Protection of ‘sensitive’ receiving sites

Paper for RA Working Group on HF Mains Signalling

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Executive summary

Various new communication systems are being proposed which exploit the existence of cables, such as mains or telephone wiring into or within homes or business premises, by superimposing an additional data signal. This is a convenient way to provide new services, and in particular gives a commercial opportunity for the owners of the wiring infrastructure.

However, these cables were not designed for this new purpose, and as a result there is the undesirable side-effect that the data signals ‘leak’, having the potential to cause interference to radio systems. As a general rule, systems using mains wiring (so-called Power-Line Transmission/Telecommunication, PLT) are likely to be the more troublesome.

The level of interference caused by distributed sources of this type is analysed for a range of reception and propagation scenarios. In the first instance it is assumed that these distributed interference sources arise from the use of PLT. However, with the appropriate change in parameters the analysis would also be applicable to other types of communication systems, such as those using existing telephone wiring.

A major area of concern is interference to so-called ‘sensitive’ receiving sites that are required to intercept weak radio signals, whether for reasons of aeronautical/marine safety, monitoring, surveillance or indeed radio astronomy. A BBC example is the World Service Monitoring reception site near Caversham. Discussions in UK regulatory bodies have come up with the idea of defining an ‘exclusion zone’ around designated important sites of this nature, within which communications systems of this type could not be used. Unfortunately, as explained in this paper, a calculation which led to a proposed radius of 10 km contained various flaws.

Calculations based on ITU ground-wave propagation curves show how the level of interference would vary with the size of exclusion zone. The pertinent size must then be chosen by the operators of the sensitive sites themselves, in the knowledge of their existing noise-floor values. An exclusion radius of 50 to 100 km may be necessary for many installations.

Ground-wave propagation of PLT interference presents the greatest threat to the operation of ‘sensitive’ receiving sites, but it could in principle be controlled by the application of a sufficiently large exclusion zone. Once this has been done, there remains a degree of risk from interference propagated by sky wave. Calculations show that wide-scale deployment of PLT transmission could present a threat, via sky-wave propagation, against which there is no obvious effective counter-measure. (An exclusion zone is shown to have little practical benefit in this case).

As well as ‘sensitive’ sites, two other classes of users will also be affected by interference from PLT systems:

- ships at sea (and out of range of VHF) make use of HF communications. As ground-wave propagation over salt water is particularly efficient, it appears very likely that PLT operation along the nearest coast will cause interference. This might require the application of an exclusion zone to the entire coastal strip.
- aircraft flying over areas containing PLT installations appear certain to suffer a noticeable increase in the level of man-made interference.

The implications of both of these should be rigorously studied by the relevant competent authorities.

□ 1. Introduction

Various new forms of communication systems are being proposed which exploit the existence of cables originally provided for some other purpose, such as mains or telephone wiring into or within the home or business premises, by superimposing an additional signal to convey data. Obviously the use of such a facility is a convenient way to provide new services, and in particular gives a commercial opportunity for the owners of such wiring infrastructure which enters homes or businesses.

However, there is a downside to this. The cables were not designed as communication cables for this new purpose, and as a result there is the undesirable side-effect that the data signals ‘leak’ and have the potential to cause interference to radio systems. In effect, the cable acts as a transmitting antenna. As a general rule, systems using mains wiring (so-called Power-Line Transmission/Telecommunication, PLT) are likely to be the more troublesome of the two types, as telephone cables start out with the general intention of being balanced and correctly terminated — albeit for a lesser frequency range — although this may not always be achieved in practice.

Various interference scenarios can be considered. An obvious one is where reception takes place close to the cable carrying the additional data signal. In this case the majority of the interference comes from just this single cable. This type of interference can be regulated by imposing a limit on the permitted (interfering) field strength, as measured at some specific distance from the cable in question. This is the approach taken in the draft MPT 1570 (Ref. 1) which has been drawn up by the Radiocommunications Agency in consultation with affected parties.

The interference effect is not limited to the immediate environment of the cable. The interference detectable from one such system will of course decay with distance, and so interference might appear to be less of a problem for more-remote receivers. However, if systems of this type are installed to feed many homes and businesses, each will make its own contribution to the interference. A remote receiver will thus pick up the sum of a large number of interfering sources, each somewhat attenuated but in total still having the potential to cause difficulty.

This latter problem is of particular significance for so-called ‘sensitive sites’ that are required to intercept weak radio signals, whether for reasons of aeronautical/marine safety, monitoring, surveillance or indeed radio astronomy. A BBC example is the World Service Monitoring reception site near Caversham. Discussions in UK regulatory bodies have come up with the idea of defining an ‘exclusion zone’ around designated important sites of this nature, within which communications systems of this type could not be used. An important question is then to choose the size of these zones. Clearly the size would depend on the type of cable-communications system in question.

This paper covers the case of one type of PLT system, but with the appropriate substitution of parameter values it should be possible to extend the method to other cases which similarly have a large number of distributed interference sources. The paper shows that some previous calculations were over-optimistic — i.e. the necessary exclusion distances may be rather larger than previously considered.

The main thrust of the paper considers ground-based receiving sites suffering interference as a result of ground-wave propagation. A further step considers sky-wave propagation of interference to the same receiver. As the geometry and method of the problem is similar, the latter calculation can easily be modified to consider receivers on board aircraft. Similarly, the ground-wave and sky-wave calculations can be extrapolated for receivers on board ships at sea.

□ 2. Key steps in the analysis

The calculations involve two key steps:

- determining the interference caused by a single system at some distance

  This involves knowing how much interfering signal is radiated, and how it propagates over a distance, i.e. how much it is attenuated as a function of distance.

- accounting for the summation of interference from the many similar sources that will be present once systems of this type are fully deployed

  This includes knowing the physical distribution of the interference sources, and the manner and geometry of the propagation path(s) by which the interference reaches the victim receiver.

We can reasonably assume that the signals from the many interference sources are uncorrelated (as long as all the links are not used in some kind of broadcast mode carrying the same data!), and so their total effect on one receiver can be assessed by power addition. Furthermore, we may note that by the Central Limit Theorem, the more independent interference contributions there are, the more their combination will tend to have a normal amplitude distribution, like Gaussian noise.

Ideally we should consider the particular location of each interference source, determine the propagation from each source to the victim receiver, and perform a power summation. This is probably impractical for potentially-widespread systems, and is certainly not possible when the system is only a proposal so that the locations are unknown in detail. What we can do instead is to estimate the *density* of potential installations, treat the sources as being uniformly spread over an area and replace the summation of a finite number of sources by an integral over an area. This is a reasonable procedure as long as the sources are never too close to the receiver. This should be a fair assumption for calculating exclusion zones, but would not be the case for calculating interference where the distance from the nearest source to the receiver is small compared with the distance between sources. In the latter situation, the nearest source would clearly dominate in practice whereas its influence would be underestimated by the integration method, in which it is treated as spread-out so that part of it is, in effect, further away.

□ 3. Assumptions

■ 3.1. General assumptions, and naming of variables

- each of the (discrete) interference sources is treated as radiating interference isotropically

  If we consider one such source in isolation then this is clearly not the case — the particular cable will have some arbitrary frequency-dependent radiation pattern. But when we sum the influence of many sources (none of which is allowed to be dominant, as previously explained) the peaks and nulls of individual sources will tend to average out.

- each system is thus equivalent to a transmitter (of power equal to that deliberately injected into the cable) coupled to an antenna which is isotropic in directivity. However, because it is a lossy ‘antenna’ (we hope that most of the data signal is either transmitted through the cable to its desired destination, or dissipated in cable losses — only a part is *radiated*) the effective antenna gain takes some value less than 0 dBi.

Let the antenna effective gain just described be g_{TX} in linear units or $G_{TX} = 10\,\mathrm{Log}[10, g_{TX}]$ dBi.

Let the power injected into the cable (within the relevant bandwidth — frequently 10 kHz is used, to match measuring-receiver technique) be p_{TX} watts or $P_{TX} = 10\,\mathrm{Log}[10, p_{TX}]$ dBW. (Strictly the units of measurement are thus e.g. W/10kHz — for brevity, this will not always be spelt out).

Each system in operation thus behaves as a transmitter with EIRP (Equivalent Isotropically Radiated Power) equal to $p_{TX}\, g_{TX}$ W.

Let the density of systems in operation be D systems / m^2. An area dA containing systems in operation is thus equivalent to a transmitter of EIRP $p_{TX}\, g_{TX}\, D\, dA$ watts.

Let the propagation from a source to a receiver over distance x m (by whatever mechanism may apply) be represented by some function $f[x]$ so that the power-flux density at the receiver is given by the product of $f[x]$ and the source EIRP.

It follows that the interference power-flux density encountered at a specific receiver site can be evaluated as:

$$\text{PFD} = \int_A p_{TX}\, g_{TX}\, D\, f[x]\, dA$$

where A is the area containing the interference sources. Note that for ground-wave interference no part of A may be too close to the receiver otherwise the use of integration, instead of summation of discrete sources, will not be correct, as previously discussed.

If the Earth were flat, or we were considering only very nearby interferers, then we could choose an annulus of radius x, thickness dx and thus area $dA = 2\pi x\, dx$ which we could substitute in the above equation, while $f[x]$ would be whatever is necessary to account for propagation over a distance x by the mode under consideration.

Once we have to consider larger distances we have to take account of the curvature of the Earth. The area of the annulus which is distance x (measured over the curved surface) from the receiving point is now smaller, see Appendix A 1.1. We can still apply $f[x]$ straightforwardly for ground-wave propagation (provided we know it, of course — see § 4 and Appendix A 2.1).

