusion Zone is very conservative in directions away from the main beam. The minimum height for compliance H_{MIN} also remains valid irrespective of the direction that the antenna is beaming (but see G.1). It is more difficult to give general guidance for directions away from the main beam since this will be very dependent on the antenna directivity. If you have a good understanding of the antenna performance, a revised R_{EZ} might be determined for the desired direction by reducing the power by the assumed directivity. While it might be unwise to assume the full beam pattern has been realised close to the antenna -10 to -15 dB horizontal directivity will significantly reduce R_{EZ} away from the main beam direction.

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