Finally, for sky-wave propagation we can still use the same annulus, but in this case the signal can be considered to travel in a straight line to the ionosphere, whence it is ‘reflected’ back towards the reception point. In this case the distance travelled (and thus the attenuation) is a more complicated function of x, determined by geometry, so that the expression $f[x]$ is more complicated, see Appendix A 1.2.

Note that strictly speaking the process by which radio signals are returned to Earth is not *reflection*, but rather *refraction*. The wave therefore follows a curved path as it is turned round. However, the process can for most purposes be treated as equivalent to a simple relection at a nominal reflection height.

For either ground-wave or sky-wave propagation over the curved Earth, there is a maximum distance (π times the radius of the Earth, R_E) that the interferer can be distant from the receiver. It is also possible for signals to travel the ‘long way round’, as well as by the shortest direct Great Circle route. For the purpose of this paper such long-path propagation is neglected. For ground-wave propagation at the frequencies considered, the use of πR_E as the upper limit for x is just a mathematical nicety, as the interference (even by the direct route) from that range is always negligible — we simply avoid choosing a more arbitrary, nearer cut-off. The same may not always be true for sky-wave propagation, but this is discussed further later on.

■ 3.2. Assumptions particular to the PLT system under more detailed consideration

We need some specific numerical values to use in our calculations. The PLT proposal, as presented to the Working Group, has undergone some evolution, so definitive values are elusive. I assume that the injection power (within 10 kHz) is −3 dBm, i.e. $p_{TX} = 0.0005$ W / 10 kHz. I further assume that the effective transmitting antenna gain G_{TX} is −20 dBi. This result can be deduced from the airborne measurements reported by Nor.Web, but it also yields close-in values which are not inconsistent with those reported to be measured by the RA, see Appendix, A 2.2.

We also need to know the density of systems in operation. With the PLT proposal, all the premises connected to one electricity sub-station form a group or ‘cell’. Only one ‘modem’ out of the premises or the sub-station transmits at a time, sharing the capacity of approximately 1 Mbit / s in Time-Division Multiplex (TDM). The maximum density of instantaneously operating systems is thus the same as the density of sub-stations. At least one paper asserted to the Working

Group that the area covered by one sub-station had a diameter of approximately 600 m (presumably in built-up areas), leading to a density $D = 1/90000\pi$ systems/m^2.

There has been some discussion whether an allowance can be made for reduced usage. Note however, that only one user in a cell needs to be actively downloading data to cause that cell to radiate almost continuously. If more users are active, their individual share of the available resource falls, 'stacking' their download requests and making it even more likely that near-continuous radiation occurs. The interference radiation is thus far from being a simple linear function of the number of users.

In contrast we could note that very different conditions would apply with systems using telephone wiring. In this case the maximum system density is higher, in principle potentially matching the density of households. Assuming that those households not actively using a connection cause no interference radiation (along with those not connected), the interference radiation would in this case be directly proportional to the number of instantaneous users.

□ 4. Ground-wave interference

The main thrust of this paper is to consider the interference caused by ground-wave propagation of the interfering signals to the receiver. In this section we briefly consider the behaviour of ground-wave propagation, in comparison with that in free space, and then present some results.

■ 4.1. Allowance for propagation losses

The simplest form of propagation to analyse is *free-space propagation*. Imagine a transmitter emits p watts uniformly in all directions (in three dimensions) into a lossless medium. Now consider a sphere of radius x around it. The medium is lossless, so all the power emitted is received at the sphere's surface. The sphere has area $A = 4\pi x^2$, and the power p is uniformly distributed over it, so the power per unit area, or *power-flux density*, is thus simply:

$$\text{PFD} = \frac{p}{4\pi x^2}\ \text{W}/\text{m}^2$$

This is known as the inverse-square law. It applies equally well for directional transmissions provided we replace p by the EIRP (Effective Isotropically Radiated Power) of the transmitter in the direction in question. Its behaviour can be represented by a straight line on a graph, provided we plot Log[PFD] versus Log[x]. Usually we express the PFD in dB units (i.e. a logarithmic measure) and if we plot this against Log[x] then we get a straight line with a slope of -20 dB/decade.

It will be apparent that if there were any losses (e.g. the sphere was filled by a lossy medium) then the received PFD at distance x must be less than given in the above formula.

Ground-wave propagation over the real Earth is an example of lossy propagation, so that the received PFD is less than would be the case for free-space propagation. The extent of the added losses depends on the ground condition and frequency. Curves are given in ITU-R Rec. 368, of which an example is reproduced in Appendix A 2.1. These curves result from a complicated computer model; unfortunately there is no simple underlying formula. Close to the source, the propagation is asymptotic to the inverse-square law of the free-space case, but as distance increases the received PFD falls away more quickly, the more so as frequency increases.

Some measurements by Nor.Web suggested that the interference signal from their test site fell off as

$$\text{PFD} \propto \frac{1}{x^{2.5}}$$

In other words, plotted in dB versus Log[x], a line of slope -25 dB/decade could be drawn through the experimental points. This is a perfectly believable result, if the range of distance covered was not large. However it is not universally true, as a reference to any of the Rec. 368 curves makes clear — the true slope goes on getting steeper with increasing distance, setting a limit to the range from which ground-wave propagation is significant. In other words, the real situation is less critical than implied by the figure of −25 dB / decade suggested by Nor.Web. However, inappropriate application of a −25 dB / decade law can still lead to optimistic results. Appendix A 2.5 shows how this led to an optimistic figure of 10 km for the exclusion zone whereas, in contrast, a more rigorous application of a fixed −25 dB / decade law leads to absurdly large exclusion zones.

Appendix A 2 shows how a simple technique, appropriately approximating the application of the ITU-R curves of Rec. 368, gives the results reported in the next section.

■ 4.2. Practical results

The following results are obtained using the assumptions already outlined in § 3, applied to a frequency of 3 MHz (which is representative of one of the frequency segments used by the Nor.Web PLT proposal). The details of the calculations, including the input data derived from ITU curves, are given in Appendix A 2.3.

The calculations depend on the state of the ground, in particular its conductivity σ and permittivity ϵ, for which data is not easy to obtain. The results quoted for wet ground below are believed to be generally representative of the UK, but a few locations may have lower ground conductivity and thus be less critical. It is unlikely that anywhere in the UK has ground conductivity as low as assumed for the dry-ground results.

Finally some results are quoted for sea water — pointing out that ships may well receive significant interference from the nearest shore, if PLT is installed on the coastal strip.

▫ Results for wet ground, representative of the UK

exclusion distance, x_1 km	equivalent field strength, dBμV / m (10 kHz)
10	14.2
20	8.25
30	3.25
50	−2.4
100	−10.2
200	−25.8

These results suggest that a ‘sensitive site’ may well require an exclusion zone of the order of 100 km radius. The operators of such sites will have to judge the appropriate size for themselves, in the knowledge of the present noise floor down to which they operate.

▫ Results for dry ground, unlikely to be encountered in the UK or nearby countries

exclusion distance, x_1 km	equivalent field strength, dBμV / m (10 kHz)
10	−5.2
20	−10.4
30	−15.9

These results suggest that an exclusion zone of 10 km radius would barely be sufficient to protect a ‘sensitive site’ — even in ground conditions of low conductivity that are unlikely to be found in the UK.

▫ Results for sea water

exclusion distance, x_1 km	equivalent field strength, dBμV / m (10 kHz)
100	33.2
500	10.8
1000	−19.9

These results indicate the need for further calculations, if the use of HF radio communications to ships at sea is to be protected. PLT is not (of course!) going to be installed in the sea, but the distance of a ship from the shore can be considered as an exclusion distance, with PLT installations along at least the coastal strip. Strictly speaking, more complicated calculations are needed to take account of the mixed propagation path (part land, part sea) applicable to those interferers inland.

What the ITU propagation curves for sea water (not reproduced in this paper) do indicate is that the attenuation over sea water is very close to the inverse-square law, out to fairly large distances. Now, if PLT installations were excluded from the coastal strip (as would be needed anyway to protect coast-station sites) this might well be sufficient to protect ships at sea (and beyond the range of VHF radio).

▪ 4.3. Discussion: what about directional receiving antennas?

The analysis so far has assumed that all the interference contributions reaching the receiver, from all the directions around it, are added up on an equal basis. It would appear that this implicitly assumes that an omnidirectional receiving antenna is in use. Since ‘sensitive’ receiving sites are indeed quite likely to use a *directional* receiving antenna, we must consider this further.

Assume first of all that the incoming interference is indeed uniform with direction. It can be deduced from the definition of antenna directivity/gain that if the antenna is directional, picking up more strongly from a particular direction, then it must do this at the expense of other directions. In other words, for antennas with no loss, or of consistent losses, the output power of the receiving antenna in the presence of uniform incoming field is independent of the antenna gain. So our implicit assumption was not necessary.

Now consider more practical situations where the density D of interfering sources (installed outside the exclusion area) is not uniform. For example, a ‘sensitive‘ receiving site has a built-up area on one side, with interfering-source density D, and an uninhabited desert (no interferers at all!) on the other. It might be tempting to assert that the effective density of installations is halved, i.e. $D/2$.

If the receiver uses an omnidirectional receiving antenna, then clearly this would in effect be the case — the area A over which integration needs to be performed is halved, with symmetries such that the answer is the same as would be given by putting $D/2$ into the unmodified calculation.

The same is not true for directional receiving antennas. Suppose a directional antenna receives signals in a directionally-uniform field. As already explained, it receives the same interference power in total as an omnidirectional antenna would. However, this power comes more or less predominantly from sources in the direction of maximum sensitivity. It follows that sources lying in the direction towards which the antenna has minimum sensitivity could be removed without making significant difference to the received power. Clearly, in the case where a receiving antenna with high front-to-back ratio ‘looks’ towards the populated area (which had source density D), then the received interference will be correctly estimated by calculations made on the basis that the density is *D*, with no allowance being permitted for the uninhabited desert. So there is no general justification for averaging the density by direction.

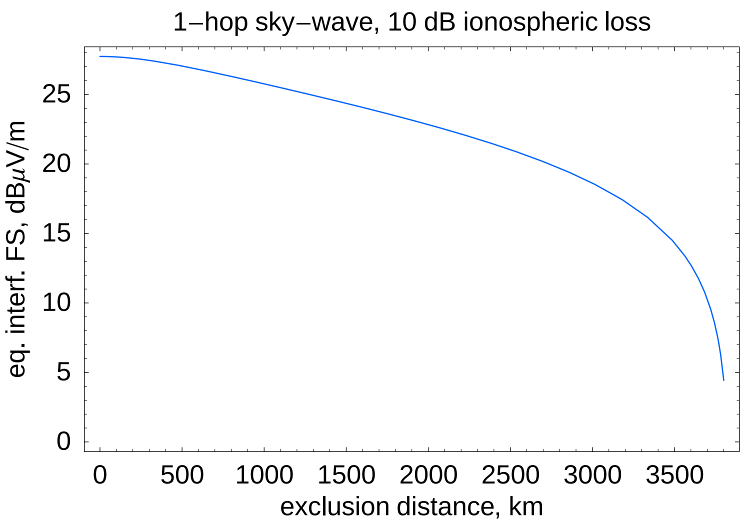
Care is similarly needed in trying to average the density along a radial from the receiver, as the roll-off of ground-wave attenuation is sufficiently steep to make this a hazardous process.

□ 5. Sky-wave interference

Sky-wave interference can be calculated in a similar way — the main difference is the calculation of attenuation as a function of (curved-Earth) distance x from the source. We can approximate the very complicated behaviour of ionospheric propagation as being equivalent to the attenuation arising from free-space propagation, over a distance equivalent to that travelled by the wave on its one or more hops, plus an allowance for ionospheric absorption in each hop, and a further allowance for the loss in reflection from the Earth, where there is more than one hop. This is now simple to calculate. In principle we should sum the power from all the modes with their different numbers of hops, but we can get at least a first indication by analysing just the mode expected to be dominant in a particular case. Note therefore that the true total interference could be greater than given in this first indication.

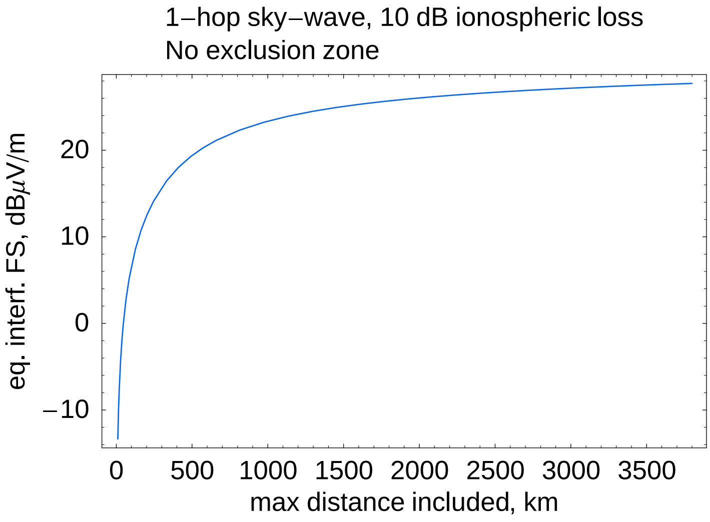
The concept of exclusion distance should strictly be replaced by a more general lower limit of integration, x_1. It should be the greater of any imposed exclusion zone, and the skip distance (below which ionospheric propagation does not occur). In fact, the frequencies we are considering will probably lie below the ionospheric critical frequency for most of the time, so we can then neglect skip. Similarly, the upper limit of integration x_{max} is now bounded by the greatest distance from which the number of hops under study is physically possible.

Details of the calculations are given in Appendix A 3. If we consider merely the case where only 1 hop is considered, with a 10 dB allowance for the loss (compared with free-space propagation) in the single ionospheric hop, we get the results summarised in the following two Figures. The first Figure shows the effect of varying the size of an exclusion zone around the receiver, while interferers over the whole remaining area within which 1-hop propagation is possible are included:



This demonstrates that exclusion zones of the order of size contemplated in order to protect against ground-wave interference would give little benefit (in protection against sky-wave interference) if PLT sources were truly widespread over a large area.

The second Figure shows the effect of varying the size of the area around the receiver within which interferers are included, this time with no exclusion zone.



This shows that once a fairly large area around a receiver (say 500 km radius) is densely populated with PLT, then the influence of more distant-interferers does not greatly increase the interference further.

Taking the two results together suggests that within a large industrialised country, containing many dense conurbations served by PLT, the contribution from sky-wave propagation of PLT interference may not be negligible, especially if the receiving site has been protected against ground-wave interference by the application of an exclusion zone.

Comparing mechanisms with the ground-wave case, we have the following situation:

- the sky-wave propagation has the added ionospheric loss (assumed constant in this calculation) compared with free-space propagation
- as distance x increases, sky-wave attenuation increases more gently, up to the point where propagation by (say) 1 hop is no longer possible. The asymptotic slope is -20 dB / decade, whereas the slope for ground-wave propagation is always more than this, and gets steeper with distance
- for short distances x, the sky-wave attenuation is much greater, because the minimum distance travelled is twice the ionospheric height

So, when there can be nearby interferers (i.e. little or no exclusion zone) ground-wave propagation provides the dominant part of the received interference. As the nearby interferers are excluded (by specifying an exclusion zone, as shown in § 4) then interference borne by sky wave can become significant.

Some amelioration compared with the results plotted in the two previous Figures may be possible.

It is unlikely that PLT systems will be established at the assumed density over the whole surface of the globe (after all, a significant part is sea). With *ground-wave propagation*, § 4.3 has already shown that we cannot *generally* use a simple allowance for reduced 'average' installation density, because of two factors:

- *azimuthal* averaging of density leads to error with directional receiving antennas
- *radial* averaging leads to error, because the regions being averaged may suffer greatly differing attenuation

For *sky-wave propagation*, the first of these remains applicable, but the second has less force as the attenuation (especially for nearby interferers) increases more slowly with distance. So a degree of radial averaging may be acceptable.

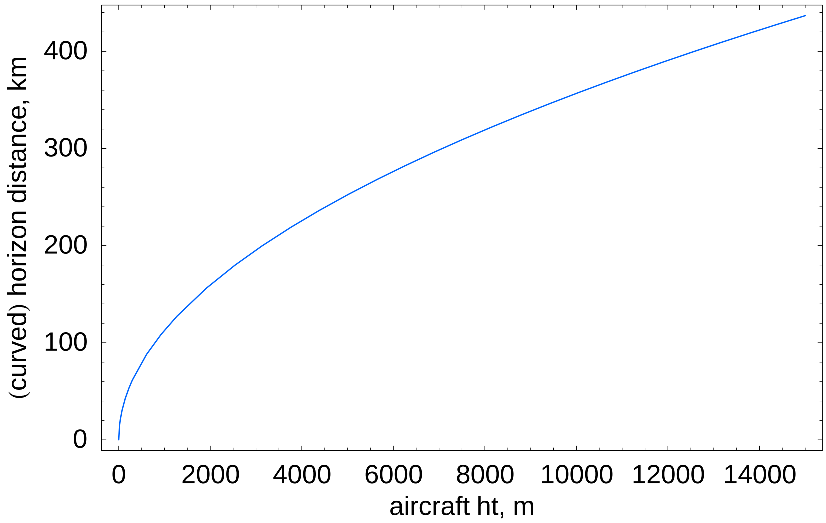
Furthermore, it may perhaps be appropriate to assume a greater degree of ionospheric loss, again as part of an averaging process. Ionospheric propagation is notoriously variable with both time and place. It is well-documented that path losses (relative to free-space) of less than the 10 dB we have assumed can occur. But it may perhaps not be the case that a loss of no more than 10 dB will be encountered for signals originating all over a large area. So some *spatial averaging* of this value is permissible. On the other hand, we must resist the temptation to apply *temporal averaging* to this value. While it is true that there will be periods when ionospheric propagation will be very poor (reducing sky-wave interference), we have to remember that sensitive receiving sites must be able to work whenever they are needed, including during periods of good propagation.

In conclusion, we may observe that where no exclusion zone is in force, then ground-wave interference will predominate over sky-wave interference. However, if an exclusion zone is applied to limit the ground-wave interference to a low value, it remains possible that sky-wave interference will then be a limiting factor, if PLT systems become widespread.

□ 6. Interference to aircraft

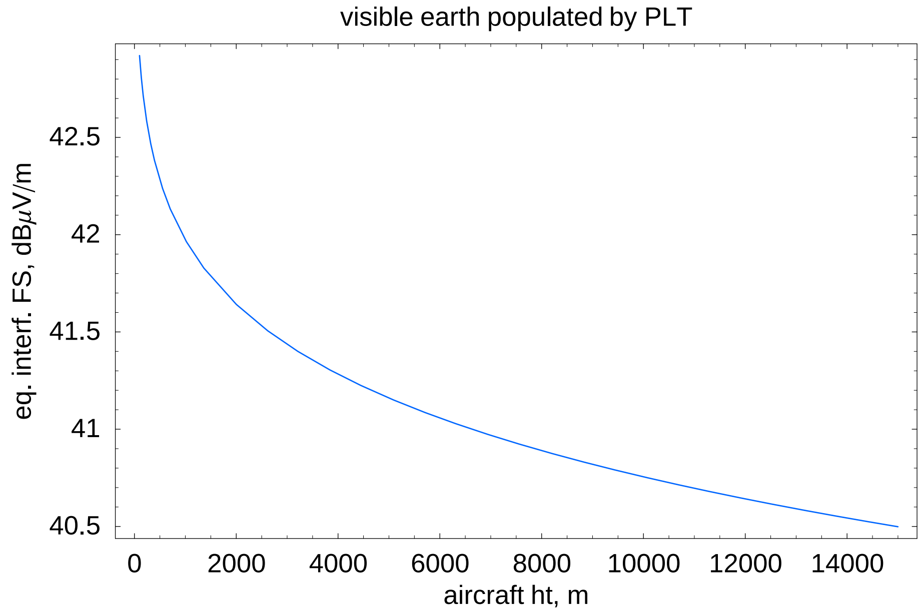
Aircraft flying over areas which are populated with PLT systems may also see an increase in the apparent noise floor at HF. The geometry of the problem has many similarities to the ionospheric sky-wave case, and is derived in Appendix A 1.3, whereupon the interfering PFD at the aircraft can be calculated assuming free-space propagation to the aircraft from the interfering systems 'visible' to it, see Appendix A 4.1 for the derivation.

The region visible to the aircraft depends on the height at which it is flying. The Figure below shows the distance (measured around the curved Earth) from the point below the aircraft to the horizon, as seen from the aircraft:



It follows that the number of PLT systems able to interfere with the aircraft increases substantially with height.

Suppose that the PLT systems are present with the same density (and other parameters) as previously specified, over the whole visible area. In this case we can calculate the interfering PFD at the aircraft, as shown (expressed as an equivalent electric field strength) in the following Figure:



Interestingly, under the assumption that all the visible Earth is populated with PLT systems at the same density, there is relatively little variation in the interfering PFD with aircraft height. In effect, as height increases, the strength of the contribution from any one interferer decreases, but the number of visible interferers increases nearly as quickly.

Now, the assumption of constant PLT density can perfectly reasonably be challenged for aircraft flying at great height, as in this case even while flying over a major conurbation there will be areas of countryside also visible. So some allowance could reasonably be made for this case.

Nevertheless, it appears that there is scope for problems which would require more detailed examination. Aircraft often fly over major conurbations (especially London) while on approach to airports, and in this case the height is sufficiently low that all of the visible Earth *is* densely populated. Furthermore, the level of interference suggested by the Figure is sufficiently high that it would appear that a very significant amelioration will be necessary.

None of this should be surprising. The existing level of man-made noise 'seen' by aircraft over cities reaches them by exactly the same free-space propagation mechanism that we have assumed for PLT. It therefore follows that if PLT raises the noise level in its immediate environment (which is demonstrably true), then it must also increase the noise level for aircraft.

Clearly, those more familiar with the requirements for aircraft communications should study this topic closely.

☐ 7. Conclusions

The level of interference caused by distributed sources has been analysed for a range of reception and propagation scenarios. In the first instance it is assumed that these distributed interference sources arise from the use of so-called Power-Line Transmission (PLT) in which data signals are superimposed on existing mains wiring. However, with the appropriate change in parameters it would be possible to consider other types of communication systems, such as those using existing telephone wiring. Most parameter changes from those assumed herein can be accounted for on a dB-for-dB basis.

One area of concern is interference to so-called ‘sensitive’ receiving sites, such as the site near Caversham that is used by BBC Monitoring. It has previously been proposed that one way to protect such sites is to designate an exclusion zone around them, within which PLT operation would be prohibited. Unfortunately the calculation [2] leading to a proposed radius of 10 km contained various flaws, as explained in the Appendix of this paper.

Calculations have been made based on ITU ground-wave propagation curves which show how the level of interference would vary with the size of exclusion zone. The requirements are more stringent. The appropriate size of exclusion zone must be chosen by the operators of the sensitive sites themselves, in the knowledge of their existing noise-floor values. An exclusion radius of 50 to 100 km may be necessary for many installations.

Ground-wave propagation of PLT interference presents the greatest threat to the operation of ‘sensitive’ receiving sites, but it could in principle be controlled by the application of a sufficiently large exclusion zone. Once this has been done, there remains a degree of risk from interference propagated by sky-wave. Calculations have been presented which show that wide-scale deployment of PLT transmission could present a threat, via sky-wave, against which there is no obvious effective counter-measure. (An exclusion zone has little practical impact in this case).

While this note primarily concerns the protection of ‘sensitive’ sites, it emerges from the calculations that two other classes of users will also be affected by interference from PLT systems:

- ships at sea (and out of range of VHF) make use of HF communications. As ground-wave propagation over salt water is particularly efficient, it appears very likely that PLT operation along the nearest coast will cause interference. This might require the application of an exclusion zone to the entire coastal strip.
- aircraft flying over areas containing PLT installations appear certain to suffer a noticeable increase in the level of man-made interference.

The implications of both of these should be rigorously studied by the relevant competent authorities.

☐ 8. References

1. Radiocommunications Agency, 1999. *Draft* MPT 1570. Radiation limits and measurement standard. Electromagnetic radiation from telecommunications systems operating over material substances in the frequency range 9 kHz to 300 MHz.

Note: this document is a draft subject to revision.

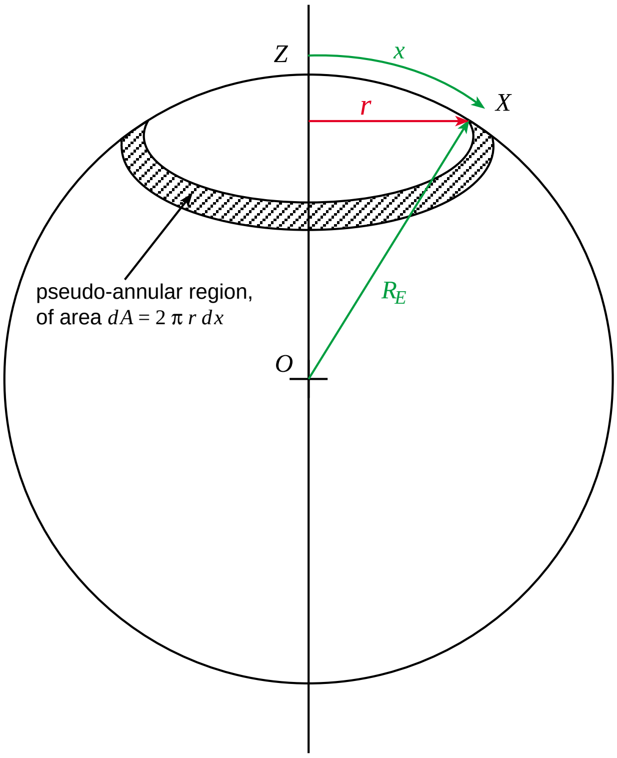
2. Ministry of Defence, 1999. RAFSEE Technical Report 99002, February 99.

Note: this document is not public.

Appendices

☐ A 1. Geometry

■ A 1.1. Annulus on curved Earth



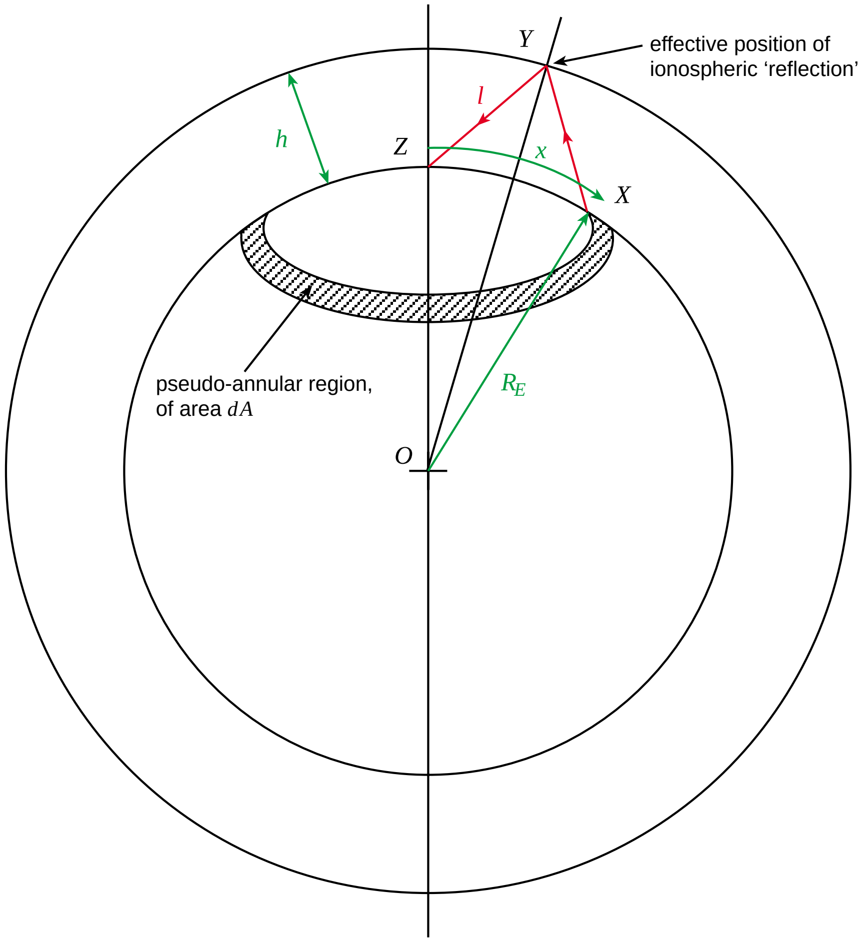
The Figure above shows an annulus-like infinitesimal ring of area dA on the curved surface of the Earth, whose radius is R_E and whose centre is at O. The ring is at distance x from the receiving point Z (as measured round the curved surface), and has a radius, measured from OZ, of r. The angle ∠ ZOX, i.e. half that subtended at O by the ring, is $\frac{x}{R_E}$ radians and so r is given by:

$$r = R_E \, \mathrm{Sin}\left[\frac{x}{R_E}\right]$$

and so the area of the ring is given by:

$$dA = 2\,\pi\,r\,dx = 2\,\pi\,R_E \, \mathrm{Sin}\left[\frac{x}{R_E}\right] dx$$

■ A 1.2. Geometry of sky-wave propagation



Consider sky-wave propagation from a point X to a receiver at Z. The curved-surface distance ZX is x. The angle $\angle$ ZOX is thus $\frac{x}{R_E}$ radians. Suppose that the signal makes n hops in general (each from earth to ionosphere to earth), and that reflection takes place at an effective ionospheric height of h. (The Figure above shows a single hop for clarity, $n = 1$). Assuming constant effective ionospheric height h, each half-hop involves a slant-path (e.g. ZY) of identical length l, which can be computed using the Cosine rule for the triangle ZYO, noting first that angle $\angle$ ZOY is, in general, angle $\frac{\angle \mathrm{ZOX}}{2n}$. The total sky-wave path length s is thus given by:

$$s = 2\,n\,l = 2\,n\sqrt{R_E{}^2 - 2\,\mathrm{Cos}\left[\frac{x}{2\,n\,R_E}\right] R_E\,(h + R_E) + (h + R_E)^2}$$

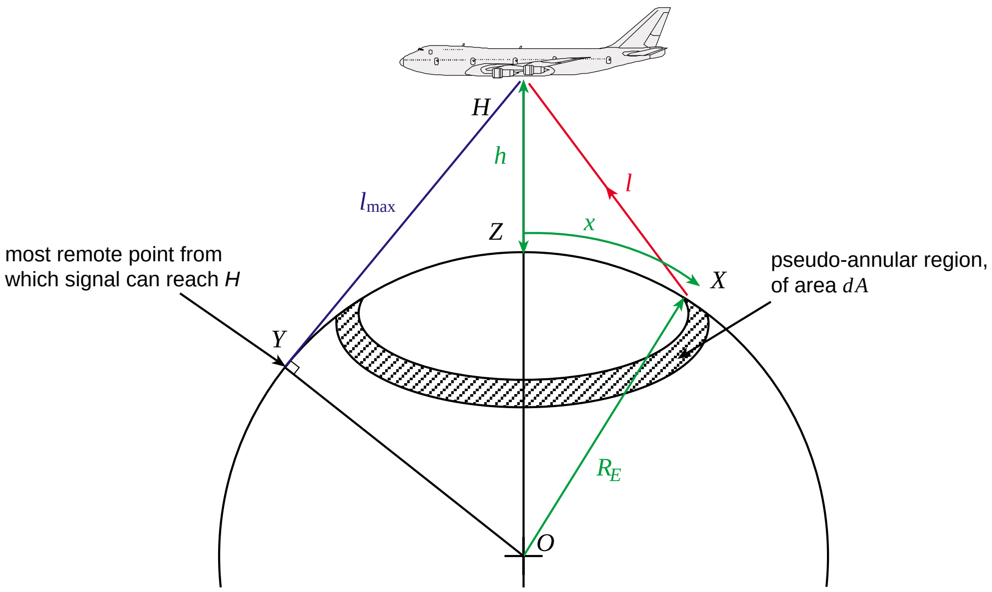
Note that using n hops there is a *maximum* distance $x_{\mathrm{Max},n}$ which can be reached, whereupon rays leave the Earth tangentially, given by:

$$x_{\mathrm{Max},n} = 2\,n\,R_E\ \mathrm{ArcCos}\left[\frac{R_E}{R_E + h}\right]$$

If the operating frequency $f > f_C$, where f_C is the critical frequency above which a wave normally incident on the ionosphere is not reflected, then there is also a *minimum* distance (the *skip distance*) at which a single-hop path can be detected. The skip distance depends on the ratio f / f_C. However, as the PLT system we are most concerned with uses relatively low 'high frequencies' we may not need to take this into account.

■ A 1.3. Geometry of propagation to aircraft

Interference from PLT and other distributed-source systems can reach aircraft. The geometry of the problem bears some similarity to that for sky-wave propagation, see Figure below:



The aircraft is flying at height h above the Earth, and is at point H vertically above Z. Signals from point X travel to the aircraft along the slant path XH, whose length l is given by:

$$l = \sqrt{R_E^{\,2} - 2\,\mathrm{Cos}\left[\frac{x}{R_E}\right] R_E\,(h + R_E) + (h + R_E)^2}$$

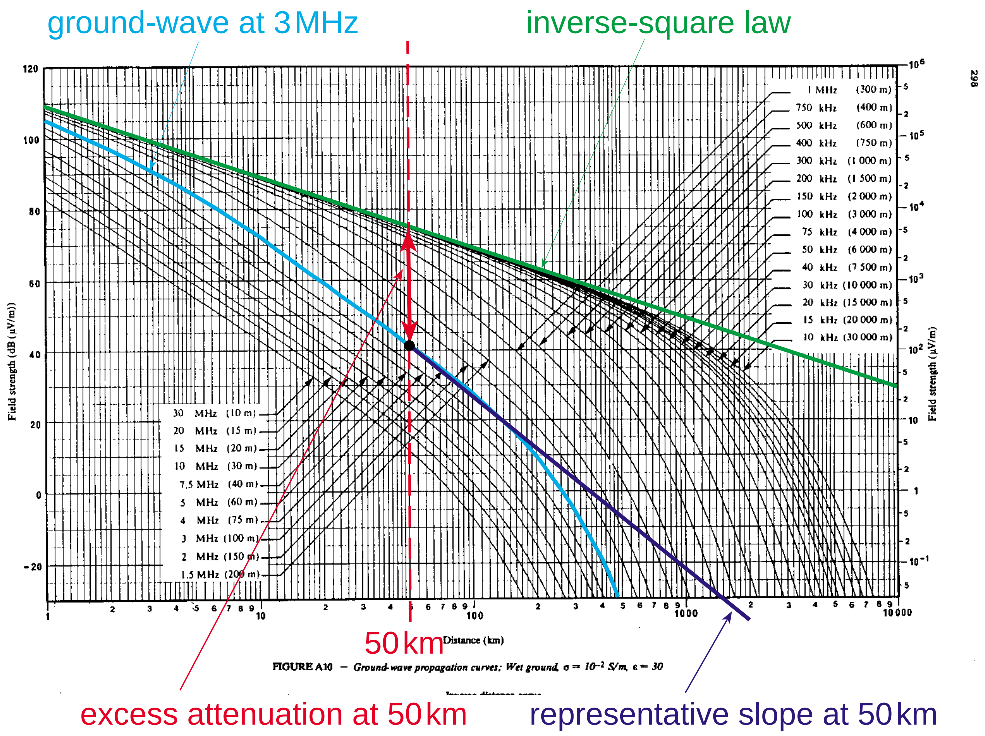
Note that there is a limit to the distance from which signals can reach H, since the aircraft can only 'see' a limited area of the Earth. The furthest position from which signals can directly reach H is Y, where HY is tangential to the Earth's surface. The distance (over the curved surface) from Z to Y is then given by:

$$x_{\mathrm{Max}} = R_E\ \mathrm{ArcCos}\left[\frac{R_E}{R_E + h}\right]$$

Finally, the distance l_{max} from aircraft to Y is simply $\sqrt{h(h + 2\,R_E)}$.

□ A 2. Ground-wave propagation calculation

■ A 2.1. Basis: the ITU ground-wave curves



This figure above shows the ITU-R Rec. 368 curves for ground-wave propagation over “Wet ground, $\sigma = 10^{-2}\ S/m$, $\epsilon = 30$” (actually taken from p 298 of the “ITU Handbook of curves for radio wave propagation over the surface of the Earth”, 1991).

The vertical scale represents field strength in dB, while the horizontal axis represents distance x from the source (transmitter) on a logarithmic scale. The line highlighted in green shows the attenuation that would occur under an inverse-square law (as would apply for free-space propagation). This line is the asymptote for the actual ground-wave curves for small distance and low frequency. The curve highlighted in light blue is the ground-wave curve at 3 MHz. The vertical line in red is at distance 50 km, and the bold double-headed line superimposed on it shows the excess attenuation, relative to inverse-square law, at 50 km and 3 MHz. The dark blue line shows a simple approximation to the signal strength (equivalent to a power-law relationship) which might be applied from 50 km onwards. Its slope is representative of the slope of the true curve at 50 km.

This suggests the method we can use to estimate interference. In § 2, it was explained that we want to integrate the interference from sources all around the receiver, at a range of distances, and to do this we need a function $f[x]$ (defined in § 3) which quantifies the attenuation with (curved-earth) distance x. Clearly, the ‘true’ $f[x]$ is given by the ITU-R Rec. 368 curves (assuming the ground conditions are uniform, matching one of the published set), but this is impractical to apply simply, as there is no underlying explicit formula on which to perform the integration. It could be done numerically, if values were spotted off the curve. However, for this paper, we do something simpler. We assume that the attenuation, starting from an assumed hypothetical exclusion distance x_1 (e.g. the example value of 50 km drawn on the Figure) follows a simple power law (corresponding to the dark blue straight line in the Figure), so that the received interference PFD from a single source would be:

$$\frac{c_1}{\left(\frac{x}{x_1}\right)^m}$$

where c_1 is the PFD at distance x_1. We can determine c_1 as follows. We calculate the value that would arise according to the inverse-square law, and reduce it by a factor γ that accounts for the excess attenuation relative to the inverse-square law at this distance. We read γ (or more strictly, its value expressed in dB, 10 Log[10, γ]) off the ITU-curves Figure as the distance between the relevant curve and the line representing the inverse-square law, for distance x_1 — i.e. the length of the bold red double-headed line. We then determine the downward slope m at the same point; it is one-tenth of the number of dB by which the dark blue line falls in one decade of distance x.

Note that by working in this way we do not need to use the absolute vertical calibration of the ITU curves, which are actually expressed as numerical field strength for some assumed type and power of transmitter. As a dB scale is used, we can simply express the attenuation relative to the inverse-square law.

We can therefore approximate $f[x]$ as:

$$f[x] = \frac{\gamma}{4\pi x_1^2} \cdot \frac{1}{(\frac{x}{x_1})^m} = \frac{\gamma x_1^{m-2}}{4\pi x^m}$$

We substitute this, and the geometry of Appendix A 1.1. into the integral propounded in § 3 to obtain the PFD resulting from uniformly-distributed interference sources lying at distances between a hypothetical exclusion distance x_1 and some maximum distance $x_{\max}$ from the receiver:

$$\text{PFD} = \int_A p_{\text{TX}}\, g_{\text{TX}}\, D\, f[x]\, dA = \int_{x_1}^{x_{\max}} p_{\text{TX}}\, g_{\text{TX}}\, D\, \frac{\gamma x_1^{m-2}}{4\pi x^m}\, 2\pi R_E\, \text{Sin}\left[\frac{x}{R_E}\right] dx$$

$$= \frac{\gamma\, p_{\text{TX}}\, g_{\text{TX}}\, D\, R_E\, x_1^{m-2}}{2} \int_{x_1}^{x_{\max}} \frac{\text{Sin}[\frac{x}{R_E}]}{x^m}\, dx.$$

The integral cannot be performed in general, but once particular numerical values are inserted for m, R_E and the limits of integration it can always be evaluated using *Mathematica*. (The solution involves the use of Hypergeometric Functions!).

The results are given in PFD (units of watt/m^2); they can be converted to the more familiar electric field strength, expressed in dBμV/m, using the following formula:

$$\text{field strength, dB}\mu\text{V/m} = 120 + 10\,\text{Log}[10,\ 120\,\pi\ \text{PFD}]$$

To determine the necessary exclusion zone to protect a particular receiving site, we simply try a range of hypothetical values until the resulting predicted interfering PFD (or equivalent field strength) is compatible with the receiving operation carried out at the site.

■ A 2.2. A simple check on the assumptions about the PLT system

If we assume that for small distances x from a source, ground-wave propagation offers attenuation similar to that given by the inverse-square law, then we can check the assumptions made in § 3.2 give sensible results. To restate the values, we assumed that the power injected in 10 kHz was $p_{\text{TX}} = 0.0005$ W and the effective transmitting antenna gain was -20 dBi, i.e. $g_{\text{TX}} = 0.01$, giving an EIRP (in 10 kHz) of 5×10^{-6} W.

The PFD at 10 m is therefore $\frac{p_{\text{TX}}\, g_{\text{TX}}}{4\pi \times 10^2} = 3.98 \times 10^{-9}$W, or a field strength of 61.8 dBμV/m (10 kHz). This is not inconsistent with the reported measurements made by the Radiocommunications Agency.

■ A 2.3. Input data and results obtained

Further to the specific assumptions about the PLT system, we also have to supply the calculation with values of the excess-attenuation factor γ, and downward slope m for each assumed hypothetical exclusion distance x_1. We also have to assume an upper limit x_{max} for the integration, for which the highest possible value is the distance to the antipodal point, πR_E. The significance of this assumption is checked in Appendix A 2.4.

We obtain these values by reading off the appropriate ITU-R curves. These are available for various ground conditions, of which the "Wet ground" appears to be representative of much of the UK, including the BBC Monitoring site at Caversham.

▫ Values for "wet ground, $\sigma = 10^{-2}$ S / m, $\epsilon = 30$"

The following values are for 3 MHz and are thus representative of the 'lower' of the two PLT 'bands' used by Nor.Web. Note that values for γ can only be read off the curves to an accuracy of about a dB, and so the results cannot be expected to have any greater accuracy than this.

exclusion distance, x_1 km	excess attenuation at x_1, 10 Log[10, γ] dB	slope, m	PFD in 10 kHz, W / m^2	equivalent field strength, dBμV / m (10 kHz)
10	17	4.5	7×10^{-14}	14.2
20	23	4.5	1.8×10^{-14}	8.25
30	28	4.5	5.6×10^{-15}	3.25
50	33	4.9	1.5×10^{-15}	−2.4
100	40	5.5	2.5×10^{-16}	−10.2
200	53	8.3	7×10^{-18}	−25.8

▫ Values for "dry ground, $\sigma = 3\times 10^{-4}$ S / m, $\epsilon = 7$"

The following values are for 3 MHz, as before, but in this case for dry ground. This in effect gives a lower bound to the likely exclusion distances — there is also a "very dry ground" in the ITU set, but the "dry" case is already much drier than likely to be found in the UK.

exclusion distance, x_1 km	excess attenuation at x_1, 10 Log[10, γ] dB	slope, m	PFD in 10 kHz, W / m^2	equivalent field strength, dBμV / m (10 kHz)
10	37	4.2	8×10^{-16}	−5.2
20	42	4.3	2.4×10^{-16}	−10.4
30	47	4.6	6.8×10^{-17}	−15.9

▫ Values for “sea water, average salinity, $\sigma = 5\,\mathrm{S/m}$, $\epsilon = 70$”

The following values are for 3 MHz, as before, but in this case for sea. Of course, PLT is not going to be installed in the sea, but ships do make use of HF communications, and the distance from shore can be considered as an exclusion distance.

exclusion distance, x_1 km	excess attenuation at x_1, 10 Log[10, γ] dB	slope, m	PFD in 10 kHz, $\mathrm{W/m^2}$	equivalent field strength, $\mathrm{dB\mu V/m}$ (10 kHz)
100	2	3	5.5×10^{-12}	33.2
500	17	7.5	3.2×10^{-14}	10.8
1000	44	15	2.7×10^{-17}	−19.9

▪ A 2.4. Some checks on sensitivity of the results

Many of the data values assumed have an obvious simple dB-for-dB impact on the result. This clearly applies to the values assumed for p_{TX}, g_{TX}, D, and the value read off the ITU curve for γ. The effect of other assumptions is not so obvious, and these are discussed below.

▫ Upper limit of integration

It can reasonably be argued that the method used must overestimate the level of interference, since the curves always roll off progressively faster, and thus the interference contributed by far-distant locations is over-estimated by the simple straight-line approximation that is used. It can also be argued that the use of the antipodal point as the upper limit of integration is excessive. In fact neither is a significant issue, simply because the rate of roll-off — even at the slower rate implied by the straight-line approximation — is sufficiently great that the region for which the straight line is a good match to the true curve makes the predominant contribution to the integral. We can confirm this by setting much closer upper limits to the integral.

If we take the “wet ground” case previously considered, and take an exclusion distance of 10 km (thus making the slope have a small value), then vary the upper limit of integration x_{max} we get the following results:

upper limit of integration, x_{max} km	equivalent field strength, $\mathrm{dB\mu V/m}$ (10 kHz)
30	14
100	14.2
1000	14.2
20016 (antipodal point)	14.2

A further check for an exclusion distance of 100 km shows similar lack of sensitivity:

upper limit of integration, x_{max} km	equivalent field strength, dBμV / m (10 kHz)
150	−11.4
200	−10.6
300	−10.3
1000	−10.2
20016 (antipodal point)	−10.2

This means that we may take the use of the straight-line as a good approximation affording little error. It also means that we do not have to worry about whether signals from near the antipodal point travel by the 'long' path as well as the 'short' path.

▫ Slope sensitivity

Reading the downward slope *m* off the ITU curves is a matter of visual judgement, so it is interesting to check what difference it would make to the results. The following values are calculated for the "wet ground" case for an exclusion distance of 10 km, and explore a range of values for *m* around the nominal one of 4.5:

slope, *m*	equivalent field strength, dBμV / m (10 kHz)
4	15.2
4.25	14.7
4.5	**14.2**
4.75	13.8
5	13.5

It can be seen that for this situation at least, the difference caused by changes in the estimates of *m* are small and of similar order to other errors — in particular, γ can only be estimated to about a dB.

▪ A 2.5. Some comments on previous results

Previous studies have given widely different results for the size of exclusion zone needed to protect sensitive sites. Part of the reason for this was the use of widely-different assumptions for the attenuation occurring in ground-wave propagation.

In particular, frequent mention has been made of a 10 km exclusion distance. This originates from a study by the RAF [2]. That study involved several steps, of which the last two contained questionable assumptions.

The first step was to estimate the interference which would be caused by a single PLT system.

Propagation was first assumed to follow the inverse-square law that would be applicable to free space. Doing this, and following some detailed evaluation of system parameters, the study in effect derived the standard expression $\mathrm{PFD} = \frac{\mathrm{EIRP}}{4\,\pi\,x^2}$, but with a specific value for the EIRP.

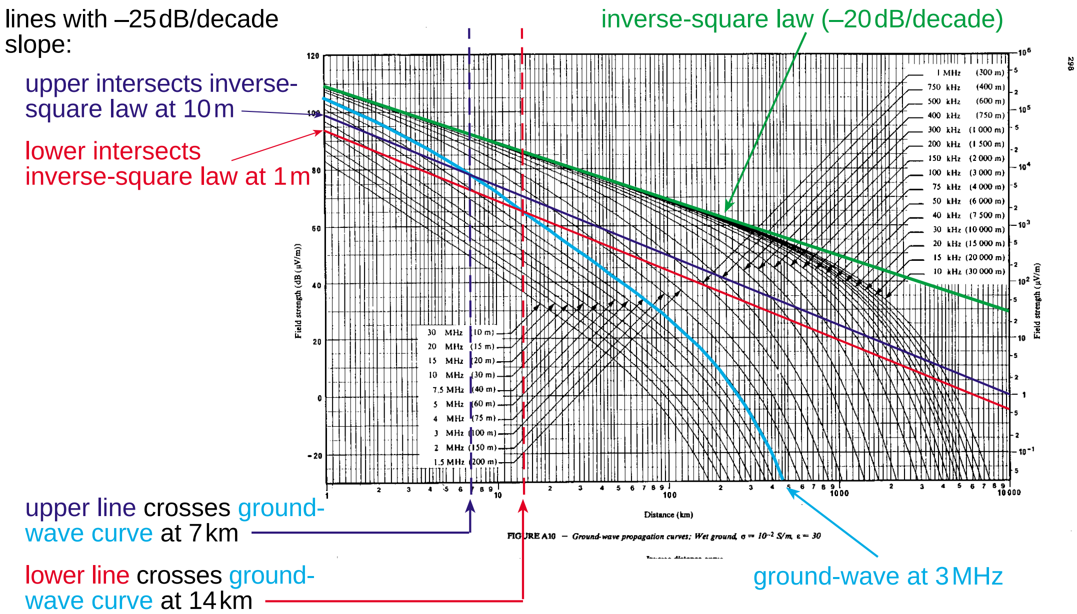
The next step was to take note of an assertion made by Nor.Web that the signal was attenuated more rapidly, falling at 25 dB / decade of distance, rather than the 20 dB / decade of the inverse-square law. To take account of this, the exponent 2 was replaced by 2.5, thus in effect giving the new law:

$$\text{PFD} = \frac{\text{EIRP}}{4\,\pi\,x^{2.5}}$$

Note that doing this contains a *hidden assumption* that the PFD under the new formula should match that given by the standard formula at the distance of 1 metre. This is more than the Nor.Web measurements say — they merely indicated the slope of roughly 25 dB / decade.

Using this formula, together with the EIRP estimates and whatever was assumed to be a tolerable level of interference, the study concluded that a single PLT system could be no closer than 4.4 km to the receiving site.

We can study these assumptions by reference to the ITU curves once more, see below:



The Figure shows the same set of ITU curves as used in Appendix A 2.1, with the curve for 3 MHz once again highlighted in light blue, and the inverse-square-law line in green. The line in red has a downward slope of 25 dB / decade, and would intersect the inverse-square-law line at 1 m, and illustrates the assumption made by applying the law $\text{PDF} = \frac{\text{EIRP}}{4\,\pi\,x^{2.5}}$.

Note in particular that the red line (in effect, that applied by the RAF study) lies below the ‘true’ curve until they cross at a distance of 14 km. It follows that the law assumed in the RAF study would *underestimate* all interference that was closer to the receiver than 14 km, thus calling its conclusion about single interferers into question.

The second step of the RAF study attempted to account for the possibility of multiple interferers by arbitrarily extending the radius of the exclusion zone from the distance of 4.4 km (for a single interfering system) to 10 km.

We can simply demonstrate that this takes inadequate account of the possible interference. Following the assumed 25 dB / decade law, increasing the distance for a single interferer up to 10 km would reduce the interference by about 9 dB. However, with each substation serving an area of 600 m diameter, there could be roughly 100 PLT systems around the immediate periphery of the 10 km exclusion zone. This would increase the interference power by a factor of 100, or 20 dB, giving a net increase (compared with the original single system at 4.4 km) of roughly 11 dB. Furthermore, there is no reason to suppose that the only installation of PLT systems is in a thin circle around the periphery — there could be another 100 in a ring around them, and so on. These further interferers would suffer only slightly increased attenuation, making the situation even worse. It is clear that integration over the installed area is necessary.

The present author made simple calculations to illustrate the need for more careful consideration of propagation than simply applying a slope of 25 dB / decade. In this case he took the line shown in dark blue on the Figure; it intersects the inverse-square law at 10 m. This removes the first arbitrary (and hidden) assumption of the RAF study. The value of 10 m was chosen since this ensures that the formula roughly matches the results of RA measurements at this distance. Calculations which integrated the effects of all the interference sources outside the exclusion zone using this relationship gave rise to absurdly large exclusion zones — bigger than the country! (Since the assumption of a fixed 25 dB / decade slope is now known to be manifestly false, the details of these calculations are not reported here).

This is easily explained by reference to the Figure once more. The dark blue line crosses the ‘true’ curve at 7 km, implying that the effect of all the interferers taken into account (which were always more distant than this) was over-estimated.

Indeed, looking at the curves shows that the interfering signals are attenuated at a rate of more than 25dB/decade for all the distances (and frequencies) shown. There will be some lesser distance, closer to the source than 1 km, at which the slope would have the value 25dB/decade — presumably this is the range within which the Nor.Web measurements were made.

□ A 3. Sky-wave propagation calculation

■ A 3.1. Derivation

Taking the geometry of the situation from Appendix A 1.2, and making a simple allowance for losses by applying an attenuation factor α to account for the power lost to ionospheric absorption in each hop, and another factor β to account for the loss involved in each ground reflection, we obtain the following form for $f[x]$:

$$f[x] = \frac{\alpha^n \beta^{n-1}}{4\pi s^2}$$

$$= \frac{\alpha^n \beta^{n-1}}{16\pi n^2 \left(R_E{}^2 - 2\,\mathrm{Cos}\left[\frac{x}{2 n R_E}\right] R_E (h+R_E) + (h+R_E)^2\right)}$$

We can then apply this in the integral we use to calculate the interference:

$$\mathrm{PFD} = \int_A p_{\mathrm{TX}}\, g_{\mathrm{TX}}\, D\, f[x]\, dA =$$

$$\int_{x_1}^{x_{\max}} p_{\mathrm{TX}}\, g_{\mathrm{TX}}\, D \frac{\alpha^n \beta^{n-1}}{16\pi n^2 \left(R_E{}^2 - 2\,\mathrm{Cos}\left[\frac{x}{2 n R_E}\right] R_E (h+R_E) + (h+R_E)^2\right)} 2\pi R_E\, \mathrm{Sin}\left[\frac{x}{R_E}\right] dx$$

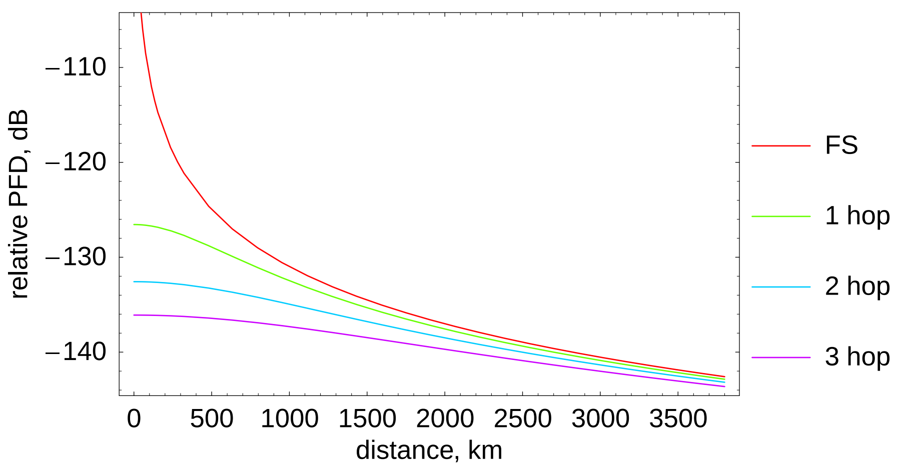
$$= \frac{\alpha^n \beta^{n-1} p_{\mathrm{TX}}\, g_{\mathrm{TX}}\, D\, R_E}{8 n^2} \int_{x_1}^{x_{\max}} \frac{\mathrm{Sin}\left[\frac{x}{R_E}\right]}{\left(R_E{}^2 - 2\,\mathrm{Cos}\left[\frac{x}{2 n R_E}\right] R_E (h+R_E) + (h+R_E)^2\right)} dx.$$

Note that the upper limit of integration $x_{\max}$ that we choose may not exceed $x_{\mathrm{Max},n} = 2 n R_E\, \mathrm{ArcCos}\left[\frac{R_E}{R_E+h}\right]$ (for which rays are tangential to the ground).

■ A 3.2. Results

□ Comparison with free-space propagation

It is instructive to plot $f[x]$ for various numbers of hops, and to compare these with free-space propagation over a distance equivalent to the curved-Earth distance x. This is illustrated in the following Figure, for which values of $\alpha = \beta = 1$ have been assumed (i.e. no losses in reflections), together with an ionospheric height of 300 km:



As expected, free-space attenuation (red curve) decreases dramatically for small distances. In contrast, the variation with distance is less marked for the ionospheric-propagation cases. This is because the signal has to go to the ionosphere and back anyway, so the distance travelled is approximately $2\,n\,h$ for any nearby points. This also explains a difference of 6 dB between 1- and 2-hop cases. For more-distant locations, it makes little difference how many hops there are, as the polygonal path does not deviate so much from the Great Circle around the surface of the Earth. The *x*-axis range of the plot has been limited to the distance over which one-hop propagation is possible — care must be taken not to apply the formula over longer ranges as this would be equivalent to rays passing through the Earth!

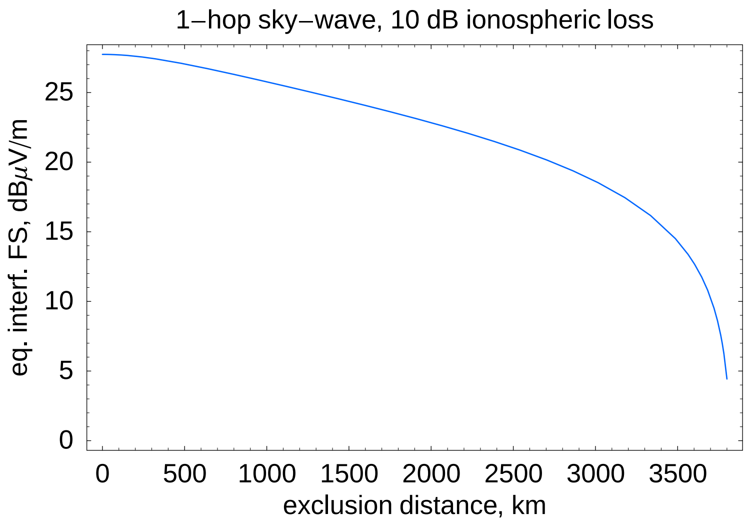
Note that subsequent calculations do make a simple allowance for reflection losses, as a result of which the attenuation will increase with the number of hops. The above-noted difference of 6 dB between 1- and 2-hop cases (for short distances) will therefore be greater in practice.

▫ Calculated PFD

For the following we use the same PLT parameters as set out in § 3.2. of the main text, assuming that the density applies over the whole area which is integrated. Only 1-hop propagation is considered, and an ionospheric reflection loss of 10 dB, i.e. $\alpha = 0.1$, is assumed, together with an ionospheric height of 300 km.

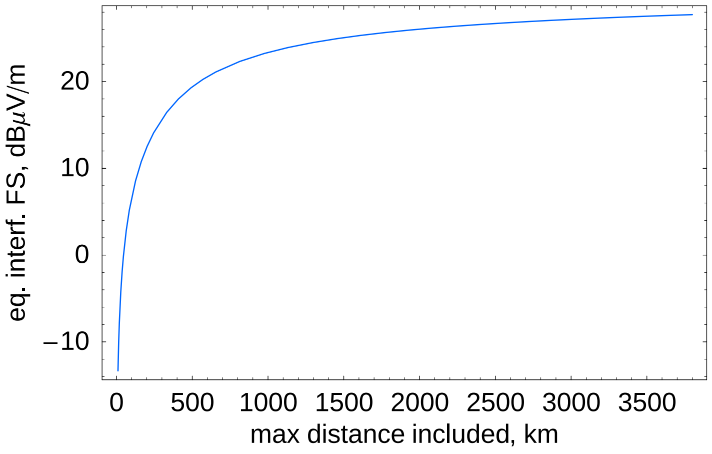
It is of interest to look at the problem two ways: we can vary the inner integration limit, to see the value of any exclusion distance, and we can vary the outer limit — in effect limiting the area over which PLT is assumed to be deployed (supposing that it is centred on the receiving site).

The Figure below applies the above assumptions to the 1-hop case, while the upper limit of integration is set to the maximum distance for which 1-hop propagation is possible:



It can be seen that the interference decreases only slowly until a very large exclusion distance is reached. This is easily explained in combining two concepts. The rate of attenuation with distance from the receiver is not dramatic, as previously explained, while the nearby part of the Earth has a relatively small area compared with the whole area included in the calculation. So only when the exclusion distance is large is the number of interferers greatly reduced, and their value further diminished by distance, whence the shape of the curve follows.

Similarly, if we assume no exclusion zone, and vary the outer limit of integration, we get the following Figure:



At first there is a rapid increase in interference as the outer limit is increased — the number of interferers included increases rapidly, while the attenuation of the added outermost ones is scarcely less than for the nearest ones. For larger distances, the added area is relatively less important and the attenuation of its contributions greater.

What these calculations show is that PLT interference via sky wave would be a significant problem were large areas of the Earth to be covered with PLT systems at the assumed density.

□ A 4. Calculation of interference to aircraft

■ A 4.1. Derivation

The geometry and calculation of this case is very similar to the case of sky-wave interference to a ground-based receiver, except that the path is similar to one-half of a hop, the height h is lower, and there are no ionospheric losses to allow for. Taking the geometry from Appendix A 1.3, we have a slant-path length l given by:

$$l = \sqrt{R_E{}^2 - 2\,\mathrm{Cos}\left[\tfrac{x}{R_E}\right] R_E\,(h + R_E) + (h + R_E)^2}$$

while the maximum distance around the Earth from the point below the aircraft to the horizon (as seen from the aircraft) is given by:

$$x_{\mathrm{Max}} = R_E\ \mathrm{ArcCos}\left[\tfrac{R_E}{R_E + h}\right].$$

We may assume that simple free-space propagation applies, so:

$$\begin{aligned} f[x] &= \frac{1}{4\,\pi\,l^2} \\ &= \frac{1}{4\,\pi\,(R_E{}^2 - 2\,\mathrm{Cos}[\frac{x}{R_E}]\,R_E\,(h+R_E)+(h+R_E)^2)} \end{aligned}$$

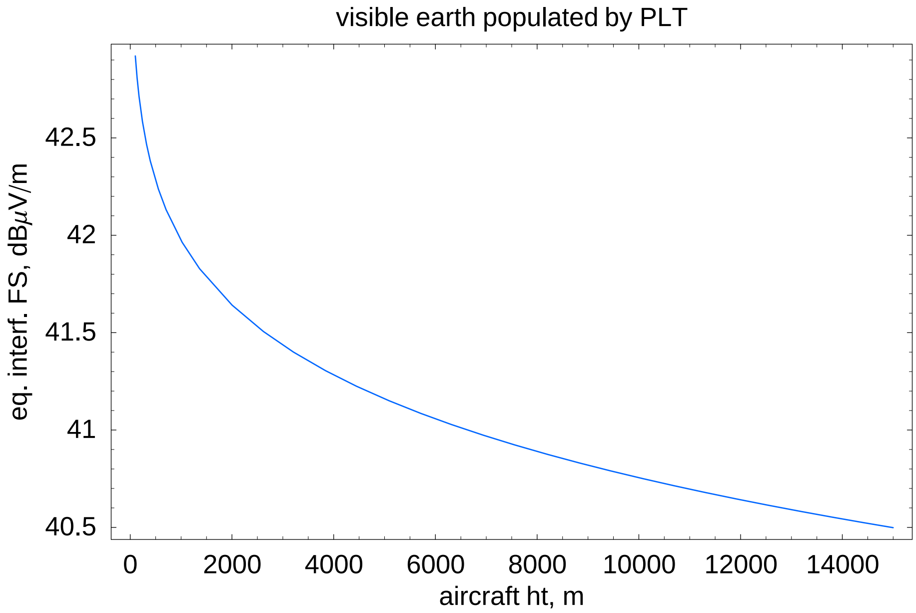
so the integrated interference becomes:

$$\mathrm{PFD} = \int_A p_{\mathrm{TX}}\,g_{\mathrm{TX}}\,D\,f[x]\,dA = \int_{x_1}^{x_2} p_{\mathrm{TX}}\,g_{\mathrm{TX}}\,D\,\frac{1}{4\,\pi\ (R_E{}^2 - 2\,\mathrm{Cos}[\frac{x}{R_E}]\,R_E\,(h+R_E)+(h+R_E)^2)}\ 2\,\pi\,R_E\ \mathrm{Sin}\left[\tfrac{x}{R_E}\right] dx$$

$$= \frac{p_{\mathrm{TX}}\,g_{\mathrm{TX}}\,D\,R_E}{2} \int_{x_1}^{x_2} \frac{\mathrm{Sin}[\frac{x}{R_E}]}{(R_E{}^2 - 2\,\mathrm{Cos}[\frac{x}{R_E}]\,R_E\,(h+R_E)+(h+R_E)^2)}\ dx.$$

■ A 4.2. Results

We make the same assumptions as in § 3.2 concerning PLT parameters, and assume that the entire visible Earth is populated at the assumed density. Note that the latter assumption might be reasonable for moderate aircraft heights when flying over an extended conurbation. Then we can plot the equivalent interfering field strength as a function of aircraft height by setting $x_1 = 0$ and $x_2 = R_E \text{ ArcCos}\left[\frac{R_E}{R_E + h}\right]$, with the following results:



In effect, as height increases, the strength of the contribution from any one interferer decreases, but the number of visible interferers increases nearly as quickly. Of course, from *very* great heights the visible surface would be unlikely to be fully populated with PLT.

We can put this into perspective by plotting the distance to the aircraft's visible horizon (measured around the Earth from the point vertically below the aircraft) as a function of height: