Effect of Altitude on Audible Noise Generated by AC Conductor Corona

by

Hendrik Adriaan Roets

Thesis presented in fulfilment of the requirements for the degree of
Master of Science in Engineering at the Stellenbosch University

Supervisor: Prof. H.C. Reader

December 2012

Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Summary

Power utilities are expected to keep the cost of electricity as low as possible. They are also expected to be environmentally friendly and, amongst other things, not to produce unacceptable audible noise. When the electric field on a conductor is high enough corona is produced and this is accompanied by audible noise. Air pressure, which is directly related to altitude, has an effect on the voltage at which corona will start. It is more difficult to ionise the air at sea level (high air pressure) than at high altitude (low air pressure). Altitude does not only affect the corona inception voltage, but also the intensity of the audible noise. A thorough scan of literature revealed that there is very little evidence of prior research work on the effect of air density on corona under *fair weather (dry)* conditions.

In South Africa, transmission lines are built at altitudes higher than 1800 m above sea level. The cost of a 400 kV line is in the region of R2M per km. It is important to predict the noise levels under a proposed line accurately, before it is energised. This research indicated that the altitude correction for conductor corona audible noise, under *dry conditions*, might be steeper than the general accepted correction of 1 dB/300m. This correction, however, appears to be valid for *heavy rain* conditions.

Under heavy rain conditions the corona is mainly determined by the water droplets, whereas under dry conditions the condition of the conductor plays the biggest role. The air density therefore has a bigger effect on the corona performance under dry conditions. The implication of a steeper altitude correction for dry conditions is that too low noise levels will be predicted for a higher altitude, which could lead to complaints. On the other hand, predictions for lower altitudes will be too conservative.

Opsomming

Daar word van kragvoorsieners verwag om die koste van elektrisiteit so laag as moontlik te hou. Hulle is verder onder druk om omgewingsvriendelik te wees en om onder andere nie onaanvaarbare hoorbare geraas te veroorsaak nie. Wanneer die elektriese veld op ‘n geleier hoog genoeg is, kan korona ontstaan wat dan hoorbare geraas veroorsaak. Die lugdruk, en daarom die hoogte bo seevlak, beïnvloed die spanning waarby ‘n geleier in korona sal gaan. Dit is moeiliker om die lug te ioniseer by seevlak (hoë lugdruk) as hoog bo seevlak (lae lugdruk). Die hoogte bo seevlak beïnvloed daarom nie net die spanning waarby korona sal begin nie maar ook die intensiteit van die hoorbare geraas. Dit wil voorkom of die effek van hoogte bo seevlak, op hoorbare geraas, a.g.v. geleier korona tot op datum baie skraps nagevors is. Baie min kon in die literatuur gevind word op die effek onder droë toestande.

In Suid-Afrika is dit nodig om transmissielyne op hoogtes van 1800 m en hoër te bou. So ‘n lyn (400 kV) kos in die omgewing van R2M per km. Dit is daarom van uiterste belang om die geraasvlakke wat ‘n beplande lyn sal veroorsaak, akkuraat te bepaal, voordat so ‘n lyn aangeskakel word. Hierdie navorsing het gewys dat die effek van hoogte bo seespieël op hoorbare korona geraas onder *droë toestande* groter kan wees as wat algemene aanvaar word. Die helling van die korreksiefaktor vir hoogte bo seevlak blyk steiler as 1 dB/ 300 m te wees vir *droë toestande*. Die implikasie hiervan is dat geraas voorspellings vir hoër hoogtes bo seespieël te laag sal wees en die vir lae hoogtes te konserwatief kan wees. Die navorsing stem egter saam met die korreksiefaktor van 1 dB/300 m onder *swaar reën* toestande. Dit wil voorkom of die invloed van die waterdruppels op geleier korona groter is as lugdruk. Onder droë toestande speel die toestand van die geleier ’n groter rol en is die effek van lugdruk groter.

Table of Contents

Table of Figures

Acknowledgements

I would like to thank the following people and institutions for their part in making this research possible:

Arthur Burger and Trans Africa Projects for funding the initial part of this project (cage measurements at different altitudes during dry conditions).

Kiepersol Technology for supplying the instrumentation and the funding of cage measurements under wet conditions.

Nishal Mahatho and Eskom for the use of their high voltage test transformer.

Professor Reader and Stellenbosch University for providing me with a study bursary. Prof, thank you for “teaching an old dog new tricks”, without your help this would not have been possible.

Coenie Esterhuizen, my photographer, colleague and friend, thank you for all your help on every trip, towing of one of the trailers over long distances, taken of all pictures used in this document, and for assisting with the measurements.

My wife and children, Malia, Tanita and Drikus, thank you for your moral support and help with setting-up of measuring sites in far-off places, sometimes in extreme weather conditions.

Chapter 1

Introduction

1.1 Background

Power utilities are under pressure to build cost effective transmission lines with no, or very little, impact on people and the environment. The transmission of power over large distances has made it necessary to use higher transmission voltages. At higher voltages, the effects of conductor corona can be very severe. Audible noise caused by conductor corona is one of the factors that can have a huge impact on people and the environment. Great care has to be taken when a line is designed, not to produce unacceptable audible noise since the mitigation thereof, after a line has been built, is very costly and impractical.

We have learnt that at high altitudes, audible noise is not only a concern during wet conditions but also during fair weather. The reason is twofold; the background noise is very low in rural areas and the corona noise is higher because of the lower air pressure at higher altitudes. We have also found that existing empirical formulae for the prediction of audible noise, under dry conditions, cannot be used, since they predict levels that are too low (practical experience and reasons for the inaccuracy are shared in Chapter 3).

Eskom, the power utility in South Africa, has developed a prediction method using a corona cage to predict noise levels under transmission lines. However, the generally accepted correction factor of 1 dB/300 m appeared not to be valid for dry and light rain conditions. Field measurements that raised this concern and literature supporting the correction factor of 1 dB/300 m for heavy rain conditions are discussed in Chapter 3.

This research project was undertaken, as part of Eskom’s corona research, to validate the effect of altitude on conductor generated audible noise. A mobile corona cage was constructed for this purpose to enable the movement of the same test setup to different altitudes. Audible noise measurements were performed at different altitudes and voltages. Measurements from the small cage, at 1500 m above sea level, agreed with the ones from the large Eskom cage (1500 m above sea level) for dry conditions (Chapter 4). However, the measurements at different altitudes supported the field measurements and also produced a steeper altitude correction factor (Chapter 5).

The research was then taken a step further and the mobile cage was equipped with tanks, a water pump and water sprayers. Measurements were performed during artificial heavy rain conditions, at three altitudes (Chapter 5). The results during heavy rain agreed with the correction factor of 1 dB/300 m. Further, unlike in the fair weather case, the heavy rain measurements in the corona cage agreed well with empirical predictions (Chapter 6).

The research has shown that during heavy rain, the water droplets produce substantial corona and audible noise. The effect of altitude on corona generated audible noise is therefore masked by the corona produced by the water on the conductor surface. During dry conditions, the condition of the conductor plays a more prominent role and the air density has a bigger effect on the corona and audible noise.

The measurements in the mobile cage support the correction factor of 1 dB/300 m for heavy rain conditions. However, for dry conditions, the cage as well as field measurements suggest a much steeper correction factor, in the order of 1 dB/100 m.

The author is responsible for the design and implementation of all the experimental material presented in this thesis. The observation of the steeper correction factor was of a result of the author’s research over the last 10 years. The experimental procedures and interpretations were discussed together with members of Eskom and the supervisor (HC Reader). During the project C Esterhuizen was responsible for the towing of one of the two trailers (the high voltage transformer), taking of pictures and the control of the voltage during measurements.

Chapter 2

Corona and Audible Noise in High Voltage Systems

2.1 Corona as a source of interference

When the electric field around a conductor is high enough, atoms are excited and air molecules close to the conductor are ionised. When an excited atom returns to its original state (electrons move back to their valence bands) the excess energy is released in the form of a photon [1]. This light is visible to the human eye (Figure 2.1 and Figure 2.2).

Figure 2.1
Conductor Corona: Triple Tern Conductor Bundle at 25 kV/cm in Eskom Corona Cage, 1500 m above sea level

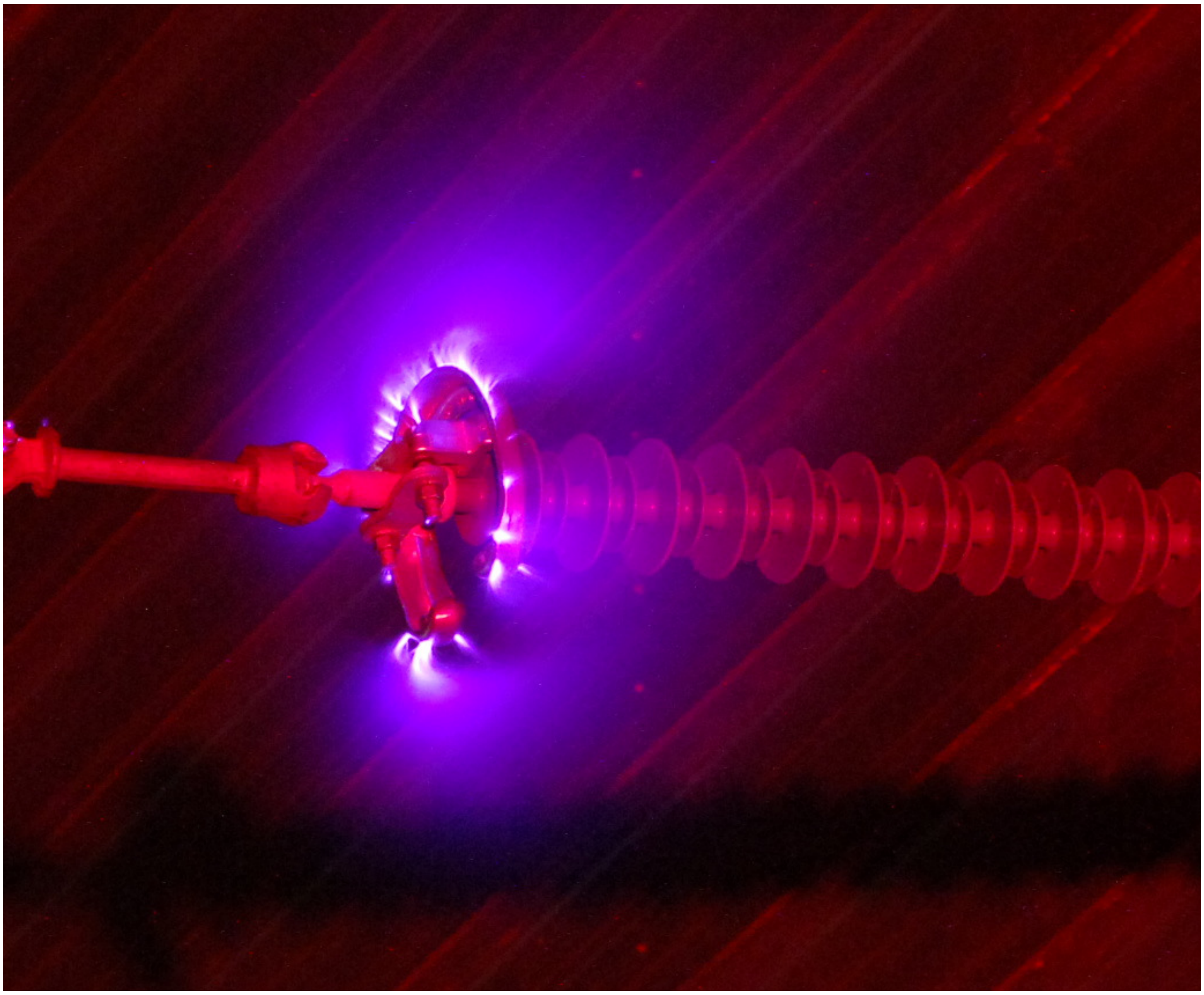


Figure 2.2
Corona on insulator grading ring

Corona is a phenomenon inherent to transmission lines of 88 kV and above. Corona is self-sustaining and occurs when the critical field strength in a non-uniform field is exceeded. In a uniform field, corona cannot occur, without a flashover taking place [2],[3]. The physics of corona and the ionisation processes are well described in [1], [2], [3], [4], [5], [6], [7].

The term surface gradient or gradient is used to quantify the electric field at the conductor. Corona occurs when the electric field, at the conductor surface, reaches a certain critical value, called the corona inception gradient.

Peek developed an empirical formula to calculate the corona inception gradient in a cylinder (Peek's Law) [1], [2], [3], [4].

$$E_c = 21.1m\delta\left(1 + \frac{0.301}{\sqrt{\delta r_c}}\right) \tag{2.1}$$

where

$E_c =$ corona onset gradient in $\frac{kV}{cm}$ (rms)

$m =$ roughness factor

$r_c =$ conductor radius in cm

$\delta =$ relative air density (RAD)

$$\delta = \frac{273+t_0}{273+t} \cdot \frac{P}{P_0} \tag{2.2}$$

where

$t =$ temperature in ℃

$t_0 =$ reference temperature in ℃

$P =$ atmospheric pressure in mm of mercury

$P_0 =$ reference atmospheric pressure in mm of mercury

The corona inception gradient is a function of air pressure, temperature, conductor radius and the surface condition of the conductor. The roughness factor is a critical parameter and varies between 0.6 and 0.85 for stranded conductor of AC lines (on DC lines it could be as low as 0.5 when insects and dust are collected) [1], [3], [4], [7].

The corona effects that are considered in transmission line designs are power loss, electromagnetic interference (EMI) and audible noise [1], [2] ,[3], [7], [8], [9]. However, in modern designs, EMI and corona power loss play lesser roles. Corona EMI is predominant at frequencies below 30 MHz [1], [9], [10], [11], [12]. It therefore interferes with amplitude modulation (AM) radio receivers (0.535 – 1.605 MHz) [1], [13]. Frequency modulated (FM) radio (88 – 108 MHz) virtually replaced AM radio and therefore corona EMI does not affect the general public. EMI by power lines is mainly caused by distribution lines, in particular, arcing between metal parts on wood poles [10], [11], [12], [13], [14].

Corona losses are normally very small compared to I^2R losses, under dry conditions, and are also of no concern to the average person in the street. Audible noise, on the other hand, has become one of the main design constants with the introduction of lines of 500 kV and above, including compacted and double circuit 400 kV lines [1], [2], [3], [18], [19], [21],[22]. It is not easy to mitigate excessive audible noise after a line has been built.

2.2 Conductor Generated Audible Noise on AC lines

The discharge activities associated with the ionisation of the air molecules cause the generation of acoustic pressure waves. The random pressure waves of different pulses are observed simultaneously under a conductor power line, which is perceived as frying noise. The noise is mainly caused by positive streamer corona [1], [2], [3], [4], [7].

At higher gradients or under foul weather conditions, negative streamers are also formed. This means that the frying noise is generated twice, in one power frequency cycle (50 Hz or 60 Hz), at the positive and negative peak. A pure tone hum is therefore perceived by the human ear at a frequency double that of the power frequency, ie 100 Hz or 120 Hz. This noise component sounds like transformer hum. (The human ear is not sensitive at 50 Hz or 60 Hz, but can hear 100 Hz and 120 Hz – Figure 2.3.) Conductor corona therefore produces a frying and a humming noise.

2.3 Audible noise as a function of rain

The corona activity, and therefore the audible noise produced by a conductor, is dependent on the weather conditions, mainly rain and rain rate [1], [3], [4], [16], [23], [24], [25], [26]. For this reason the corona performance is expressed for different rain conditions, namely fair (L50 dry), wet (L50 Wet) and heavy rain (L5 Wet).

- Fair weather: This is also referred to as dry condition. The term fair weather only refers to corona activity during absolute dry conditions and not necessarily to pleasant conditions. Fair conditions exclude rain, fog snow and ice. When corona cage measurements are performed and noise predictions are made, the statistical term, L50 dry, is normally used for fair conditions. The term L50 dry means that the noise level referred to, will only be exceeded 50% of the time, under dry conditions. A L5 dry level will only be exceeded 5% of the time under fair weather conditions (the rest of the time (95%) the noise will be below the L5 level.

Foul weather refers to conditions where the conductor is subjected to forms of moist, like rain, snow, ice and fog. In South Africa we only consider rain conditions namely, wet conductor and heavy wet conductor.

- Heavy Rain: This term refers to rain rates of 7.7 mm/h and higher. The statistical term *L5 Wet is* used to classify the noise levels that occur under this condition (the level that will only be exceeded 5% of the time under wet conditions). In corona cages, L5 Wet measurements are made while the conductor is sprayed with artificial rain in excess of 7.7 mm/h.

- Wet: The statistical term L50 wet is used to quantify noise levels that will be exceeded 50% of the time under measurable rain conditions. In corona cages, L50 Wet measurements are made 1 minute after the conductor was sprayed with artificial rain in excess of 7.7 mm/h [19].

2.4 Sound Pressure Level (dB)

From [27]: The sound pressure at a certain point is the difference between the instantaneous pressure and the ambient mean pressure. The unit of Sound Pressure (p) is Pascal (Pa) which is equal to Newton per square meter (N/m²). The reference value for Sound Pressure Level (SPL) is twenty micro-Pascal (20 µPa). The Sound Pressure Level (Lp) is defined by the formula below:

$$Sound\ pressure\ level\ (L_P) = 20\log_{10}\left(\frac{sound\ pressure}{reference\ pressure}\right) \quad (2.3)$$

Sound Pressure and Sound Pressure Level generally refer to the root mean square (rms) value of the pressure. The rms value is considered if no specific reference is stated. A pressure equal to the reference value is thus equal to zero dB while 1 Pa equals 94 dB (93.98 dB). The zero dB value corresponds to the threshold of hearing at 1000Hz for a young person with normal hearing ability. The pressure has no direction and is thus a scalar.

Table 2.1 shows the analogy between the propagation of sound and electrical circuits. The equivalent electrical parameter for sound pressure is voltage.

Acoustic Parameter	**Unit**	**Equivalent Electric Parameter**	**Unit**
Sound Pressure	$Pa = N/m^2$	Voltage	V
Compliance	$m^3/Pa = m^5/N$	Capacitance	F
Stiffness	$Pa/m^3 = N/m^5$	1/Capacitance	F^{-1}
Mass	$kg/m^4 = Ns^2/m^5$	Inductance	H
Acoustic Resistance	$Pas/m^3 = Ns/m^5$	Resistance	Ω
Volume Velocity	m^3/s	Current	A

Table 2.1
Acoustic and Equivalent Electric Parameters
used for modelling of condenser microphones [27]

2.5 A-weighted sound pressure levels (dBA)

The human ear is frequency dependent, and is most sensitive between 1 and 5 kHz (Figure 2.3). The A-weighted filter network with a response close to the human ear was introduced to measure annoyance (Figure 2.4). (It is of no use to measure the annoyance, of noise levels at frequencies, where the human ear is not sensitive). The unit for a sound level measured with an A-weighed filter is dBA and is referred to 20 µPa. Audible noise produced by conductor corona is therefore expressed in dBA. In Figure 2.5 the sound levels of different noise sources are compared.

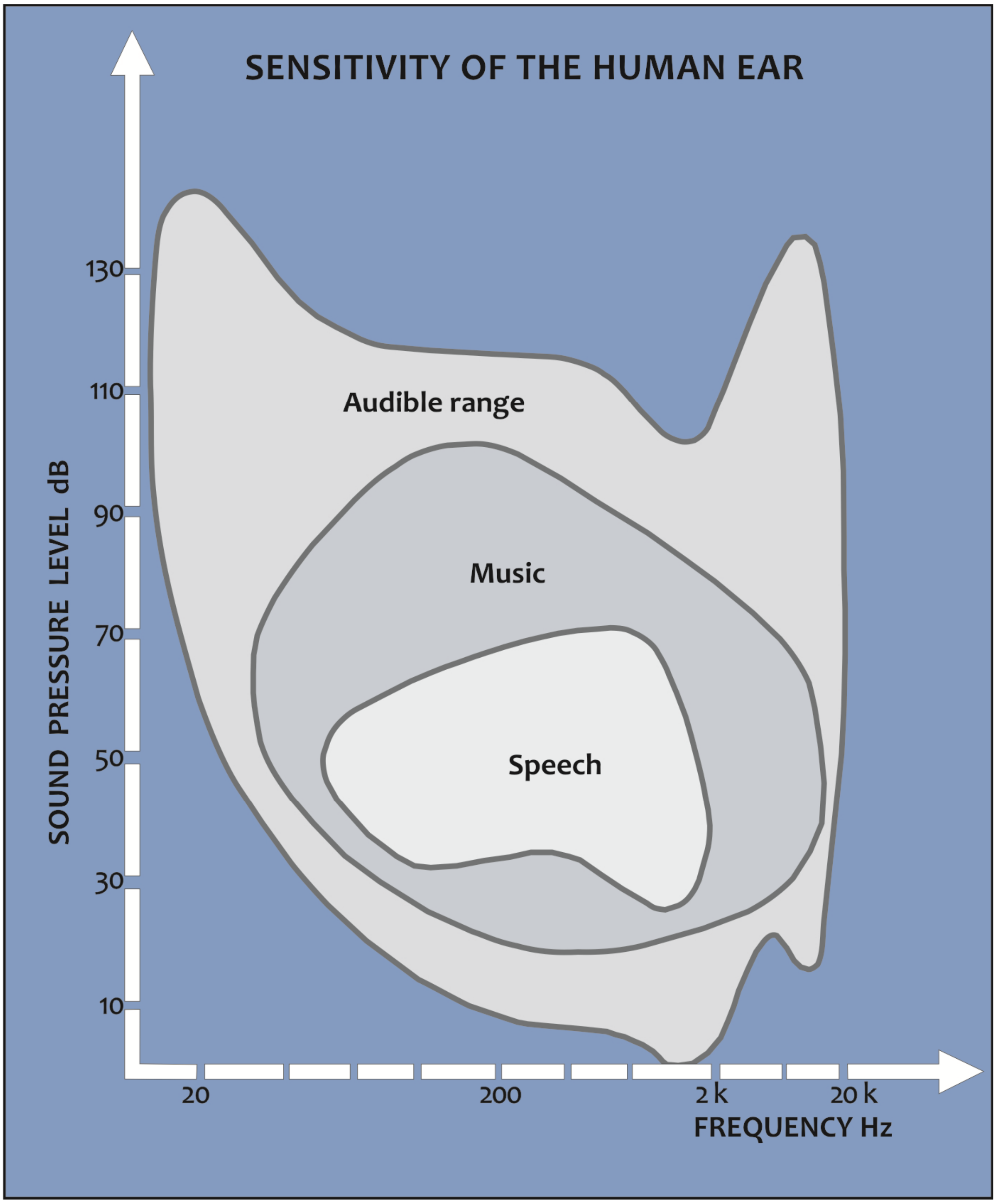


Figure 2.3
Sensitivity of the human ear (from [28])

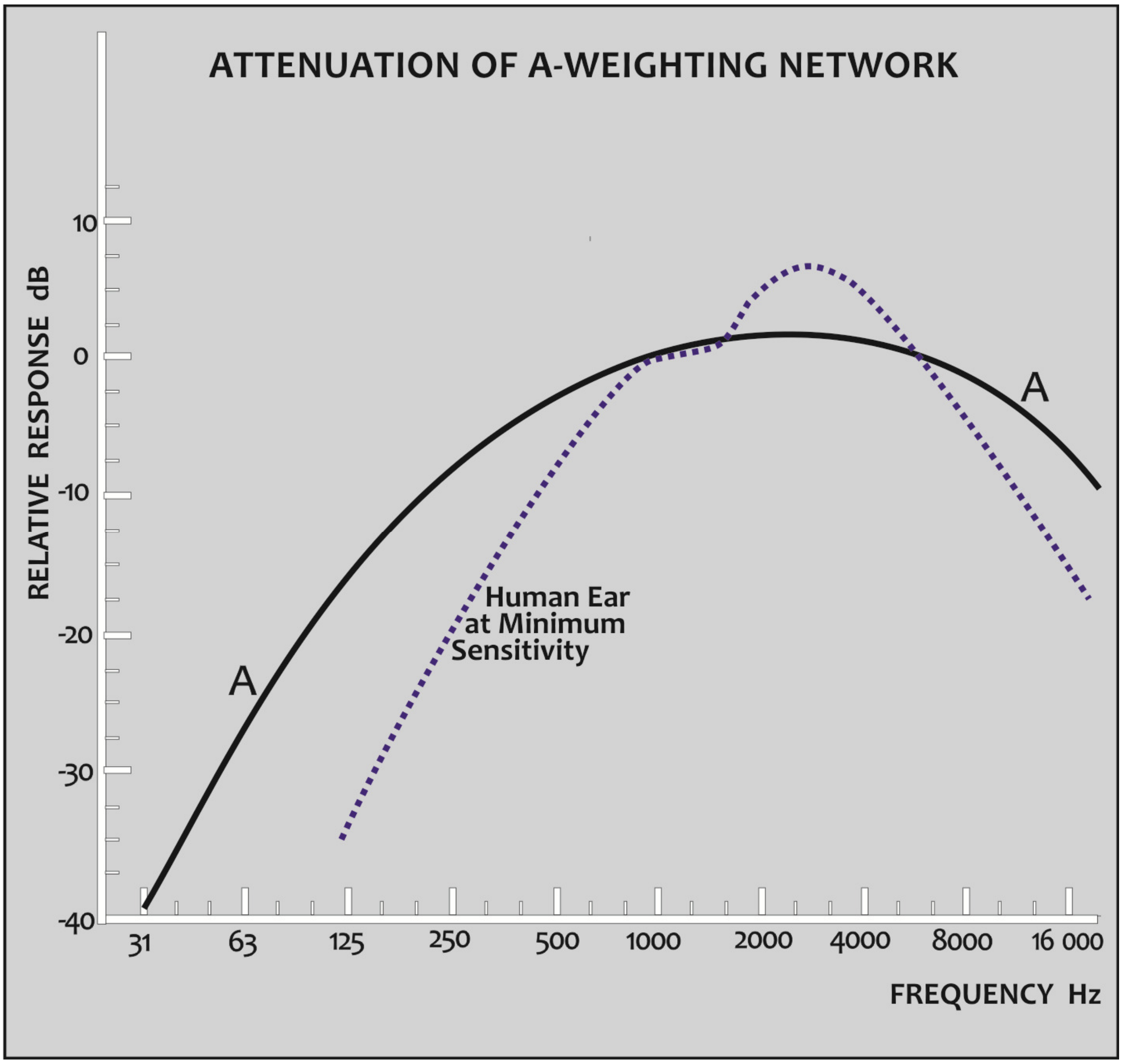


Figure 2.4
Attenuation of A-weighting network used in sound-level measurements ([1], [28])

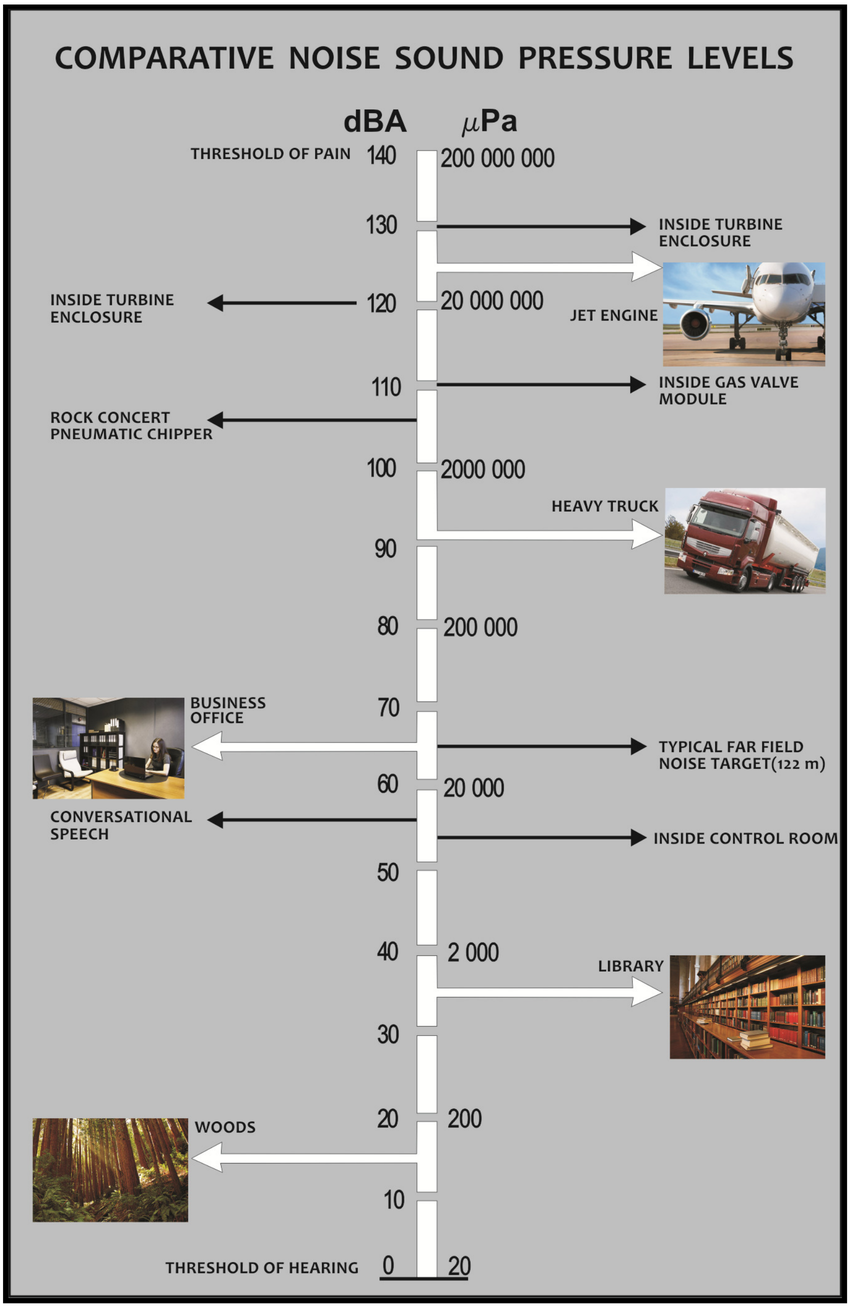


Figure 2.5
Comparative Noise Sound Pressure Levels (dBA) [29]

2.6 Conclusion

Conductor corona can be a source of audible noise and is worst under wet conditions for AC voltages. Sound pressure levels are measured in dB referenced to 20µPa. Since the human ear is frequency dependant, a filter that approximates the human hearing is used to measure noise nuisance (A-weighted). In Chapter 3, the impact of audible noise on transmission line design is considered.

Chapter 3

Audible Noise and AC Transmission Line Design

3.1 History

It is only in the last two to three decades that audible noise produced by conductor corona on high voltage lines has been recognised as a factor in the design of transmission lines. Today, audible noise is one of the main design constraints in transmission line designs [1], [2], [3], [16], [9], [18]. The reason for this is twofold: People are more aware of possible health hazards, and a noisy power line will automatically focus the attention on the negative effects of the line. The second reason is that transmission utilities are building more compact transmission lines, at higher voltages which lead to higher surface gradients, and hence higher audible noise, even under dry conditions. Utilities also have to build transmission lines through densely populated urban areas, some of which have low background noise levels at night.

Conductor bundles were generally chosen with the corona inception gradient much higher than the operating gradient, due to large bundles and wide phase spacings. In South Africa, we have learnt that corona under dry conditions can lead to serious complaints [34].

The perceived audible noise is dependent on the difference between the noise and the background noise. Corona noise is worst under heavy rain conditions, but the rain is also responsible for an increase in background noise and could mask the corona noise. In areas of low background noise a conductor bundle can be perceived as being very noisy during fair weather conditions, but be acceptable during wet conditions.

From a practical point of view, the audible noise under *dry* condition is of a greater concern in this country since it causes a permanent discomfort. Noise under wet conditions, only applies when it is wet and our rainfall is relatively low.

In South Africa, our coal reserves, and therefore our coal driven power stations are mainly situated at high altitude (1500 – 1800 m above sea level). The distances between our power stations and coastal areas are in excess of 1500 km. This means that we have to transport power at high voltages and at high altitudes.

3.2 Field Measurements

In 2004 we simultaneously measured audible noise, at two different altitudes, under a selected 400 kV transmission line (line cannot be identified due to commercial reasons), operating at a surface gradient of 16.5 kV/cm [34]. The audible noise, winds speed and rain rate were captured every second and the averages logged every minute. The measurements were performed in accordance with the IEEE Standard for the measurement of audible noise from overhead lines [31]. The microphones at both sites were placed under the outside phase, 1.5 m above the ground for maximum noise levels. Dry measurements were not possible due to the low line noise compared to the background. We were fortunate to have captured some measurements during light rain (0.1mm/min - 0.2mm/min) in the early morning between 02h30 and 03h30 (the average wind speed at the time was 1.1 m/s and did not exceed 2.8 m/s). The measurements are depicted in Figure 3.1 below. Histograms of the two curves for this period indicated a difference of 1 dB/90 m (2.8 dB/260 m) [34].

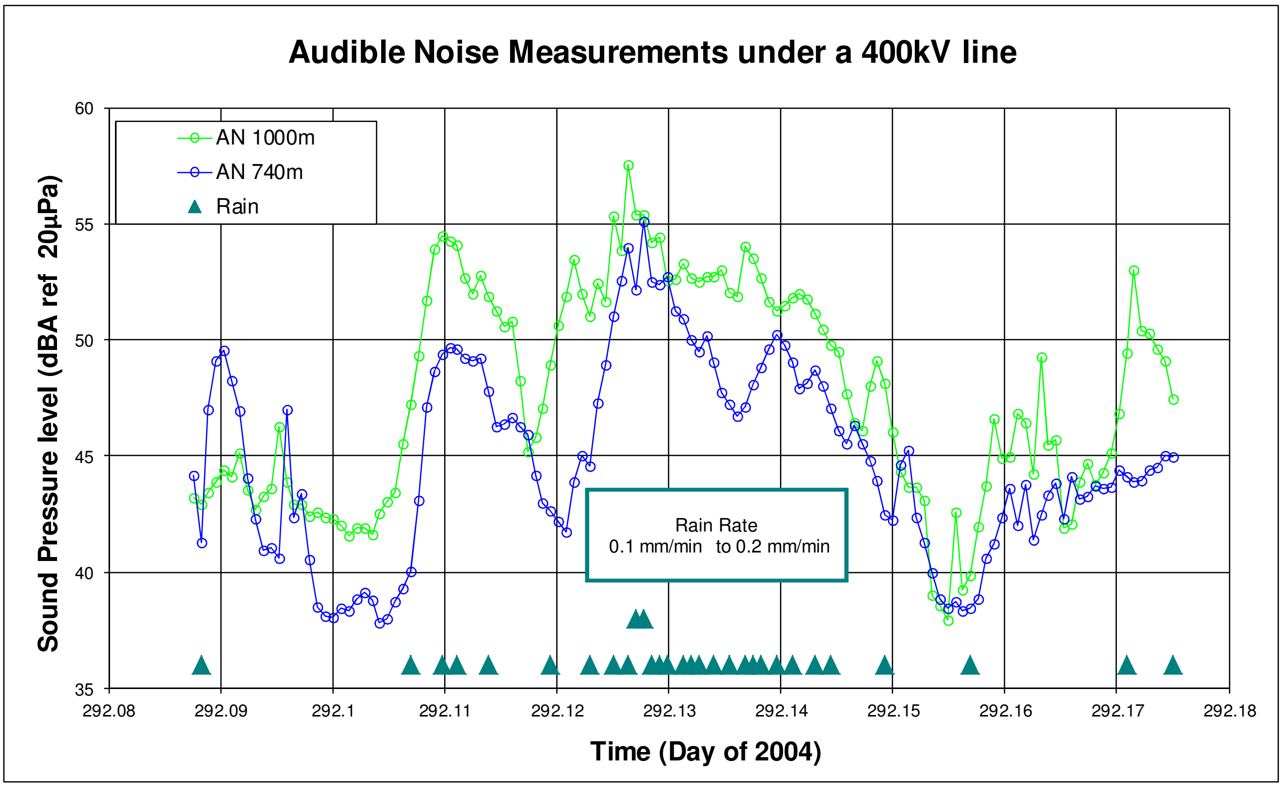


Figure 3.1

Audible noise measurements under a 400kV line at different altitudes

(740 m and 1000 m above sea level)

At both sites the noise levels increased by about 12 dB during rainy conditions. This is in accordance with corona cage measurements that were performed on a similar conductor bundle (triple Tern) that is used on this line (Appendix A). The difference between the dry condition curve and the L50 wet curve at 16.5 kV/cm is also about 12 dB.

The stable noise levels between interval 292.1 and 292.11 are depicted in Figure 3.2 below. The difference between the two curves is almost a constant 4 dB, which translates to a correction factor of 1 dB/65 m. The rain was measured with a tipping bucket, which registers 0.1 mm rainfall per tip. The audible noise points were logged every minute. This means that 0.3 mm rain was recorded over the 10 minutes between the first and last tip. The correction of 1 dB/65 m was therefore measured for a rain rate of 0.03 mm/min.

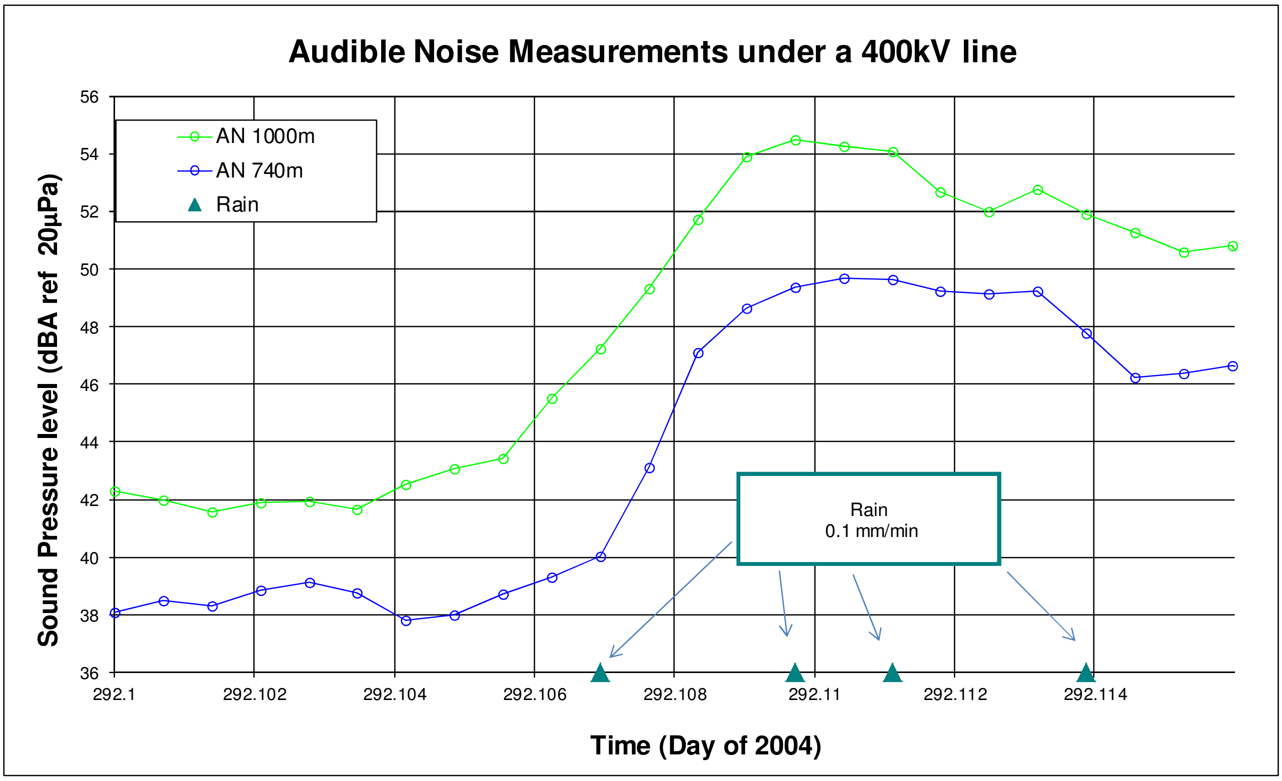


Figure 3.2
Audible noise measurements under a 400kV line at two different altitudes (740 m and 1000 m above sea level) with a rain rate up to 0.1 mm/min

Over the 11 minute period between the first and the last rain measurement in Figure 3.3, a total of 1.1 mm rain was measured. The difference between the two curves is about 2 dB. The correction is therefore 1dB/130m for a rain rate of 0.1 mm/min.

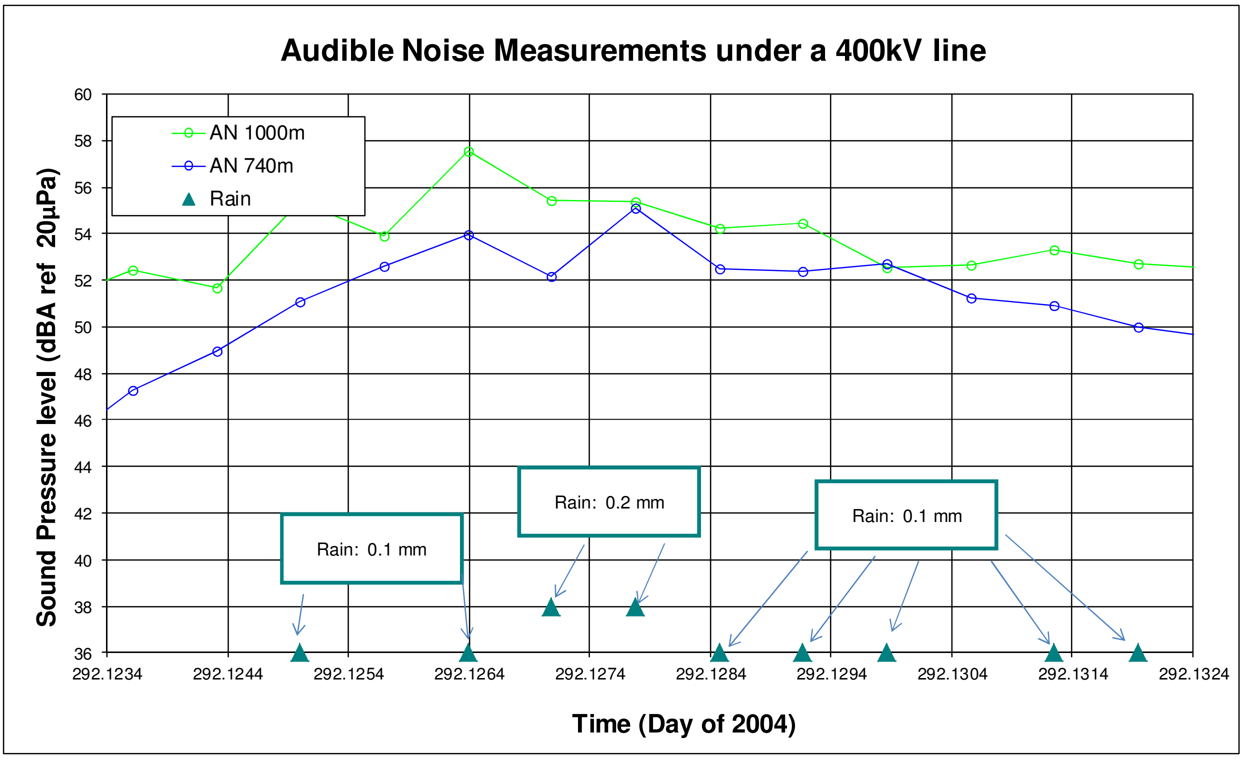


Figure 3.3
Audible noise measurements under a 400kV line at different altitudes
(740 m and 1000 m above sea level) with a rain rate up to 0.2 mm/min

In Figure 3.4, field measurements, during dry conditions, under the same line, at an altitude of 1100 m above sea level, are compared to corona cage and Bonneville Power Administration (BPA) predictions [30]. (Audible noise measurements were possible at this location under the line, due to the very low background noise). The use of corona cages in conductor design is well described in the literature [1], [9], [35], [37]. The corona cage predictions are not corrected for altitude, as in the BPA case. It is clear that the BPA predictions are much too low and should not be used for dry level predictions. The uncorrected cage predictions are much closer, but too high by about 3 to 4 dB. The cage and field measurements were performed at different altitudes, 1500 m and 1100 m, respectively. Again, an altitude correction factor of 1 dB/100 m to 1 dB/130 m would apply, and not 1 dB/300 m.

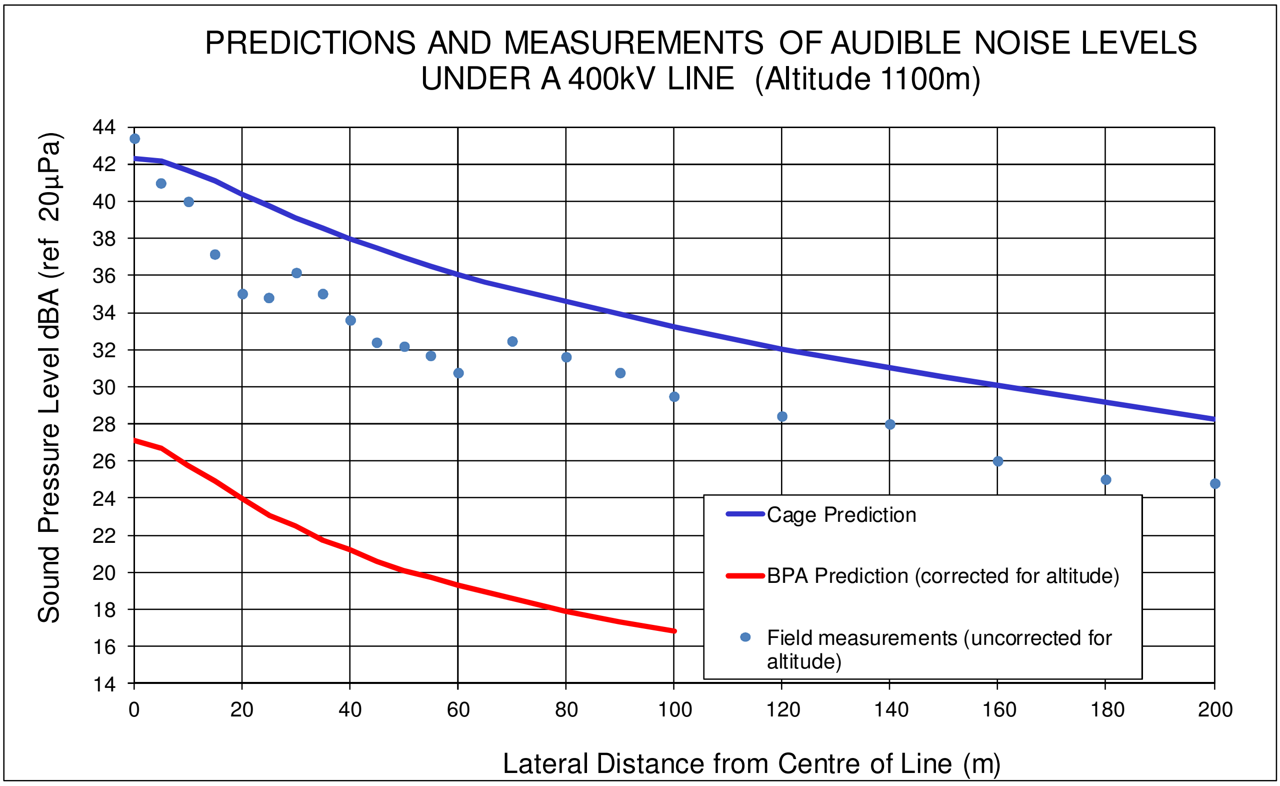


Figure 3.4
Audible noise measurements under a 400kV line at an altitude of 1100 m

3.3 Literature

Since our field measurements, under dry and light rain conditions, did not support the generally accepted altitude correction of 1 dB/300 m, the literature was studied to find the rationale behind the correction.

Measurements under transmission lines have indicated that empirical formulae for the prediction of audible noise under *dry* conditions are inaccurate [21], [34], [35],[32], [36], [37] . (This is further explored in Chapter 6). Most of the formulae are related to the so-called L5 (wet) or L50 (wet) condition [38]. The L50 (dry) levels are then obtained by mathematically deducting fixed values from the L5 (wet) or L50 (wet) level. However, the differences between the L5 (wet), L50 (wet) and the L50 (dry) levels are not constant with gradient [1], [4], [23], [23], [25], [26]. This fact can clearly be seen in results we have obtained at different gradients in a small corona cage (Figure 3.6). Similar curves and results were obtained in [1], [4], [23], [23], [25], [26]. Measurements in corona cages are further discussed in Chapter 4 and our measurements at different altitudes in Chapter 5 (wet and dry conditions).

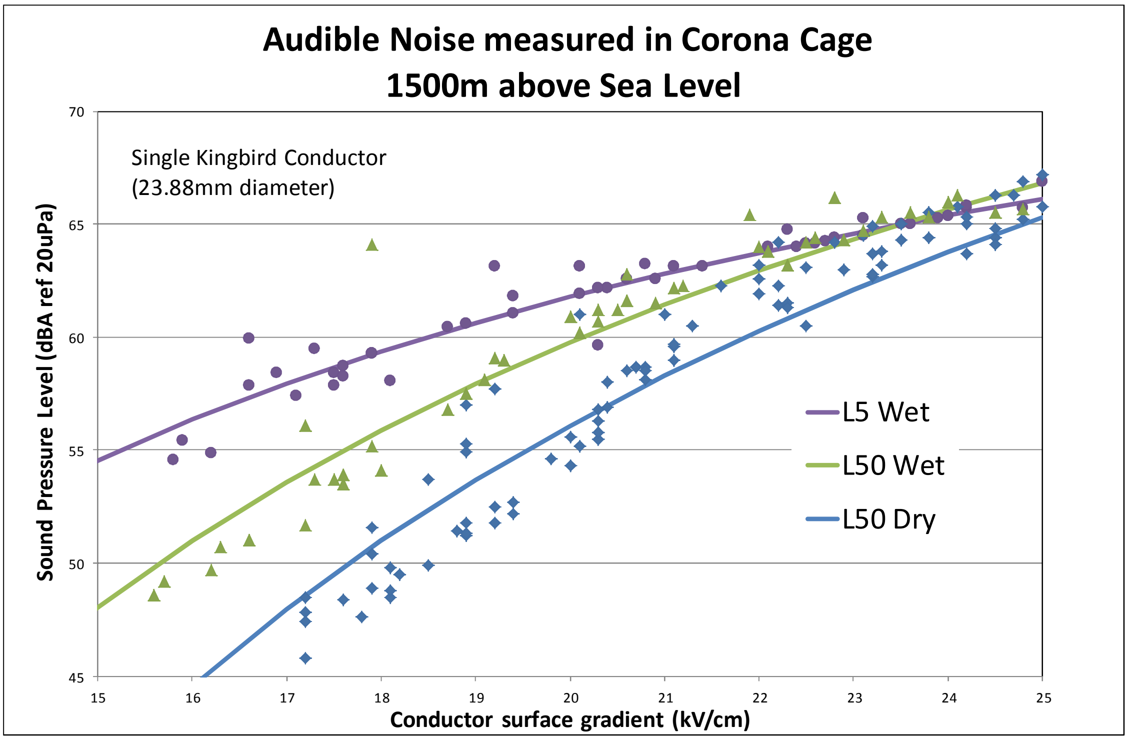


Figure 3.6
Corona cage measurements at 1500 m above sea level: audible noise from a single Kingbird conductor (23.88 mm diameter)

Audible noise from AC transmission lines under dry conditions is generally regarded as of no concern [3], [4], [21], and most documented audible noise results are for wet conditions only [4], [16], [9] [21], [33]. Sforzini [26] made the comment: ”As is known acoustic noise caused by AC corona on conductors is not a problem of real practical consequence in the case of HV and EHV transmission lines, but may become a decisive factor in the design of UHV lines”. Subsequently, in 1982, the IEEE Task Force of the Corona and Field Effects Subcommittee remarked: ”The audible noise produced by corona is one of the many constraints in the design of high voltage transmission lines”. In the same publication, the following statement is made: ”It is generally recognised that audible noise from AC transmission lines is a concern in foul weather only, principally in rain, consequently all AC methods predict some measure of noise during rain” [38]. However, in the latest EPRI red book for AC transmission it is stated that: ”In the case of compact lines operating at *high altitudes* in particular, noise levels in dry conditions can be significant. In such situations, the dry-noise limits may become an important design issue” [1]. In South Africa, we have learnt that corona under dry conditions can lead to serious complaints [34].

Paris and Sforzini [39] used a correction factor of 1 dB/300 m for radio interference, based on dielectric tests. Chartier [40] compared measurements from two double circuit 500 kV lines at altitudes of 1935 m and 277 m above sea level. Based on two different altitudes points and one, almost the same, voltage (gradient) point, he came to the conclusion that a correction of 1 dB/300 m is valid for audible noise in rain conditions. It is important to note that this was done for wet conditions and based on results obtained during three “good rain storms” at the low altitude test site. The correction has therefore been validated for “heavy rain” conditions.

In 1985/86 Eskom assisted ENEL (Ente Nazionale per l'Energia eLettrica) with the testing of two series of corona tests on two different conductor diameters in different configurations, varying from 6 conductor bundles to single conductors. The tests were performed at the two cages one at sea level and the other at 1500 m above sea level. To date, the only results we are aware of, that have been published, are Mr Cortina’s three hand drawn curves (audible noise, radio interference, and corona power loss) for a 6 conductor bundle under heavy rain, in the Chartier paper [40]. The result confirmed the correction of 1 dB/300 m for heavy rain conditions.

No correction factor with respect to audible noise under dry conditions could be found.

The probability of receiving complaints (Figure 3.1), compiled by Perry [41], is widely used as a guide for acceptable noise levels under transmission lines [1], [26], [32]. However, it is important to note that this probability is based on L50 wet and not dry conditions. The corona noise will be masked by the background noise of the rain.

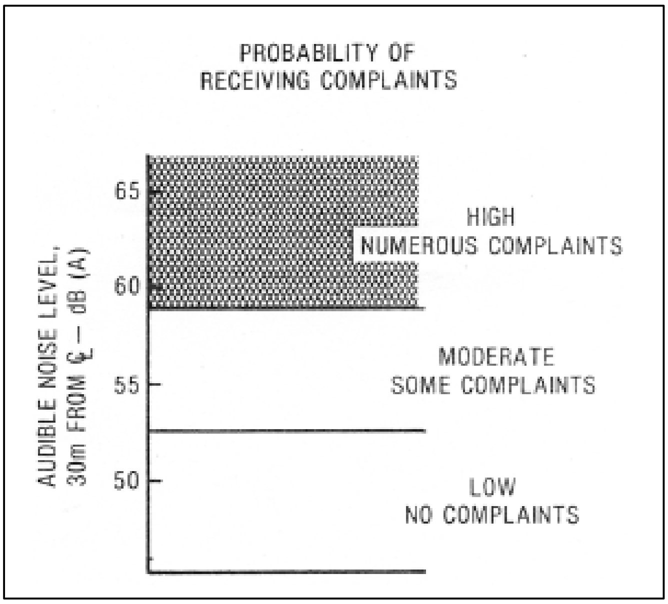


Figure 3.1
The probability of receiving complaints
with respect to audible noise under power lines [41]

The noise limit of 53 dBA cannot be applied to dry conditions. Under dry conditions, the noise nuisance is determined by the difference between the corona noise and the background. If the corona noise is more than the background noise, it will be audible and could lead to complaints, even at levels far below 53 dBA.

Published research with respect to corona and audible noise has been performed mainly at low altitudes, and mostly under wet conditions [4], [16], [9], [23], [25], [26], [41], [43]. In 1982 Chartier wrote in his course notes: ”As far as I know, there is no long-term audible noise data at high altitudes” [9]. In most cases (low altitude) the dry level noise was lower than the background noise [16], [23], [25], [26], [43], [45], [46] or barely measurable [41].

Measurements performed at Apple Grove [23], 180 m above sea level [49], [50] also showed no measurable audible noise with conductors energised to gradients of 18.5 kV/cm and

20.8 kV/cm. At a gradient of 24.1 kV/cm audible noise of 54 dBA was measured under dry conditions, 15 m from the outside phase of a test line. From practical experience, at high altitude, we know that gradients of 18.5 kV/cm and 20.8 kV/cm will cause audible noise, under dry conditions, unlike in the Apple Grove case, at low altitude, where audible noise was only measurable at a gradient of 24.1 kV/cm.

In 1992 Vosloo [46] investigated the effect of fire on conducted radio interference voltage (RIV). At that time we questioned the fact that he used impractical gradients, in excess of 24 kV/cm, for his experiments under dry conditions (we did similar measurements at an altitude of 1500 m above sea level). Now it is clear, he was doing the experiment at sea level, and the conductor only produced measurable RIV at high gradients. Altitude appears to have a bigger effect on corona under dry conditions than expected.

From the literature study we came to the conclusion that most published work on audible noise from AC lines was done at low altitudes. This explains the view of many researches that audible noise from conductor corona is only a concern under wet conditions. The research into conductor generated audible noise was limited to wet conditions because no noise could be measured from dry conductors at low altitudes.

To research the effect of altitude on the audible noise produced by conductors, under dry conditions, we have taken a new approach, by using a mobile corona cage. We are therefore not restricted to only two different altitudes. By using a mobile test facility we can use the same conductor, for all the tests in the same corona cage, making the altitude and the background noise at the tests sites the only variables.

The following chapter examines corona cages as design tools in transmission line designs.

Chapter 4

Corona Cages

4.1 Corona Cages as a Transmission Line Design Tool

The corona inception gradient is dependent on the conductor diameter, air pressure, temperature and the roughness of the conductor surface (Peek's formula, equation 2.1). The roughness factor could vary between 0.6 and 0.85 for stranded conductors. Due to the high cost of transmission lines (R1.5M – R2M / km for a 400 kV line in 2010), it is not good practice to design a conductor bundle only using Peek's formula.

Corona cages and test lines have been utilised to study the corona performances of conductors and conductor bundles [1], [4], [7], [8], [9], [17], [18], [19], [23], [26], [42], [47]. Cages are used to measure the corona performance of a conductor in terms of EMI, corona loss and audible noise. It is therefore not necessary to guess a roughness factor. The advantage of using a cylindrical cage is that the surface gradient (E_c) is easily calculated:

$$E_{C}= \frac{V_t}{R_C \ln\left(\frac{R_g}{R_C}\right)} \tag{4.1}$$

where

E_c = conductor surface gradient (kV/cm)
V_t = test voltage (kV)
R_c = conductor radius (cm)
R_g = cage radius (cm)

The performance of the proposed conductor is then evaluated, using the cage (or test line) data, at the gradient that will be experienced on the 3 phase line [1], [35], [44], [48].

4.2 Large Eskom Corona Cage

In the early 1980's Eskom designed their first 765 kV transmission lines for altitudes in excess of 1500m above sea level. Because very little data on corona effects at high altitude were available at that time, a corona test facility was built at 1500 m above sea level. The cage was designed to measure audible noise, conducted radio interference or radio influence voltage (RIV) at 500 kHz as well as power loss.

The Eskom corona cage was designed and built by ENEL, and is an exact replica of their cage at sea level [19], [20] (the ENEL cage has been dismantled in the meantime). The corona cage is 40 m long and 7 m in diameter (Figure 4.2 and Figure 4.3). The power supply consists of two 400 kV AC transformers in a cascade arrangement. Measurements are performed under heavy rain, wet and dry conditions on conductor bundles (up to 6 sub-conductors) [19].

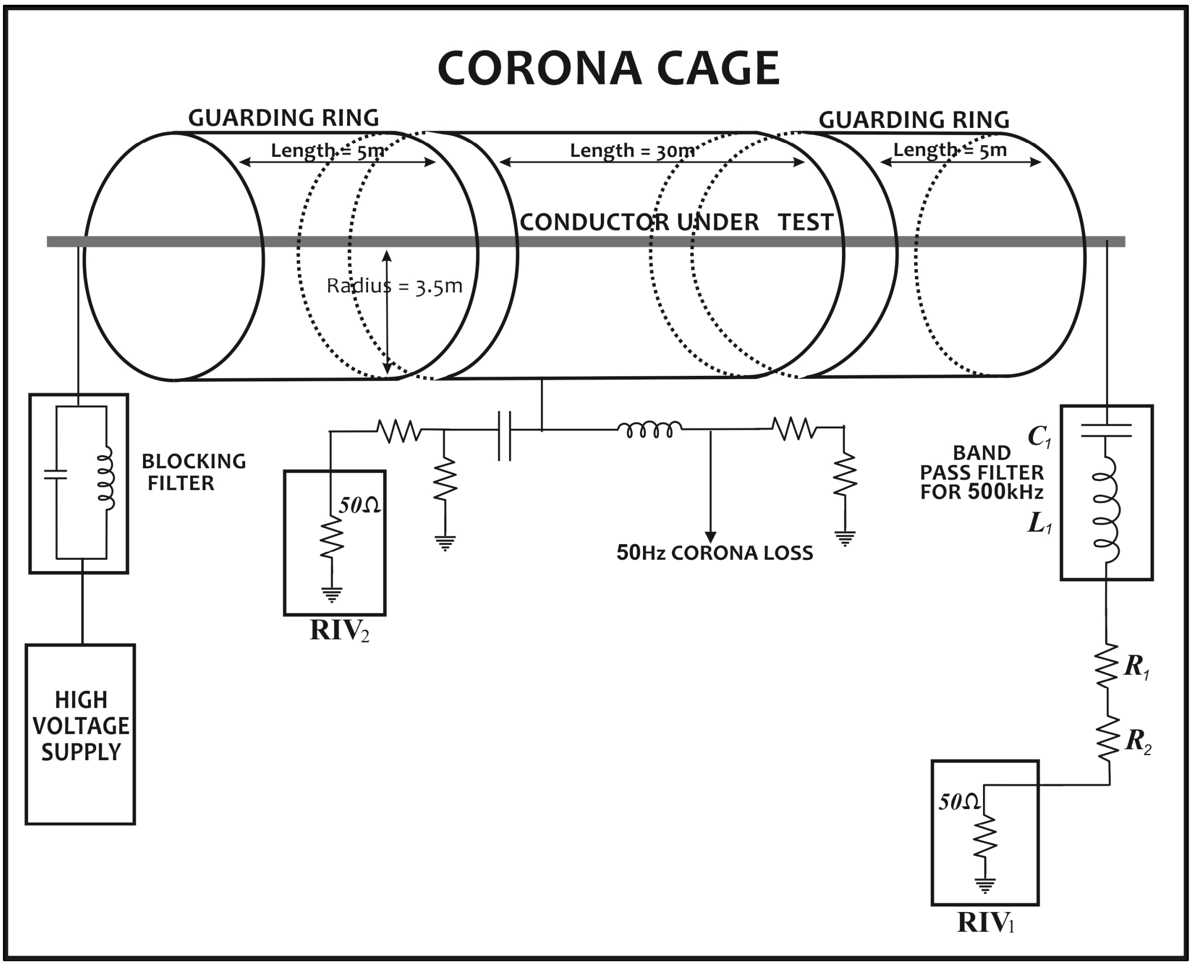


Figure 4.1
Schematic for Eskom Corona Cage

RIV measurements can be made using the capacitance of the corona cage or a coupling capacitor (Figure 4.1). The corona cage is made-up of three cages. The outer cages are earthed to avoid end effects on the centre cage when RIV measurements are made, using the corona cage as a capacitor. The measurement is then taken only over the length of the centre cage (30 m). When RIV is measured with a coupling capacitor or when audible noise is measured, the measurement is taken over the full 40 m length of the cage. The audible noise is measured with a precision sound level meter. The microphone is situated 4.25 m from the centre of the cage, pointing towards the conductor under test (Figure 4.3).

The initial purpose of the corona test facility was to engineer a suitable conductor bundle for high altitude 765 kV applications [19], [42]. This was successfully done and the design was even optimised later [44]. The facility was also used extensively in the optimisation of 400 kV lines. New conductor bundles and the aging effects are currently being researched using this facility. Audible noise measurements in the corona cage have successfully been correlated with field results [23], [34],[35].

Figure 4.2
Eskom's Corona Cage at 1500 m above sea level. The three different cages can be seen. The outer cages (smaller) are earthed to avoid end-effects. The large centre cage is earthed though the measuring equipment to enable RIV and corona current measurements.

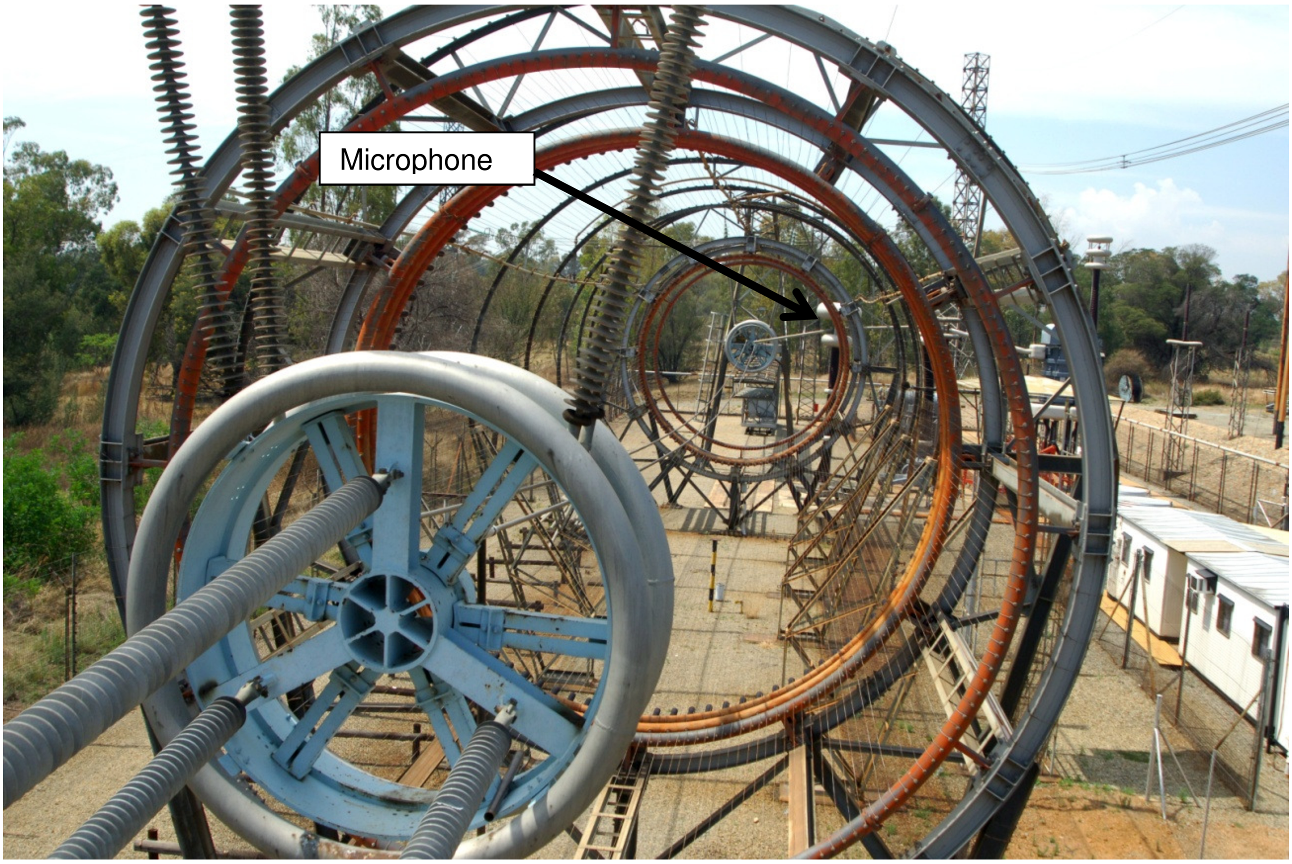


Figure 4.3
Eskom's Corona Cage at an altitude of 1500 m above sea level. The large corona rings (blue and silver) at the ends of the conductor bundle prevent unwanted corona on the dead-ends and shackles at the attachment points

4.3 Mobile Corona Cage

A mobile corona cage was constructed to further research the effect of altitude on the corona performance of conductors. The corona cage has a diameter of 1.5 m, and is 3.6 m long. The dimensions of the cage were chosen with practical limitations in mind. It had to be as big as possible but still fit on a trailer, and the diameter had to such that conductor gradients in excess of 20 kV/cm could be obtained on conductor diameters of 28 mm at a maximum voltage of 120 kV without flashing over.

With a diameter of 1.5 m, it is possible to do measurements up to 130 kV, and achieve a maximum conductor gradient of 24 kV/cm with a Zebra conductor (28.56 mm). The total length of the trailer is 6 m. The conductor is energised with a high voltage transformer. The audible noise is measured with Rion NL32 and Rion NA28 precision sound level meters.

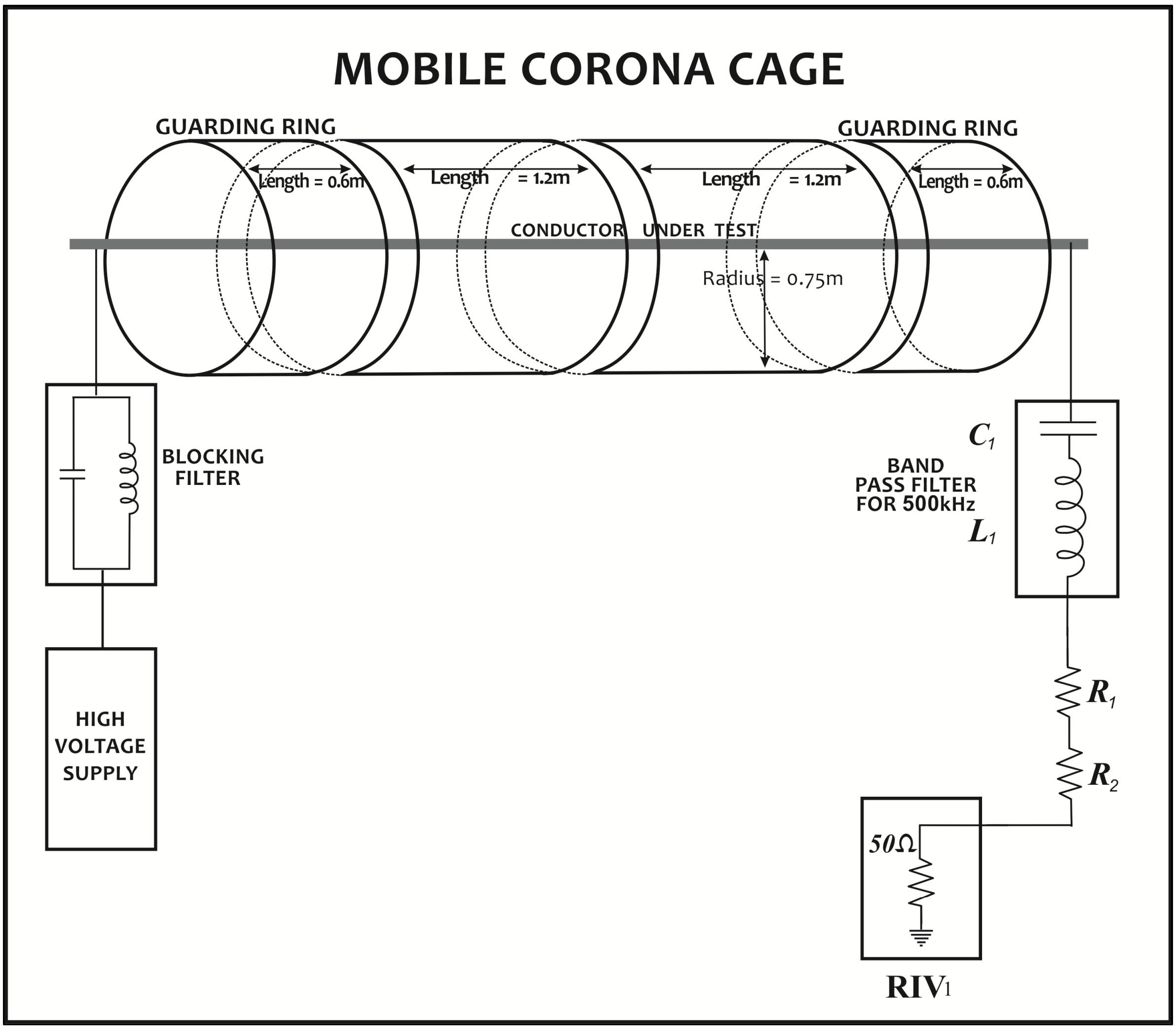


Figure 4.4
Schematic of mobile corona cage

The corona cage was, as in the case of the large Eskom cage, built with the option of insulating the centre cage to do RIV and corona loss measurements. For the purpose of this investigation all the cages were earthed (Figure 4.4).

The microphone was earthed and placed between the two centre cages, pointing towards the conductor under test, 0.75 m from centre of conductor (Figure 4.5).

The mobile corona cage and the power source are mounted on two specially built trailers (Figure 4.6).

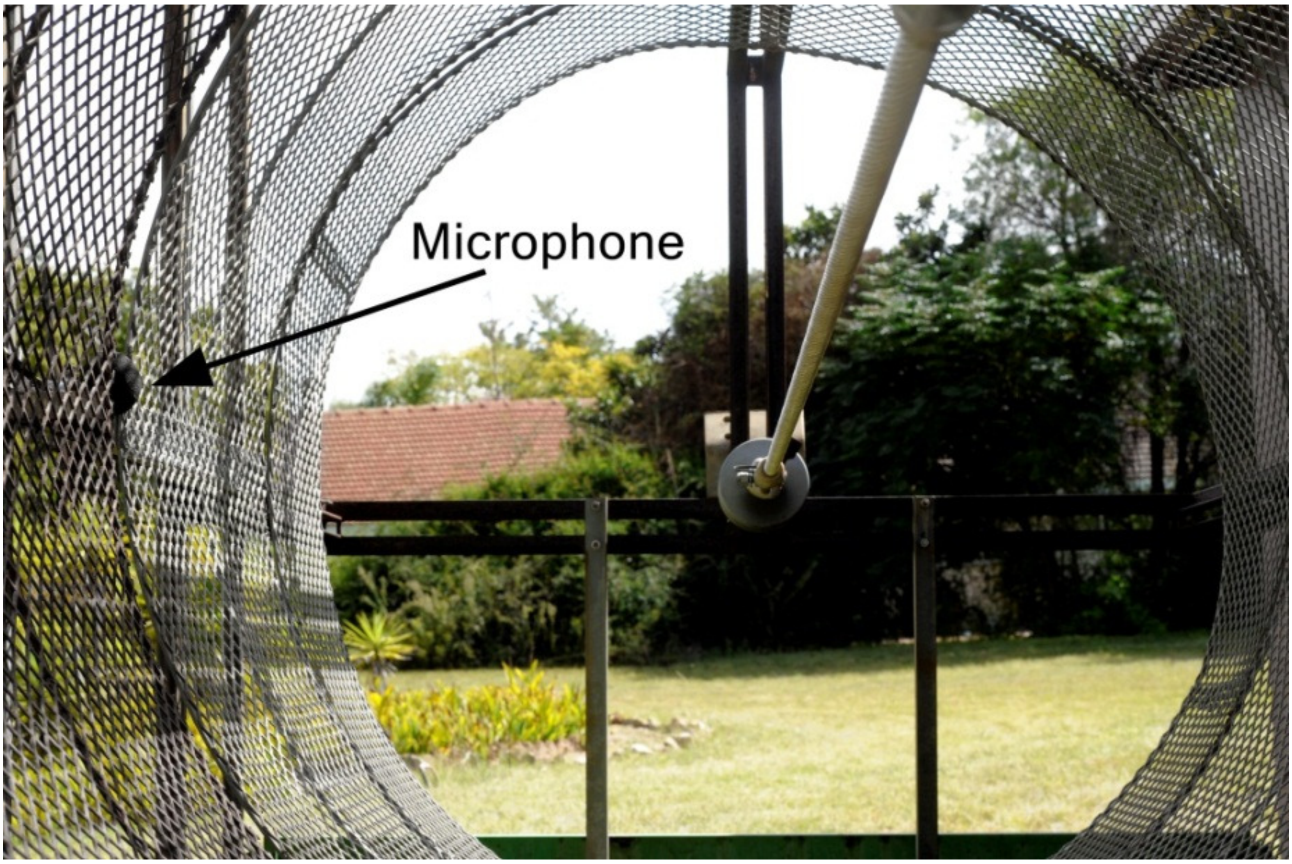


Figure 4.5
Microphone is earthed and placed between the two centre cages, pointing towards the conductor under test (0.75 m from centre of conductor).

Figure 4.6
Mobile corona cage and AC/DC source

With this mobile high voltage laboratory it was possible to investigate the uncertainty regarding the altitude correction factor for dry conditions described in Chapter 3. Conductor generated audible noise was measured at different altitudes, using exactly the same test object (two similar conductors will not necessarily produce exactly the same results).

Three different conductors were tested (one at a time) at different altitudes, ranging from sea level to 1900 m above sea level. The results are discussed in Chapter 5.

Chapter 5

Audible Noise Measurements at Different Altitudes

5.1 Introduction

The mobile corona cage was utilised to measure the corona generated audible noise at different altitudes. Three different conductors were energised at different altitudes in the mobile corona cage. To prevent any damage to the conductors during installation or storing, all tests were completed at all the different altitudes, before the conductors were changed. The Tern and Zebra conductors were first aged in the large Eskom corona cage as part of a project investigating conductor aging. The Kingbird was aged in the small corona cage. The Tern conductor was the first to be tested, and should be viewed as the teething portion of the project. We have learnt where the best measuring sites are on the route from Johannesburg to the Cape. We also did not clean the conductor between tests, in order not to change the roughness. However, we have learnt that insects, dust and dust could have stuck to the conductor and could have affected the measurements. With the Zebra and the Kingbird conductor we have wiped the conductor with a clean leather glove at each measuring site, before the start of the measurements. Our measurements on repeatability (5.6) proved that we haven’t changed the roughness of the conductor in the process. The noise measuring equipment was calibrated at 94 and 114 dB before and after each series of tests. The microphone was earthed and placed in exactly the same position on the cage at every measuring site.

Measurements were performed at different locations between 1900 m above sea level and sea level.

• Clarens	1900m
• Midrand	1500m
• De Aar	1200m
• Beaufort West (Karoo)	900m
• Prince Albert	600m
• Rawsonville	300m
• Paarl	160m

Three sets of noise measurements were taken for each gradient, at each measuring site. Measurements were taken at 5 kV intervals, starting at 130 kV and moving down until background noise was achieved (we were more concerned about corona extinction than inception).

The results under dry conditions are presented below.

5.2 Tern Conductor at Different Altitudes under dry conditions

The first series of tests was performed on a Tern (27 mm diameter) conductor. The conductor was not wiped before each measurement, which means that the conductor surface could have changed between measurements. However, from Figure 5.1, it is clear that altitude plays a big role in the corona performance of a conductor, especially at the lower gradients.

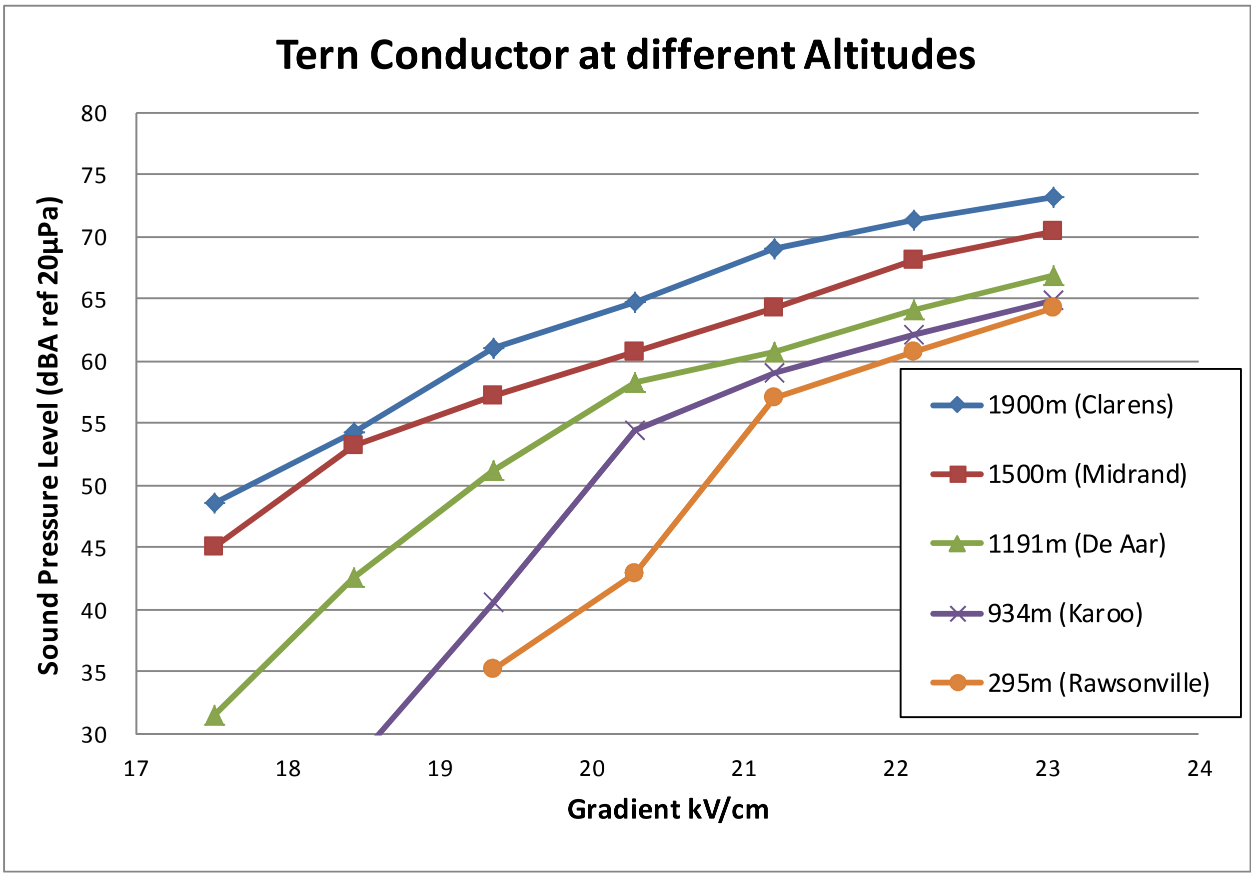
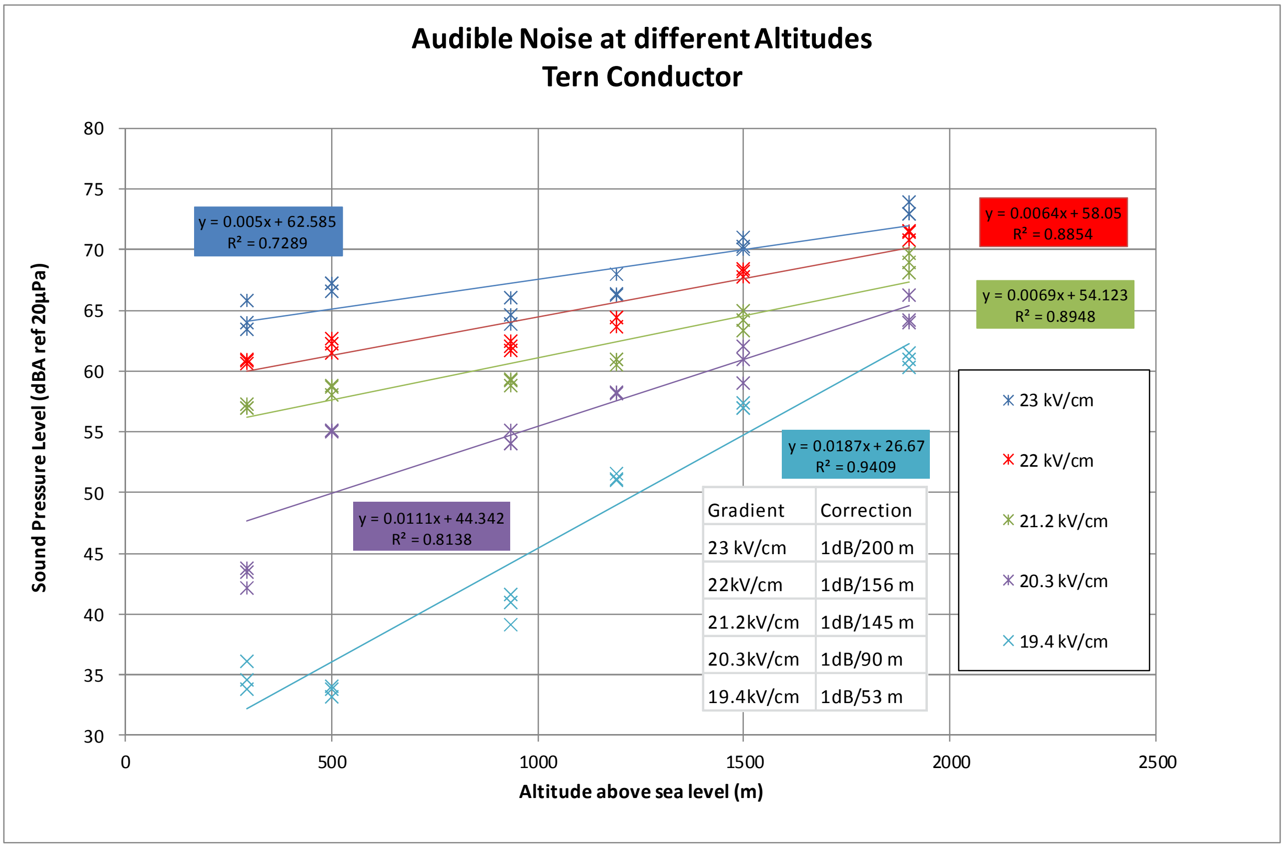


Figure 5.1
Audible noise measured in a small cage
at different altitudes using a Tern conductor

At an altitude of 300 m above sea level, no noise was measurable with a conductor gradient of 17.5 kV/cm, but at altitudes of 1500 m and 1900 m above sea level the noise was 45 dBA and 43 dBA respectively. This again shows that audible noise under dry conditions, at low altitudes, is of no concern. But at the same time, it does not necessarily mean that no noise will be generated at high altitudes if no noise is measured at sea level.

At an altitude of 1900 m and a gradient of 17.5 kV/cm the Tern conductor produced a sound pressure of 48 dBA, but at 1200 m at the same gradient only 31 dBA. At the same gradient, at lower altitudes, the Tern did not produce any measurable noise at all. This supports the finding from the literature study that audible noise is of no concern at low altitudes.

The slopes of the noise at different altitudes at the same gradient, ie. the altitude correction, varies between 1 dB/200m for 23 kV/cm and 1 dB/90m for 20.3 kV/cm (Figure 5.2).

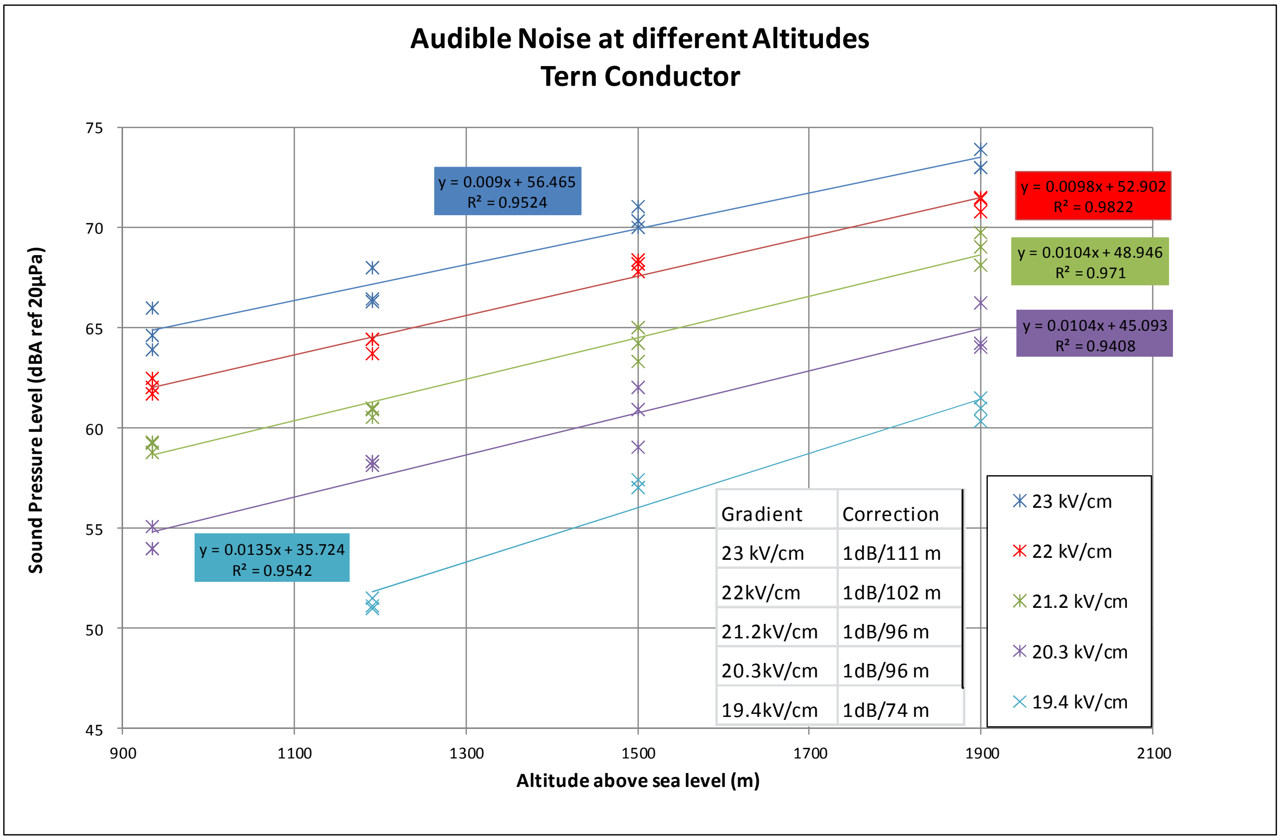


Gradient	Correction
23 kV/cm	1dB/200 m
22kV/cm	1dB/156 m
21.2kV/cm	1dB/145 m
20.3kV/cm	1dB/90 m
19.4kV/cm	1dB/53 m

Figure 5.2
Slopes of audible noise curves at different altitudes
(300m – 1900m) with a Tern conductor.

Since we did not wipe the Tern conductor, it is possible that insects and dirt on the conductor could have affected the noise performance of the conductor, especially at the lower gradients and altitudes. Further, the background noise should ideally be at least 10 dB below the conductor [31]. For these reasons, only the measurements above 900 m are analysed in Figure 5.3.

The altitude corrections of the four high gradients are all close to 1 dB/100m (Figure 5.3). The correction for a 19.4 kV/cm is 1 dB/74 m. At 1191 m above sea level (De Aar), the audible noise at this gradient is below the knee-point (at about 20.3 kV/cm) and audio extinction is about to be achieved (Figure 5.1). If the data below the knee-point is omitted, the correction at 19.3 kV is also 1 dB/100m. It is therefore clear that a prediction cannot be made from a lower altitude to a higher altitude if the noise measured at the lower altitude is below the knee point. The audible noise altitude correction factor, for dry conditions, and Tern conductor was measured to be 1 dB/100 m.



Gradient	Correction
23 kV/cm	1dB/111 m
22kV/cm	1dB/102 m
21.2kV/cm	1dB/96 m
20.3kV/cm	1dB/96 m
19.4kV/cm	1dB/74 m

Figure 5.3
Slopes of audible noise curves at different altitudes
(900 – 1900m) with a Tern conductor.

5.3 Zebra Conductor at Different Altitudes under dry conditions

With the Zebra conductor (28.56 mm diameter), we wiped the conductor with a clean leather clove before each series of tests. The Zebra results (Figure 5.4) are similar to those of the Tern. The differences between the different altitudes, at the lower more practical gradient, are very high and not measureable due to background noise constraints and complete audio extinction.

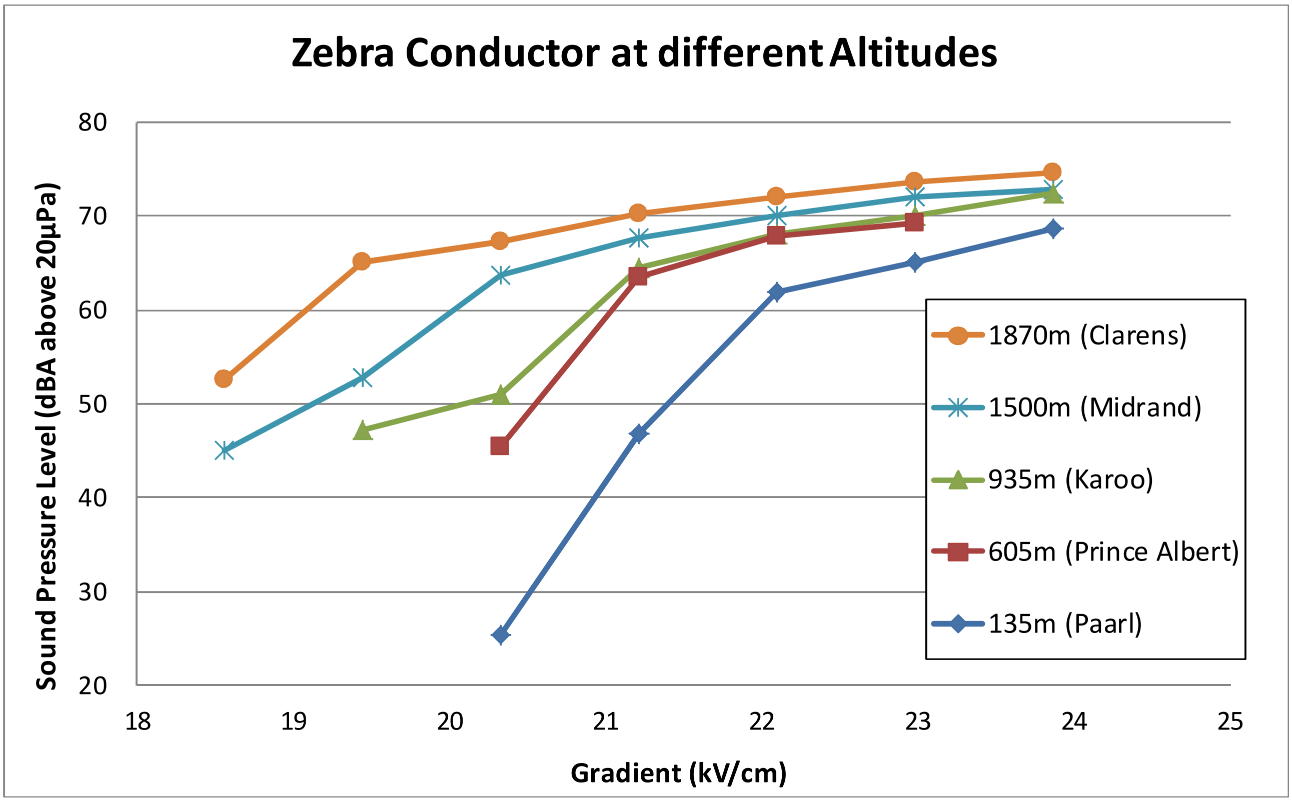
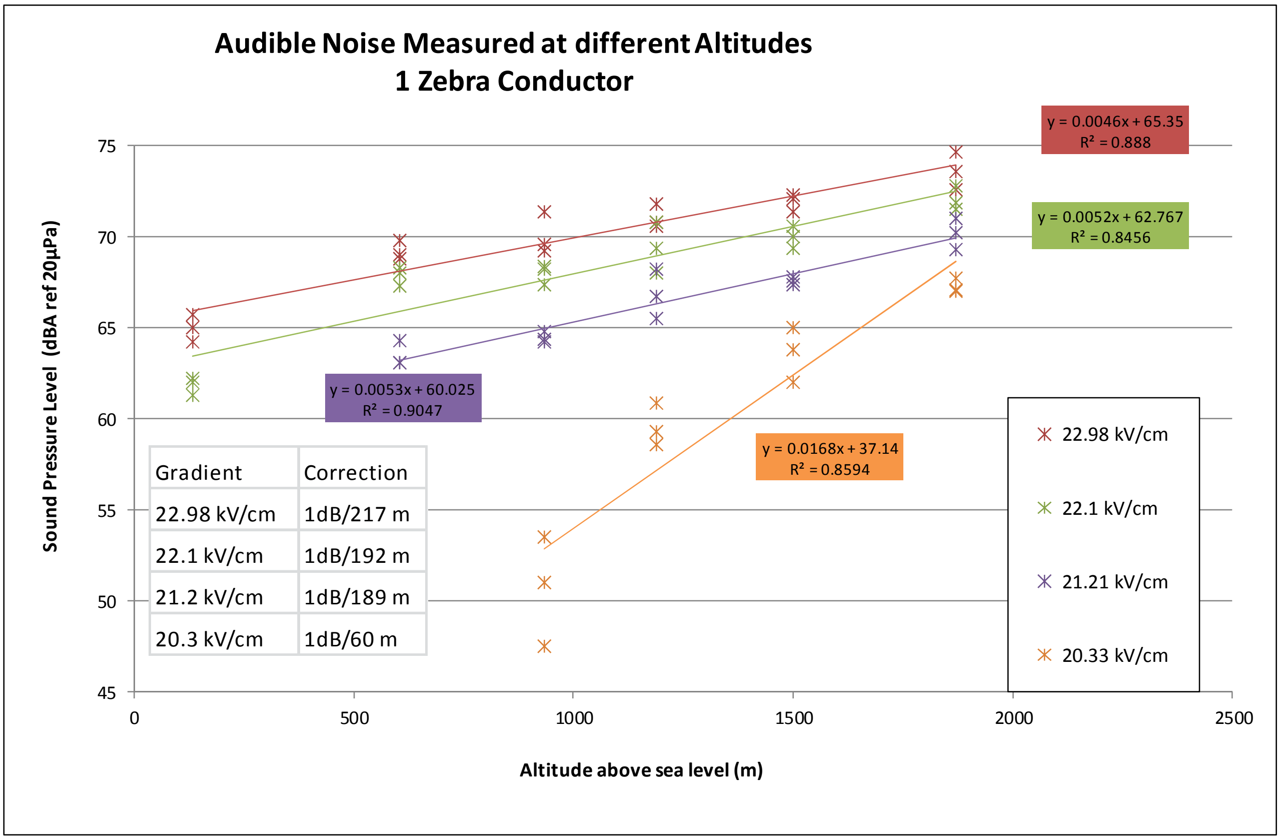


Figure 5.4
Audible noise measured in a small cage
at different altitudes using a Zebra conductor

The altitude correction for the Zebra conductor at the higher gradients is about 1 dB/ 200 m. At a gradient of 20 kV/cm, the correction dropped to 1 dB/60 m (Figure 5.5).



Gradient	Correction
22.98 kV/cm	1dB/217 m
22.1 kV/cm	1dB/192 m
21.2 kV/cm	1dB/189 m
20.3 kV/cm	1dB/60 m

Figure 5.5
Altitude corrections: Slopes of audible noise curves
at different altitudes (300m – 1900m) with a Zebra conductor.

At an altitude of 935 m above sea level, the audible noise was on the verge of extinction at a gradient of 20.33 kV/cm. The altitude correction for 20.33 kV/cm at altitudes above audio extinction is depicted in Figure 5.6. The correction factor in this case is 1dB/90 m.

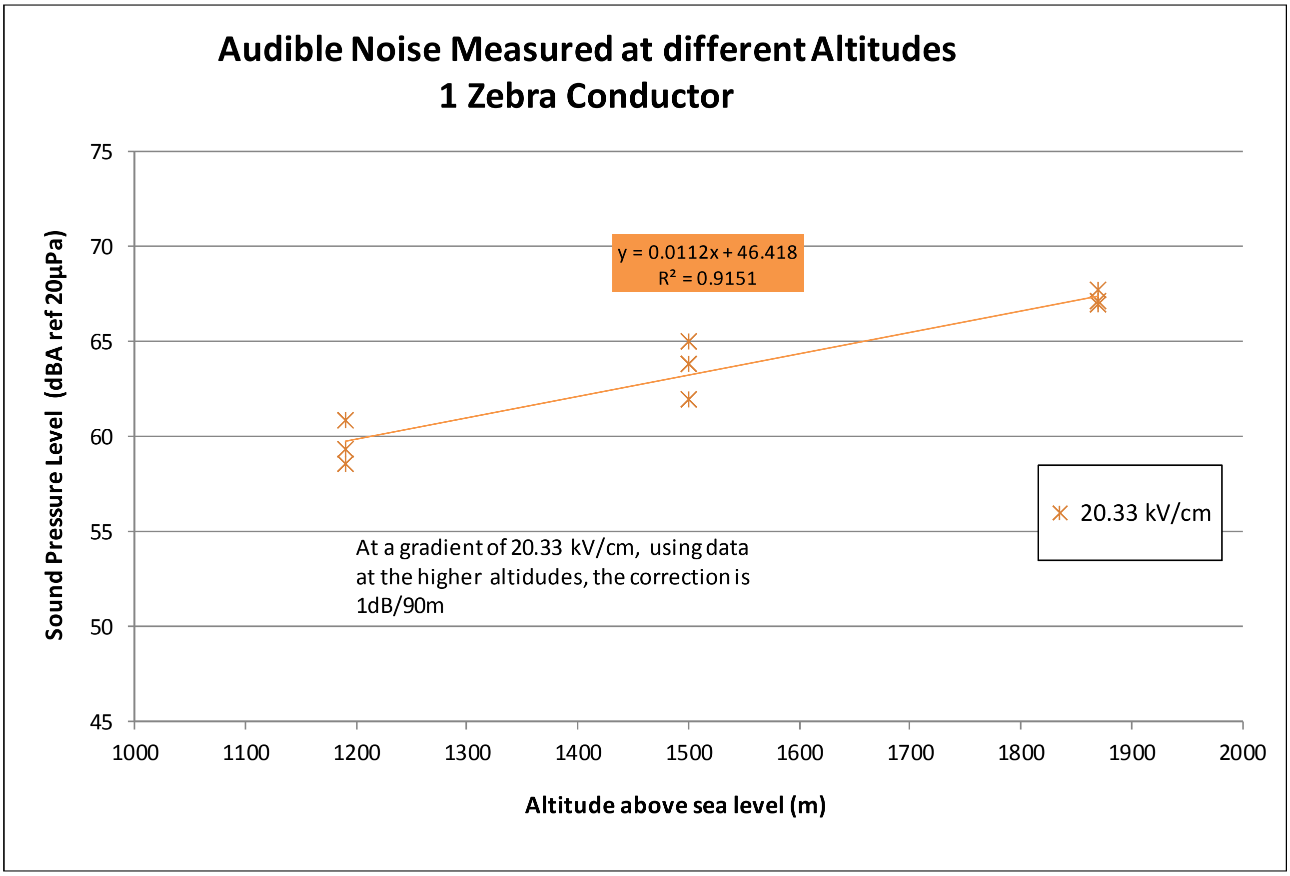


Figure 5.6

Altitude correction for 20.3 kV/cm for a Zebra conductor at altitudes above 1000 m

5.4 Kingbird Conductor at Different Altitudes under dry conditions

The Kingbird conductor diameter is 23.88 mm, much smaller than the Tern and Zebra, and higher gradients could be achieved with a voltage of 130 kV (26.5 kV/cm). Again, as with the previous conductors, altitude plays a much bigger role at the lower gradients (Figure 5.7). In South Africa, AC transmission lines seldom operate at gradients above 19 kV/cm. This means that predictions made for high altitude, using low altitude data, will be far out. Even at 21 kV/cm the difference between the noise levels at Midrand and Beaufort West is in excess of 30 dB/570 m, almost 15 dB/300 m.

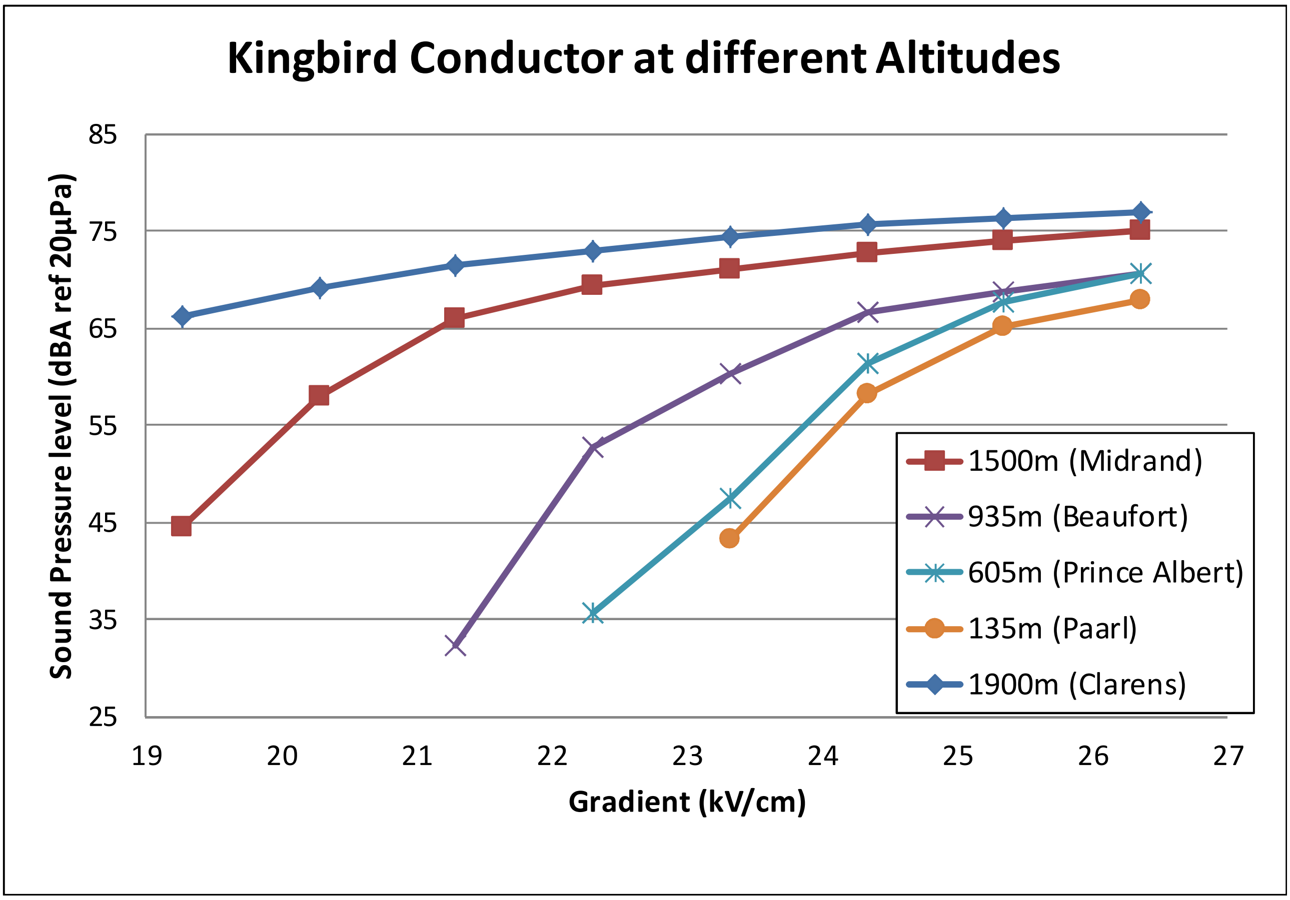
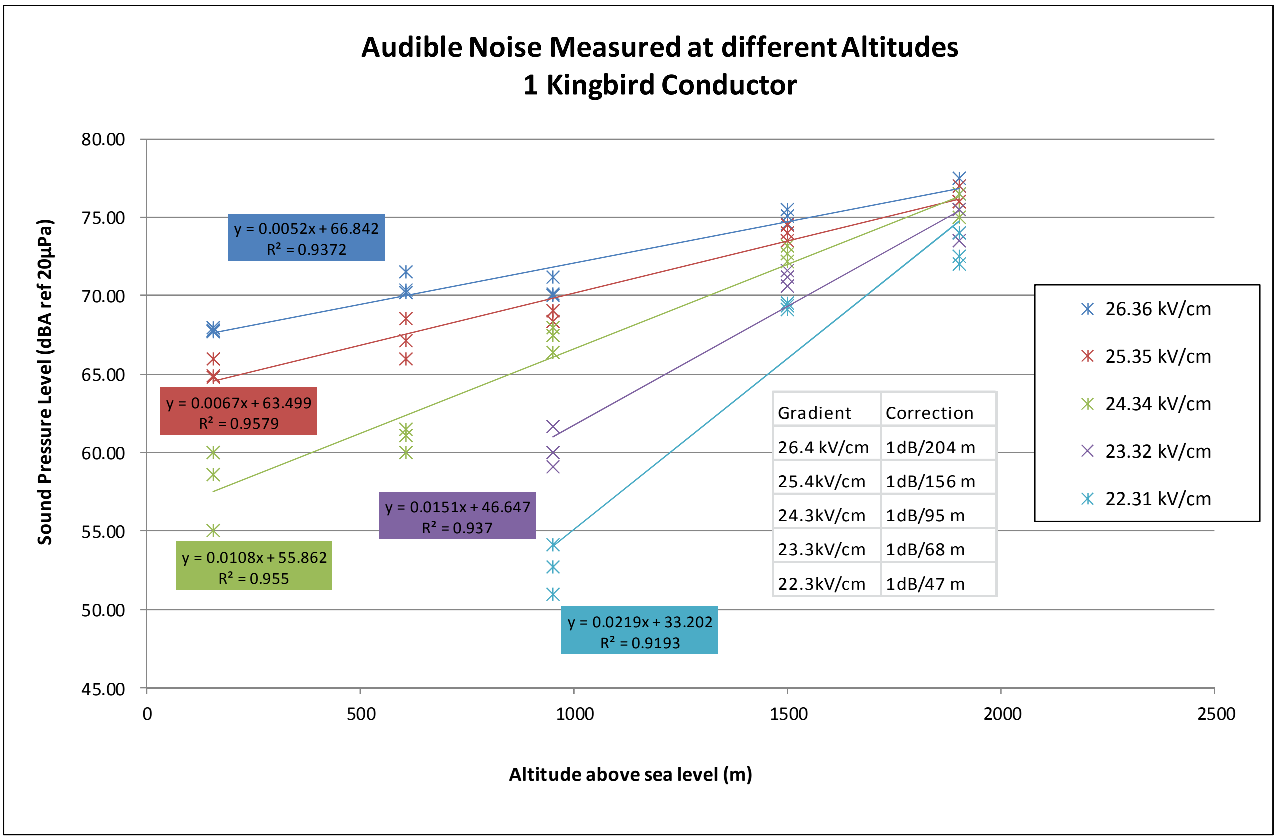


Figure 5.7
Audible noise measured in a small cage
at different altitudes using a Kingbird conductor

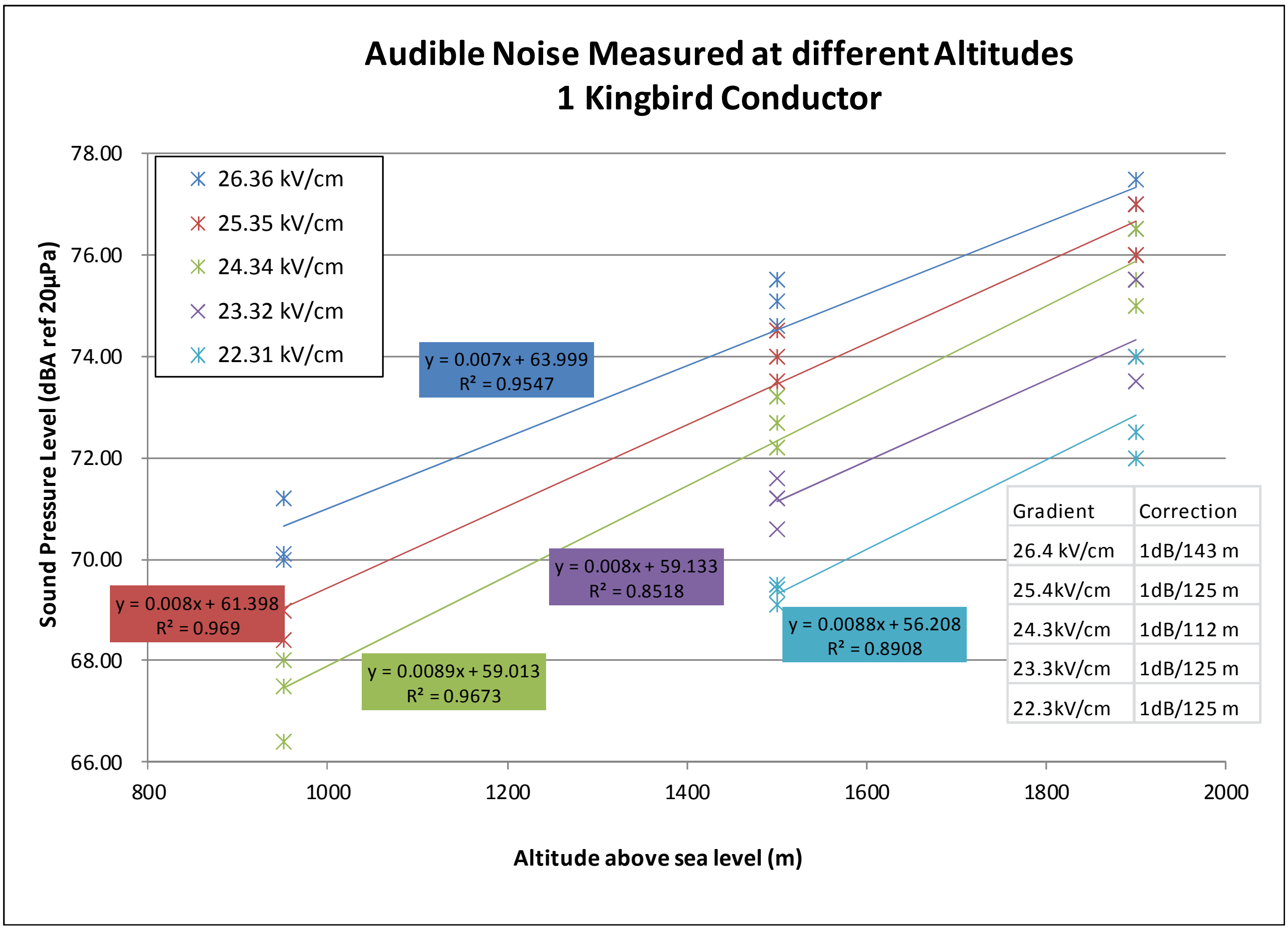
At 26.36 kV/cm and 25 kV/cm the altitude correction was measured to be 1 dB/200 m and 1 dB/150 m respectively (Figure 5.8). At lower gradients the correction was found to be much steeper (1 dB/90 m and higher).



Gradient	Correction
26.4 kV/cm	1dB/204 m
25.4kV/cm	1dB/156 m
24.3kV/cm	1dB/95 m
23.3kV/cm	1dB/68 m
22.3kV/cm	1dB/47 m

Figure 5.8
Slopes of audible noise curves at different altitudes
(300m – 1900m) with a Kingbird conductor.

Only the results above the knee-points are analysed in Figure 5.9. The correction factors vary between 1 dB/143 m and 1 dB/112 m. This agrees with the measurements performed on the Zebra and Tern conductors.



Gradient	Correction
26.4 kV/cm	1dB/143 m
25.4kV/cm	1dB/125 m
24.3kV/cm	1dB/112 m
23.3kV/cm	1dB/125 m
22.3kV/cm	1dB/125 m

Figure 5.9

Slopes of audible noise curves at different altitudes
(300m – 1900m) with a Kingbird conductor using data above knee-point.

The results for all three conductors that were tested suggest that the correction for dry conditions is much steeper than 1 dB/300 m. The effect of altitude appears to be more than expected, especially at practical gradients. When corona extinction is reached (data below knee point), the noise drops sharply, and makes the altitude correction gradient dependent. The correction factor, at high gradients, varied between 1 dB/100 m and 1 dB/200 m. At practical gradients (South African) the correction factor for dry conditions appears to be about 1 dB/100 m and not 1 dB/300 m. This was a concern, since nothing in this respect has been reported in the literature. It was therefore felt necessary to repeat some of the measurements under rain conditions.

5.4 Kingbird Conductor at Different Altitudes under heavy rain conditions

The substantial difference between the measured altitude correction (1 dB/100 m to 1 dB/50 m) and the 1 dB/300 m reported in the literature was a concern. The altitude corrections reported in the literature for audible noise are all based on wet measurements. The mobile cage was thus equipped with a water sprayer system, which produced a rain rate of 2 mm/min on the conductor (Figure 5.10 and Figure 5.11).

Figure 5.10
Mobile Corona Cage equipped with water tanks, pump and sprayers
(Clarens 1900 m above sea level)

Figure 5.11
Mobile Corona Cage during a wet test (2 mm/min)

5.5 Altitude Correction for Heavy Rain Conditions

The water sprayers are fairly noisy (60 dBA) and made measurements at the lower gradients impossible. For this reason the noise measurements were not taken manually as in the case of the dry measurements. Instead, the “store” function of the NA 28 sound level meter was used immediately after the water pump was switched off. The results were stored in the instrument’s memory and retrieved after each test series. The measurements are therefore considered as being taken during heavy artificial rain, without the pump noise. This made it possible to measure conductor corona above the prevailing background noise and not only above 60 dBA.

The measurements were performed at three different altitudes (1900 m, 1500 m and 900 m) with a Kingbird conductor. The results are depicted in Figure 5.12 and Figure 5.13 below.

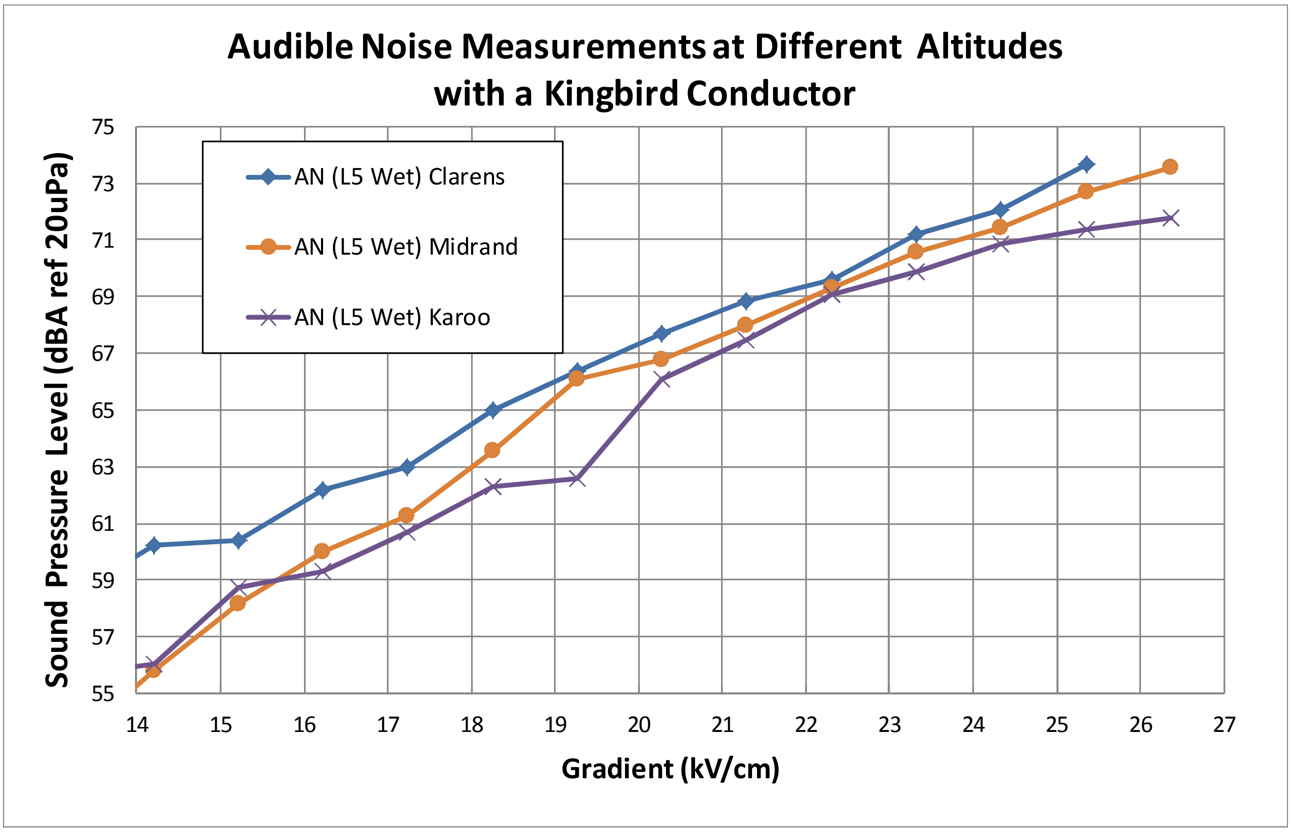


Figure 5.12
Audible noise measurements at different altitudes, under heavy rain conditions with a Kingbird conductor

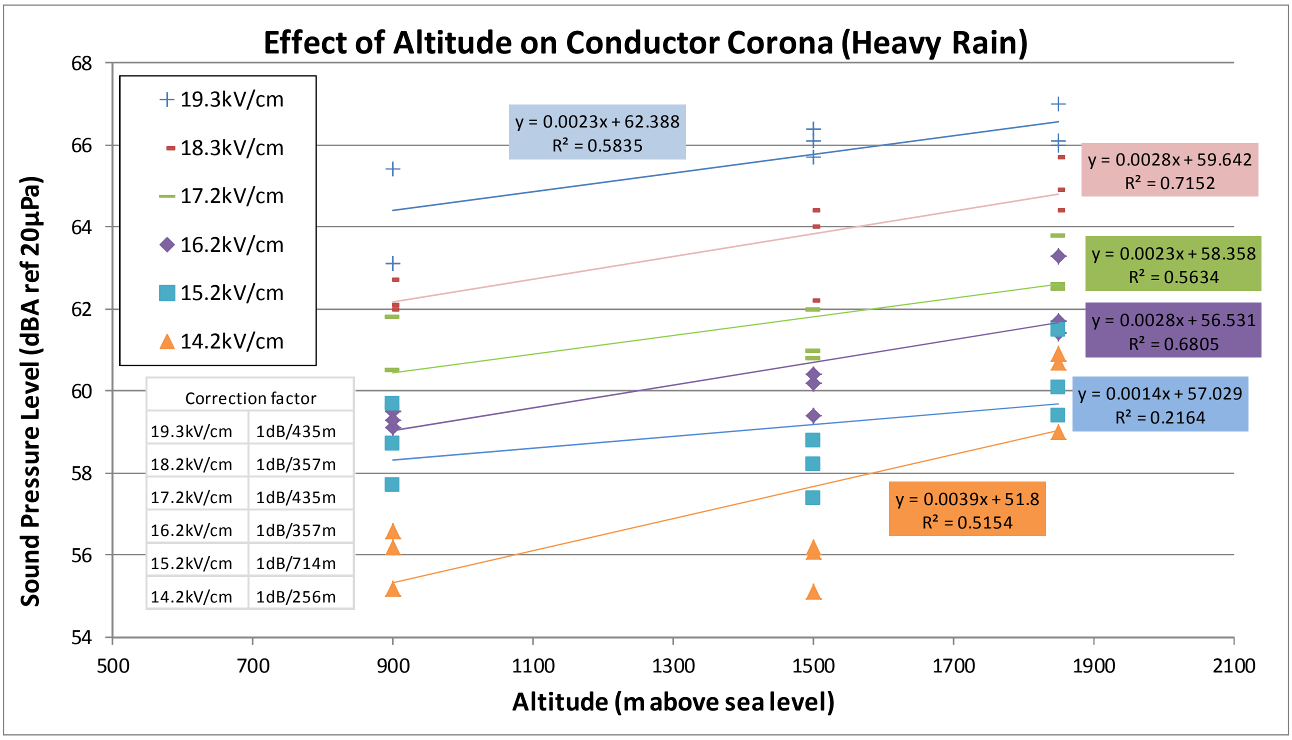


Figure 5.13

Effect of altitude on the audible noise of a Kingbird conductor under heavy rain conditions

Unlike under dry conditions, the wet-weather measurements, for the different altitudes, did not diverge at the lower gradients (Figure 5.12). Correction factors between 1 dB/430 m and 1 dB/250 m were measured in the 14 – 19 kV/cm gradient range. This agrees much better with the result of 1 dB/300 m Chartier obtained [40] and validates our method of measurements under dry conditions. The gradients on the lines Chartier used for his research was between 14 and 16 kV/cm [40]. Our results at 15.2 kV/cm are far out, but our 16.2 kV/cm and 14.2 kV/cm results are not far from the 1 dB/300 m he has measured. The results for heavy rain (Figure 5.13) are scattered which indicate that the correction factor is not necessarily linear with altitude. The results under dry conditions appear far more linear.

5.6 Repeatability of Measurements in Mobile Cage

The dry test, at an altitude of 1500 m above sea level, was repeated 2 years after the original Kingbird test (5.4 Kingbird Conductor at Different Altitudes), to verify the repeatability of our measurements in the small cage. The very same Kingbird conductor was still in the cage. As with previous measurements, the conductor was wiped with a clean leather clove before the test. The results in Figure 5.14 show that the measurements are repeatable. Only a slight improvement was measured at the very high gradients. The background noise at the time of measurements in 2011 allowed measurements below 45 dBA.

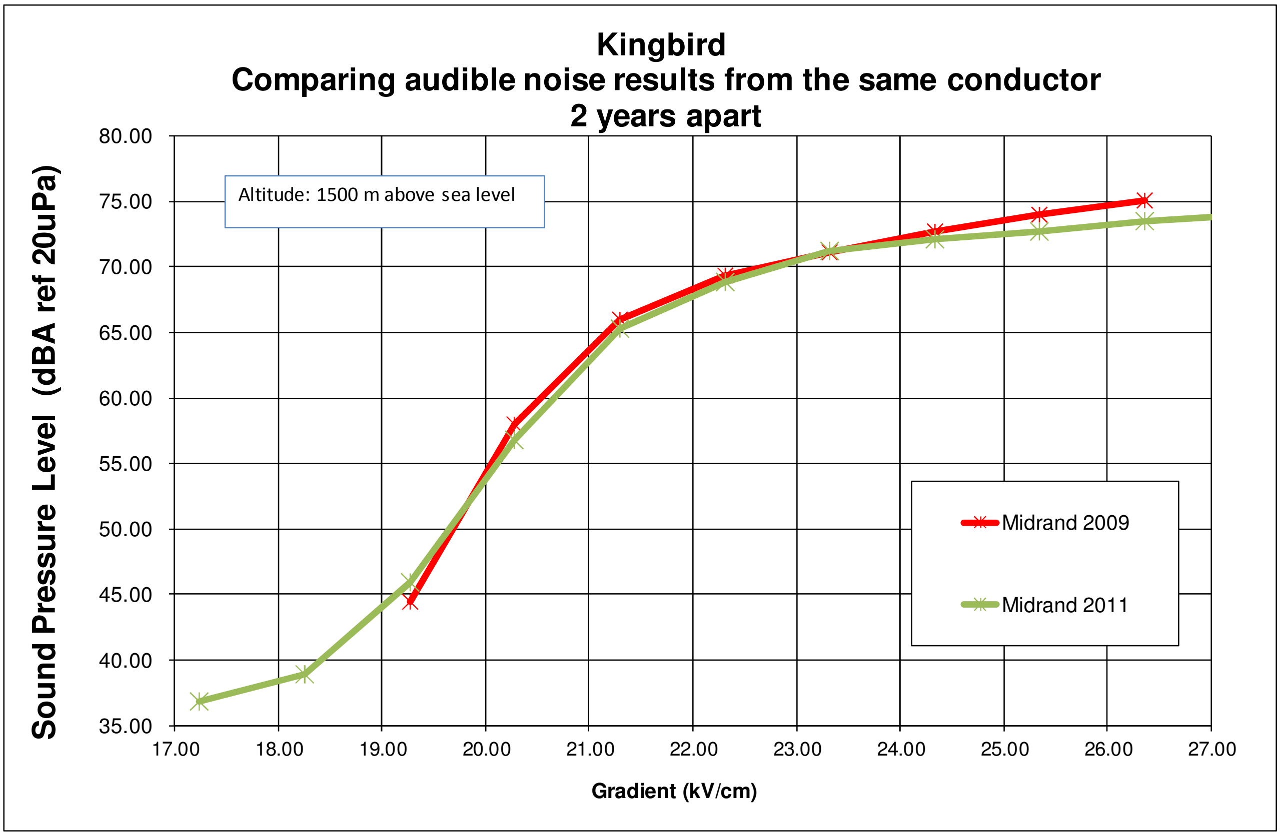


Figure 5.14
Repeatable audible noise from a Kingbird conductor in mobile cage:
measurements taken 2 years apart

5.7 Conclusions

The audible noise correction factor for dry conditions was found to be 1 dB/100 m, much steeper than the generally accepted correction of 1 dB/300 m. For heavy rain, the correction of 1 dB/300 m appears to be valid. Audible noise measurements in the small cage were shown to be repeatable. The next step is to compare the small mobile cage’s results to measurements from the large Eskom corona cage.

Chapter 6

Comparing Mobile Cage results with Large Cage and Empirical Predictions

6.1 Audible noise comparison between Large and Small Cages

The three conductors we have tested were also previously tested in the large Eskom corona cage. It was therefore possible to compare the results from the small cage in Midrand to those from the large cage, since both sites are at 1500 m above sea level.

The two corona cages are different in length and diameter. A correction factor has to be introduced to compare the sound pressure levels measured from the two cages. The lengths of the cages and the distances between the microphones have to be taken into account. The microphone of the small cage was placed 0.75 m from the centre of the cage. The large cage has an outer and inner cage and the microphone was placed just inside the outer cage, 4.25 m from the centre.

From [1], [2], [3], [4], [9], [21], [33],

$$P_1 = \sqrt{\frac{\delta c A}{2\pi R} \tan^{-1}\frac{l}{2R}} \tag{6.1}$$

where

$P1$ = *A-weighted sound pressure level (SPL) with reference to 20µPa at a distance R*

A = *A-weighted sound power (SWP) with reference to 1µW/m*

R = *Direct distance between noise source and measuring point (m)*

c = *velocity of sound in air = 331 m/s*

δ = *air density* (g/m^3)

Both P1 and A are expressed in dB

Let P_c and P_s be the SPL's for the large and small cage respectively,

then:

$$\frac{P_l}{P_s} = \sqrt{\frac{\delta_l c_l A_l}{2\pi R_l} \,.\, \tan^{-1}\frac{l_l}{2R_l} \,.\, \frac{1}{\tan^{-1}\frac{l_s}{2R_s}} \,.\, \frac{2\pi R_s}{\delta_s c_s A_s}} \qquad (6.2)$$

The measurements were performed at the same altitude in the same temperature range therefore:

$$\frac{P_l}{P_s} = \sqrt{\frac{R_s}{R_l} \,.\, \tan^{-1}\frac{l_l}{2R_l} \,.\, \frac{1}{\tan^{-1}\frac{l_s}{2R_s}}} \qquad (6.3)$$

In Logarithmic terms:

$$P_l = P_s + 10\,Log\left(\frac{R_s}{R_l}\right) + 10\,Log\left(\tan^{-1}\frac{l_l}{2R_l}\right) - 10\,Log\left(\tan^{-1}\frac{l_s}{2R_s}\right) \quad (6.4)$$

$R_l = 4.25\,m$

$R_s = 0.75\,m$

$l_l = 40\,m$

$l_s = 3.6\,m$

thus,

$$P_l \approx P_s - 6.9 \qquad (6.5)$$

The levels of the small cage have to be reduced by 6.9 dB to be able to compare the results of the two cages.

The results of the two cages are compared below:

6.2 Kingbird Conductor: Comparing Large and Small Cage Results

6.2.1 Comparing Dry Results

The results of the two cages agree in the 20 to 26 kV/cm gradient range (Figure 6.1). The difference at the lower gradients might be attributed to high background noise at the large corona cage and to a smoother conductor in the small corona cage. As mentioned before, ideally, measurements should be done at levels 10 dB above background noise [31]. The background noise at the large cage is about 45 dBA. At noise levels of 55 dBA (10 dB above background) the results of the two cages are almost the same.

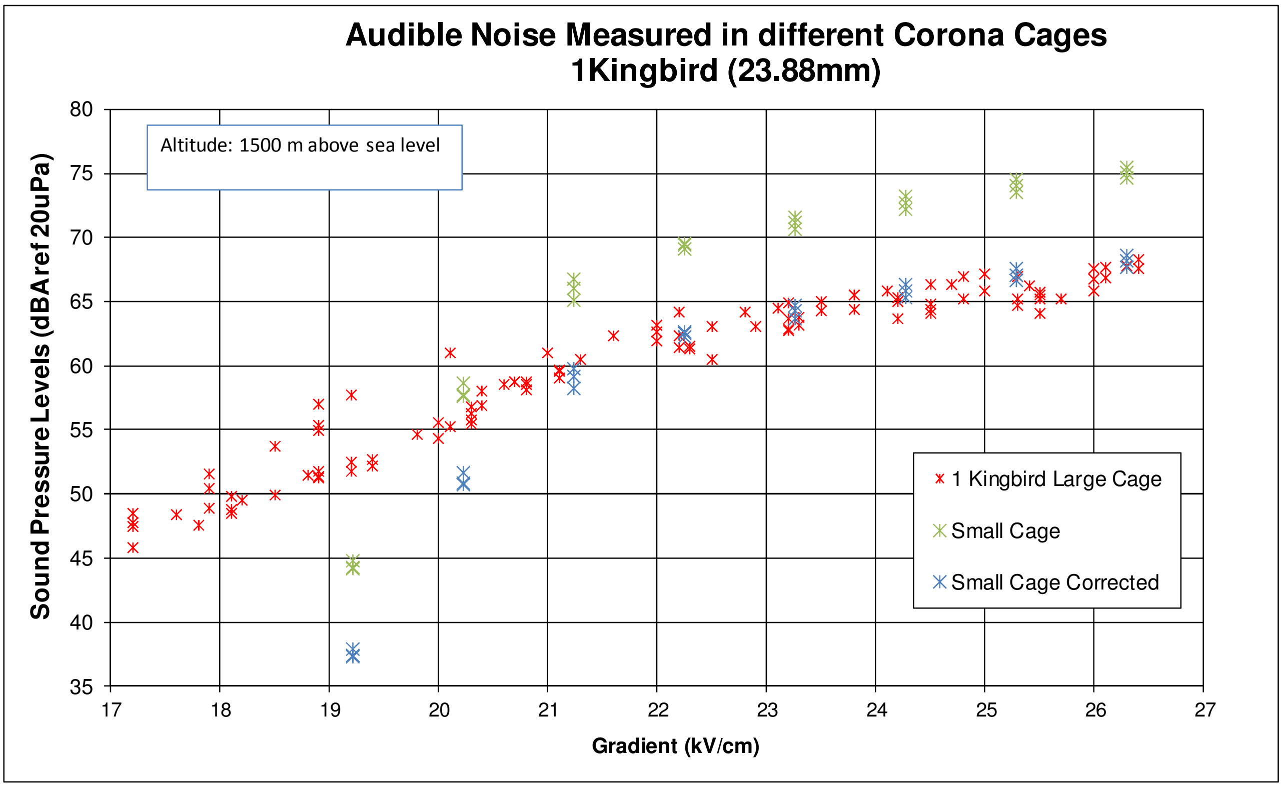


Figure 6.1
Comparison between audible noise results of a Kingbird
conductor in a large and small corona cage for dry conditions

6.2.2 Comparing Heavy Rain Results

As in the case of the dry levels, the small cage measurements were corrected using equation 4.6. The results from both cages, at 1500 m above sea level, are depicted in Figure 6.2 below. The measurements from the two cages compared exceptionally well.

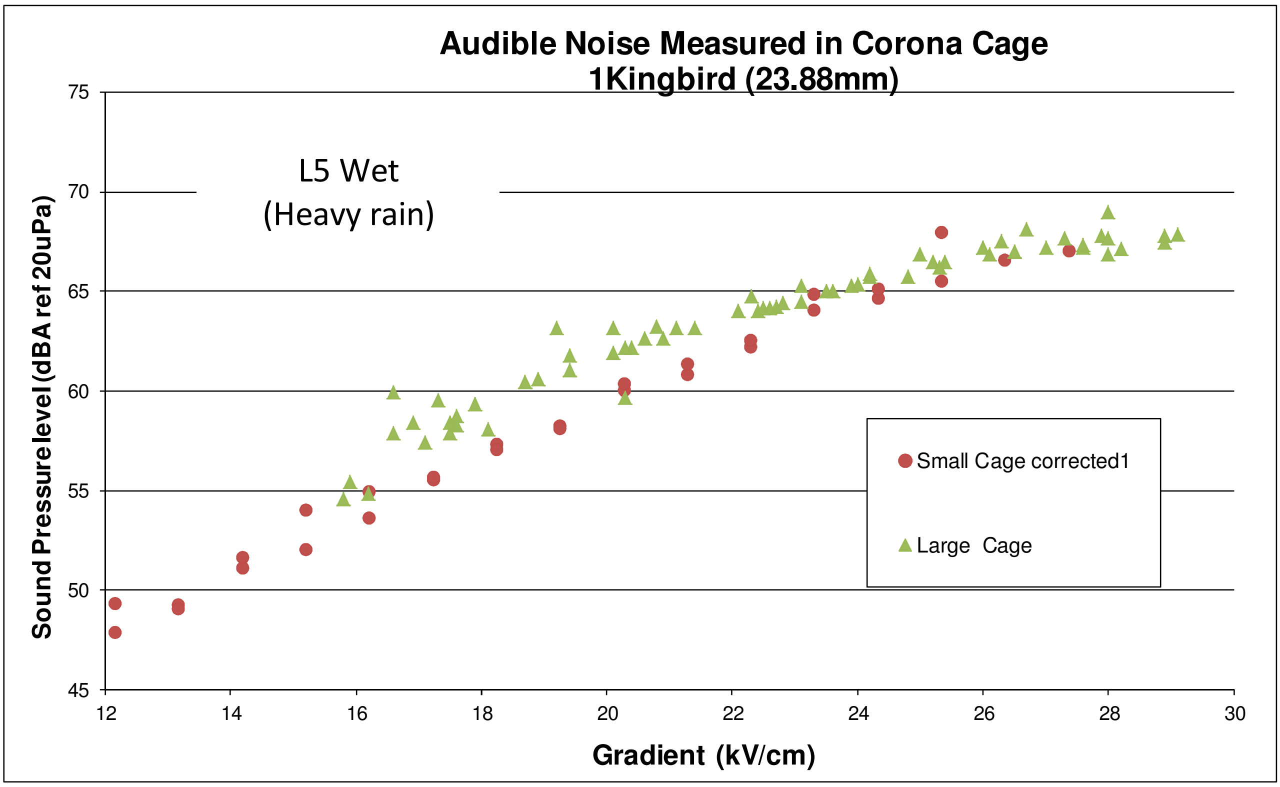


Figure 6.2
Comparison between audible noise results of a Kingbird conductor in a large and small corona cage: heavy rain

6.3 Zebra Conductor: Comparing Large and Small Cage Results

The comparison of the Zebra conductor is very similar to that of the Kingbird. In the 20 to 26 kV/cm range (10 dB above background) the results of the two cages are close (Figure 6.3).

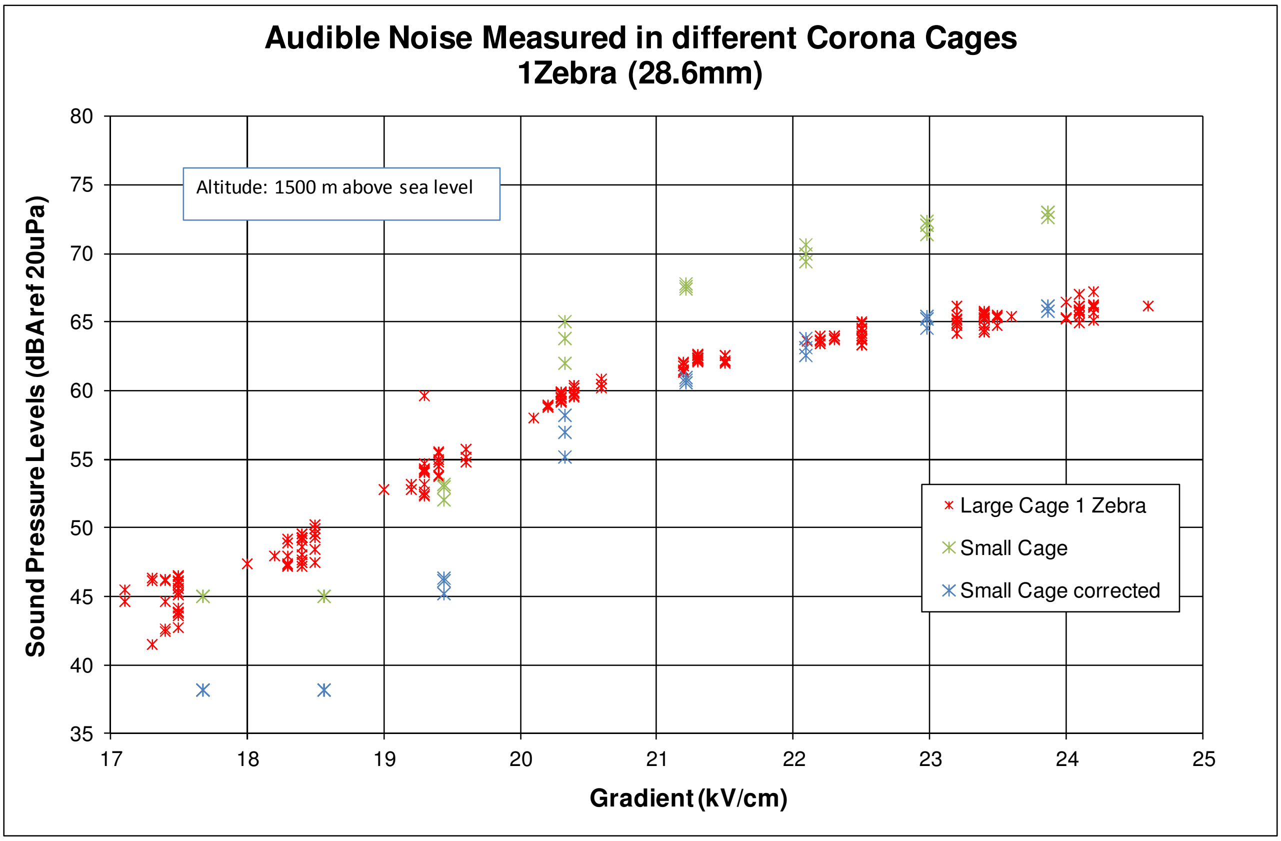


Figure 6.3
Comparison between audible noise results of a Zebra conductor in a large and small corona cage.

6.4 Tern Conductor: Comparing Large and Small Cage Results

The Tern conductor was the first conductor to be tested in the small cage. As mentioned before, this conductor was not cleaned or wiped before any tests. In this case the results of the small cage are about 5 dB more than that of the large one (Figure 4.6). The shapes of the two curves are similar and the complete extinction is not seen in the small cage, as was the case with the Zebra and the Kingbird.

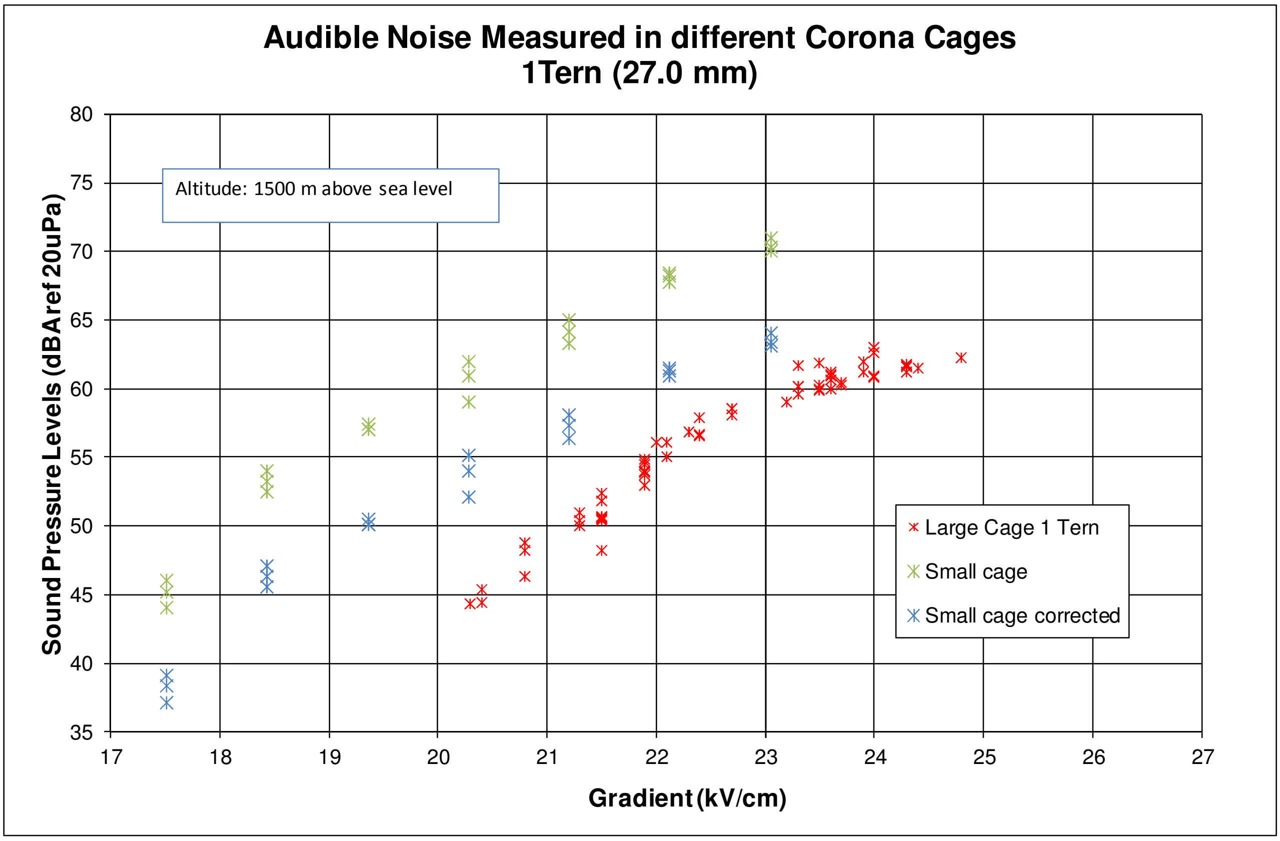


Figure 6.4

Comparison between audible noise results of

a Tern conductor in a large and small corona cage.

The Tern conductor, in the small cage, was not cleaned before the tests and produced a constant 5 dB increase in noise level, over the entire measuring range, compared with the Tern in the large cage. This difference is attributed to the dirty conductor.

The results of the small cage agree well with those obtained in the large cage for Kingbird, wet and dry, as well as the Zebra conductor. These favourable results support our method of measurement in the small cage.

6.5 Comparing Mobile Cage Results to Empirical Predictions

The results of the Kingbird in the small cage were tested against the BPA, Corona and Field Effects predictions [30]. Audible noise predictions for a Kingbird conductor in the small cage were made for altitudes of 1500 m and 135 m. The small corona cage was simulated with 24, 50 mm conductors (Figure 6.5). The approximation of the cage is considered acceptable since the gradients, calculated by the BPA programme, are within 0.5 % of the calculations for a cage (equation 4.1).

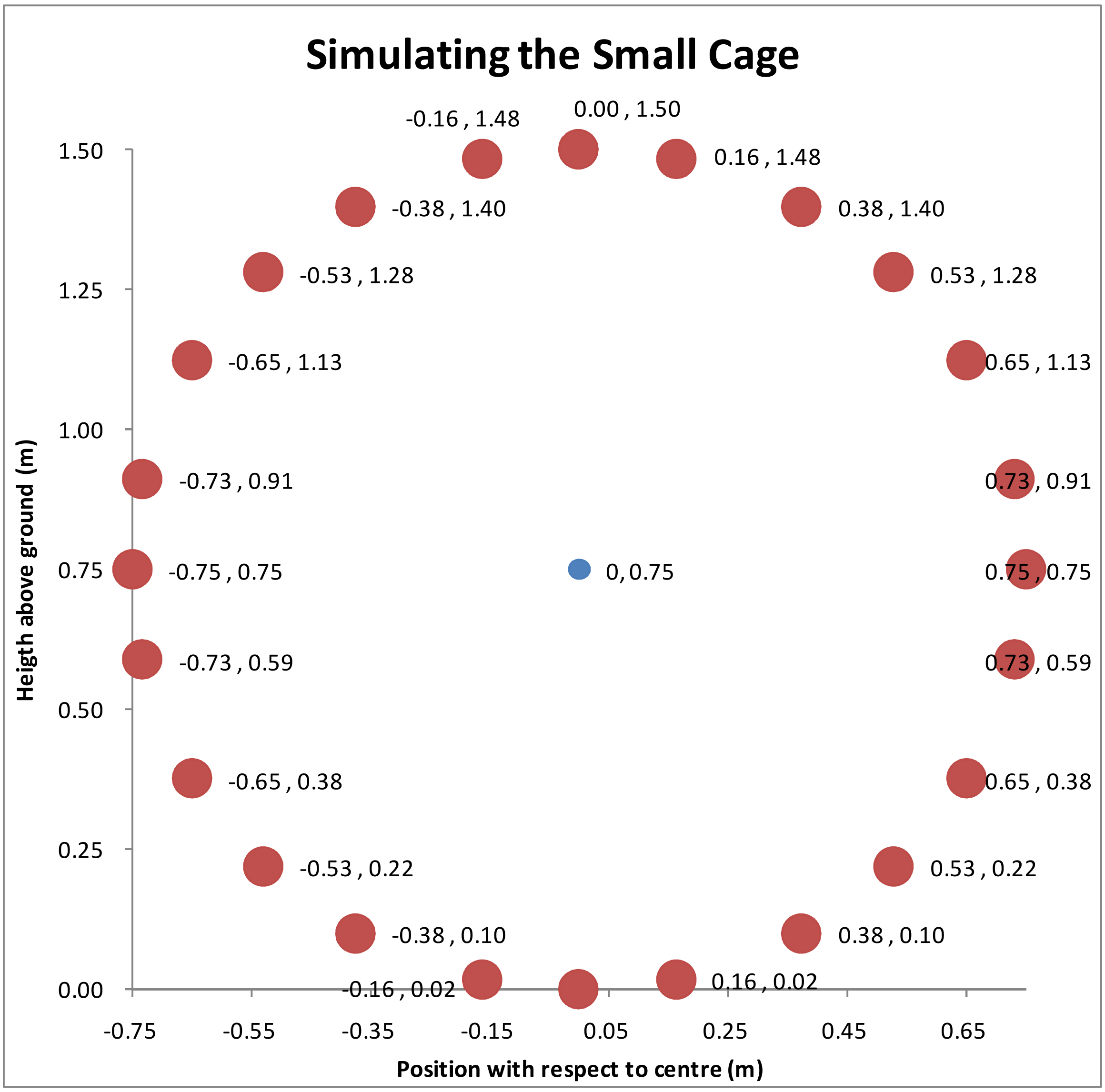


Figure 6.5
Simulating the small corona cage as a number of earth wires

The BPA results are for an infinite long cage and conductor. In equation 6.3 the term, $\tan^{-1}\frac{l}{2R} \rightarrow \frac{\pi}{2},\ because\ \frac{l}{2R} \rightarrow \infty$. However, the cage is only 3.6 m long with the distance to the microphone being 0.75 m. To compare the measurements to the predictions, the results of the cage measurements have to be adjusted upwards by a factor of:

$$10 * \log\sqrt{\frac{\pi}{2} * \frac{1}{\tan^{-1}\frac{l}{2R}}} = 1.26\ , \tag{6.6}$$

Alternatively, the BPA predictions have to be lowered by the same constant. In Figure 6.6 the BPA predictions are reduced with this correction factor.

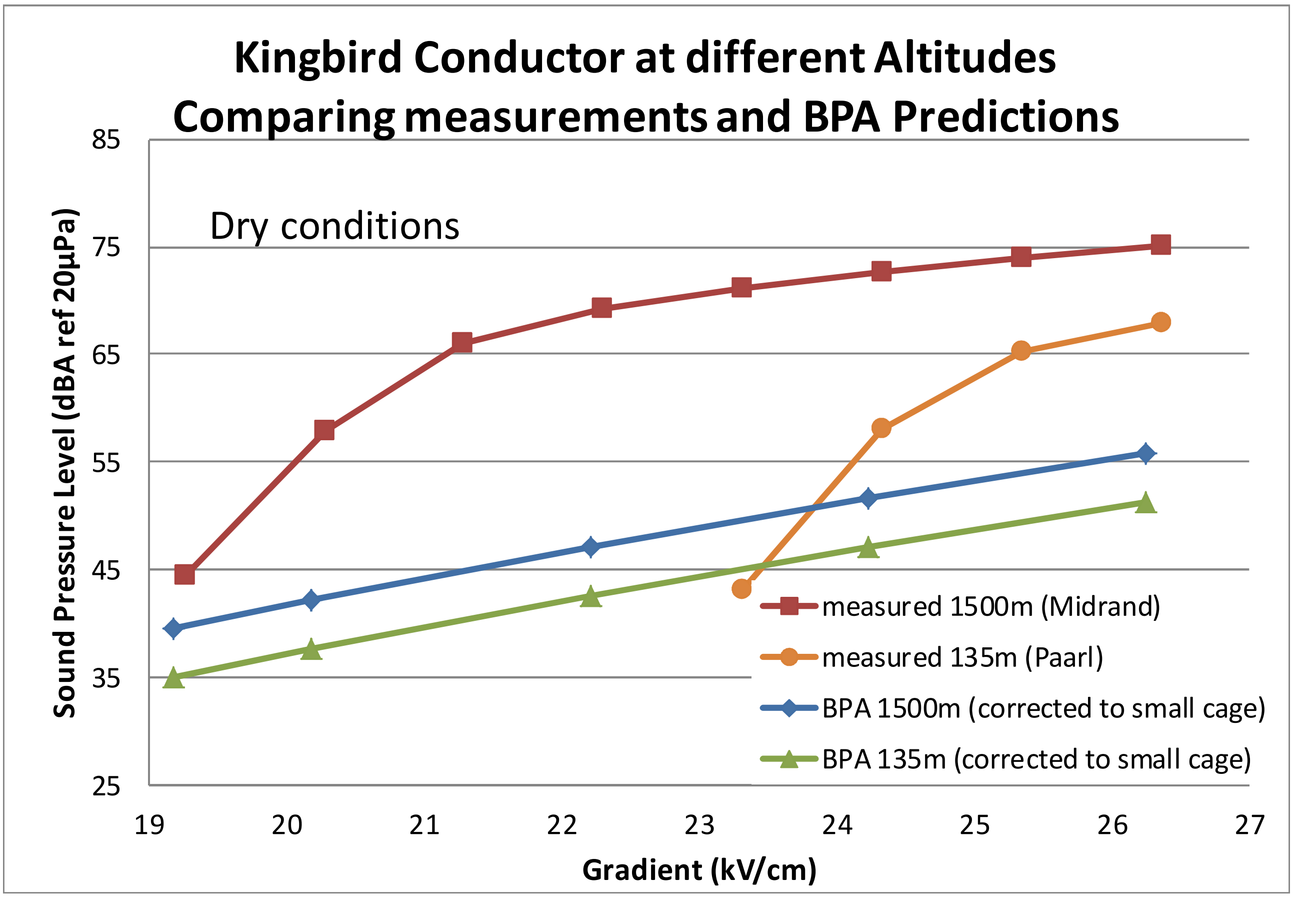


Figure 6.6
Comparing measurements at different altitudes
in a corona cage with BPA predictions for dry conditions

The results in Figure 6.6 support the findings in Chapter 3 regarding the inaccuracy of BPA and other empirical prediction methods.

Our cage measurements during heavy rain, at 1500 m are compared with BPA predictions. The results are depicted in Figure 6.7.

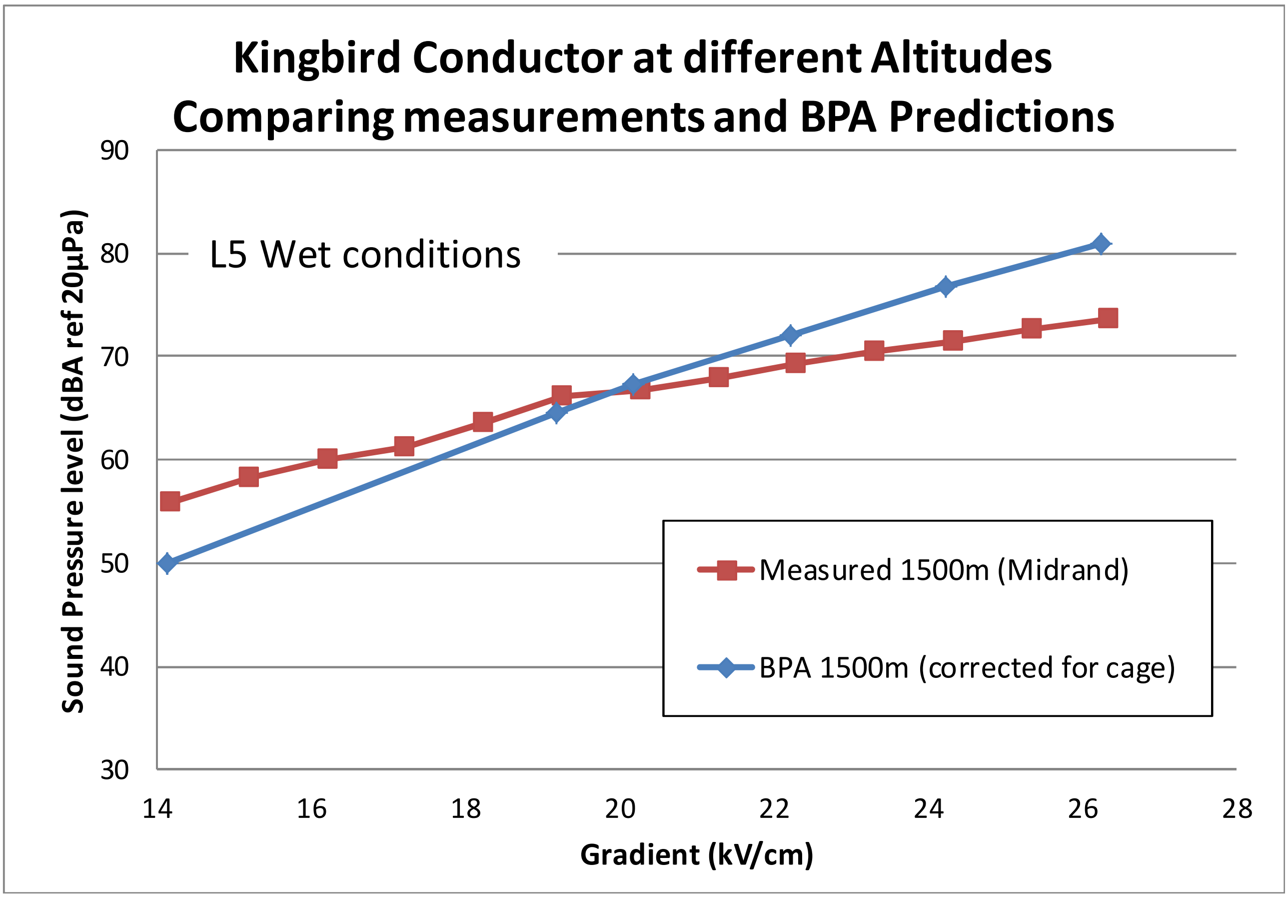


Figure 6.7
Comparing measurements at different altitudes
in a corona cage with BPA predictions for heavy rain conditions

The measurements compare well with the BPA predictions for wet conditions. This agrees with other researchers' findings regarding wet predictions [30].

6.6 Conclusion

The noise measurements from the mobile cage compare well with wet and dry results from the large cage. However, empirical predictions are only accurate for wet conditions.

Chapter 7

Conclusions and Recommendations

7.1 Conclusions

This chapter summarises the conclusions and makes recommendations for future work. The purpose of this research was to investigate the effect of altitude on audible noise generated by conductor corona. The major contribution of this thesis has been to challenge the 1 dB/300 m correction factor for audible noise under dry conditions. With a mobile corona cage it has been shown that the correction factor for corona audible noise is steeper than the previous reported, 1 dB/300 m for AC lines, *under dry conditions*. This supports field measurements which suggested an altitude correction of 1 dB/100 m for audible noise.

- Assuming that the altitude correction is steeper than 1 dB/300 m:

    - Predictions made using a high altitude measurement, predicting noise at a lower altitude, the predictions will be conservative and could lead to an over design.

    - However, should a low altitude level be used as reference, the prediction for a higher altitude will be too low, and could lead to under design and complaints from people close to the line.

- During heavy rain conditions the altitude correction factor was measured to be 1 dB/450 m to 1 dB/350 m and this agrees with other research (1 dB/300 m). The corona in wet conditions appears to depend on the rain drops, and not the condition of the conductor. The rain drops keep the conductor in corona at lower altitudes and lower gradients.

- Good comparisons for audible noise were obtained between the large Eskom corona cage and the mobile cage *for wet and dry* conditions.

- Audible noise measurements in the small cage under dry conditions are repeatable.

- Corona is a concern under dry conditions at high altitude. Empirical predictions should not be used to predict audible noise for dry conditions; see recommendations.

- Empirical predictions for audible noise under heavy rain were found to be fairly accurate. *However, dry level predictions should not be used at high altitudes;* see recommendations.

7.2 Recommendations

- Audible noise predictions for dry conditions must be done using a corona cage or a test line. *The use of empirical predictions only, can lead to serious under-designs.*

- Based on the presented research, audible noise predictions can only be accurately for dry conditions if data from a cage or a test line at the same altitude is used. However, if measurements at the proposed altitude are not possible the following approach is recommended:

    - Use a correction factor of 1 dB/100 m when predictions are made for a higher altitude, using data at a lower altitude, providing the noise is measurable at least 3 dB above background noise (a difference of 10 dB is preferable, but not always achievable). It is important to know that if no noise is measurable it does not mean there will be no noise at a higher altitude.

    - If measurements made at high altitude are used to predict levels at a lower altitude, it is recommended to be conservative and use the 1 dB/300 m correction factor.

Bibliography

[1] EPRI, ”Transmission Line Reference Book: 200 kV and Above” (Third Edition) Palo Alto, 2005.

[2] Eskom, ”The planning, design & construction of overhead power lines, 132kV and above”, Published by Crown Publications cc, Bedford Gardens, Johannesburg, February 2005.

[3] EPRI, Transmission Line Reference Book: 345 kV and Above (Second Edition), Palo Alto, 1982.

[4] Otto A. J., ”Direct Current Conductor Corona Modelling and Metrology”, Dissertation presented for the degree of Doctor of Philosophy in Engineering at Stellenbosch University, September 2009.

[5] Urban R. G., ”Modelling Corona Noise on High Voltage Transmission Lines”, Dissertation presented for the degree of Master of Engineering at Stellenbosch University, September 2001.

[6] Maruvada, P.S., ”Corona in transmission systems, theory, design and performance”, Crown publications cc, Bedford Gardens Johannesburg, February 2011.

[7] Maruvada P.S., ”Corona performance of high-voltage transmission lines”, Research Studies Press LTD., Baldock Hertfordshire, England, 2000.

[8] Juette, G.W. ; Zaffanella L.E., ”Radio Noise, Audible Noise, and Corona Loss of EHV and UHV Transmission Lines Under Rain: Predetermination Based on Cage Tests”, IEEE Transactions on Power Apparatus and Systems, July 1970.

[9] University of Rome, ”IEEE/PES Special Course Corona and Field Effects of AC and DC High Voltage Lines”, 1982.

[10] Cigre Working Group 36.01, ”Guideline on interference produced by corona effect of electric systems”, 1974.

[11] Loftness M.O., ”A practical handbook for the correction of radio interference from overhead power lines”, Bonneville Power Administration, May 1980.

[12] Roets H.A. & Britten A.C., ”Guidelines for the identification, location and correction of radio and television interference from high voltage lines”, National Energy Council, Pretoria, South Africa, 1992.

[13] Loftness M.O., ”A practical handbook for the location, prevention and correction of television interference from overhead power lines”, Bonneville Power Administration, March 1977.

[14] Roets H.A. & Britten A.C, ”Practical experience with power lines as a source of interference”, Proceedings of Cigré Conference, Durban, May 1994.

[15] Larsson C., Hallberg B., Israelsson S., ”Long term Audible noise and radio noise performance from an operating 400 kV transmission line”, IEEE Transactions on Power Delivery, Volume 3, Issue 4, Pages 1842-1846, October 1988.

[16] Task Force, ”Measurement of audible noise from transmission lines”, IEEE Transactions on Power Apparatus and Systems, Volume PAS-100, Issue 3, pages 1440-1452, March 1981.

[17] Peek F.W. jr., ”The Law of Corona and the Dielectric Strength of Air”, Transactions of the American Institute of Electrical Engineers, Volume XXX, Issue 3, Pages 1889-1965, June. 1911.

[18] Comber M.G., Cortina R, ”Audible noise generation on individual sub-conductors of transmission line conductor bundles”, IEEE Transactions on Power Apparatus and Systems, Volume 95, Issue 2, Pages 525-535, March 1976.

[19] Britten A.C. and van der Westhuizen C., ”Eskom’s Corona Cage as a Tool for Research into Corona Phenomena at High Altitudes” Power Industry Technology Trends Conference, Rosherville, May 1989.

[20] ENEL, ”Report on the study and implementation of a measuring system for radio interference and corona losses supplied to Escom-Evkom (South Africa) for EHV cage unit investigations”, report CRE1.DSR 608.410/2 CRA.DSA 754.983/-, February 1981.

[21] Jeong-Boo Kim, Dong-Il Lee, Koo-Yong Shin, Jermendy L., Forgarasi I, ”Comparison of electrical environmental characteristics of different EHV transmission lines”, High Voltage Engineering, Eleventh International Symposium, Volume1, Pages 262-265, 1999.

[22] Juette, G.W. ; Zaffanella L.E., ”Radio Noise Currents and Audible Noise on Short Sections of UHV Bundle Conductors”, IEEE Transactions on Power Apparatus and Systems, Volume PAS-89, Pages 902-913, May 1970.

[23] Kolcio N.; DiPlacido J.; Dietrich, F.M. ”Apple Grove 750 KV project - two year statistical analysis of audible noise from conductors at 775 KV and ambient noise data”, IEEE Transactions on Power Apparatus and Systems, Volume96, Issue 2, Pages 560-570, March 1977.

[24] Roets H.A., Tlhatlhetji N.P. and Sibilant G.C., ”Corona Research”, Eskom Research Report No. RES/RR/02/17511, November 2002.

[25] Lundquist J., ”Results from AC transmission line audible noise studies at the Annaberg EHV test station” IEEE Transactions on Power Delivery, Volume 5 Issue 1, Pages 317-323, January 1990.

[26] Sforzini M., Cortina R., Sacerdote G, Piazza R, ”Acoustic noise caused by AC corona on conductors: results of an experimental investigation in the anechoic chamber”, IEEE Transactions on Power Apparatus and Systems, Volume 94, Issue 2, Pages 591-601, March 1975.

[27] Brüel & Kjær, ”Microphone Handbook Volume 1: Theory” , BE 1447 –11, Brüel & Kjær World Headquarters: DK-2850 Nærum, July 1996,

[28] Brüel & Kjǽr, ”Measuring Sound” Brochure BR 0047-13. Obtainable at *www.bksv.com/doc/br0047.pd.*

[29] Daniel Ziobroski & Charles Powers, ”Acoustic Terms, Definitions and General Information”, General Electric Company, GER-4248 (06/05), 2005.

[30] Bonneville Power Administration (BPA), Corona and Field Effects Program Ver3, US Department of Energy, June 1991.

[31] IEEE Standards Board, ”IEEE Standard for the Measurement of Audible Noise From Overhead Transmission Lines”, Approved September 1992, Reaffirmed 2006.

[32] Al-Faraj M.A., Shwehdi M.H., Farag A.S.; ”Environmental effect on high voltage AC transmission lines audible noise”, Energy Conversion Engineering Conference, Proceedings of the 32nd Intersociety, Volume 3, Pages 2082-2087, 27 Jul - 1 Aug 1997.

[33] Chartier V. L., Stearns R. D., ”Formulas for predicting audible noise from overhead high voltage AC and DC lines”, IEEE Transactions on Power Apparatus and Systems, Volume PAS-100, Issue 1, Pages 121-130, January 1981.

[34] Roets H.A., Tlhathletji N.P., ”Measurements and prediction of corona generated audible noise”, Eskom Research Report No. RES/RR/04/24487, November 2004.

[35] Roets H.A., Britten A.C., ”Utilization of a corona cage to predict conductor corona generated audible noise under a 400 kV transmission line for wet and dry conditions”. 10th International Symposium on High Voltage Engineering, Montreal, Canada, June 1997.

[36] Jeong Doo Kim, Dong Il Lee, Koo Yong Shin, Kwang Ho Yang, Hee Sung Ahan, Ja Yoon Koo, ”Kepco 765 kV transmission system development: Corona and electric field effect studies”, International conference on energy management and power delivery, Volume1, Pages 288-291, November 1995.

[37] Dong Il Lee, Jeong Boo Kim; Koo Yong Shin; Kwang Ho Yang, Hee Sung Ahan; Ja Yoon Koo, ”Audible noise performance of 6-rail conductors on a 765-kV double circuit test line”, IEEE Transactions on Power Delivery, Volume 12, Issue 3, Pages 1343-1351, July 1997.

[38] Task Force, Corona and Field Effects, ”A comparison of methods for calculating audible noise of high voltage transmission lines”, IEEE Transactions on Power Apparatus and Systems, Volume PAS-101, Issue 10, Pages 4090-4099, October 1982.

[39] Paris L., Sforzini M., ”RI Problems in HV-Line Design”, IEEE Transactions on Power Apparatus and Systems, Volume PAS-87, Issue 4, Pages 940-946, April 1968.

[40] Chartier V. L., Lee L. Y., Dickson L. D.; Martin K. E., ”Effect of High altitude on High Voltage AC Transmission Line Corona Phenomena”, IEEE Transactions on Power Delivery, Volume 2, Issue 1, Pages 225-237, Jan 1987.

[41] Perry, D.E., ”An Analysis of Transmission, Line Audible Noise Levels Based Upon Field and Three-Phase Test Line Measurements”, IEEE Transactions on Power Apparatus and Systems, Volume PAS-91, Issue 3, Pages 857-865, May 1972.

[42] Britten A.C., Clark E.G. and Konkel H.E., ”Radio interference, corona losses, audible noise and power frequency electric fields as factors in the design of Eskom’s 765 kV lines”, Proceedings of Cigré Regional Conference, Johannesburg, October 1987.

[43] Kolcio, N. ; DiPlacido, J. ; Haas, R.J. ; Nichols, D.K. ; ”Long Term Audible Noise and Radio Noise Performance of American Electric Power's Operating 765 KV Lines”, IEEE Transactions on Power Apparatus and Systems, Volume PAS-98, Issue 6, Pages 1853-1859, November 1979.

[44] Britten A.C., Cretchley D.H., Sadurski K.J., Druif B. and Roets H.A., ”The compaction of conductor-to-tower clearances on Eskom’s 765 kV transmission lines”, Proceedings of Cigré Symposium, Leningrad, June 1991.

[45] Vinh, T. ; Shih, C.H. ; King, J.V. ; Roy, W.R, ”Audible Noise and Corona Loss Performance of 9-Conductor Bundle for UHV Transmission Lines”,. IEEE Transactions on Power Apparatus and Systems, Volume PAS-104, Issue 10, Pages 2764-2770, Oct. 1985.

[46] Vinh, T., King, J. V.; ”Statistical Analyses of Audible Noise and Corona Loss Data for a 10-Conductor UHV Bundle”, IEEE Transactions on Power Delivery, Volume2 Issue 1, Pages 217-224, Jan. 1987.

[47] Vosloo W. L., ”A study into the effect of sugar cane fires on AC corona noise : development of a laboratory simulation and measurement process”, Thesis (M.Ing.)--University of Stellenbosch, 1992.

[48] Kwang-Ho Yang, Dong-Il Lee, Gi-Hyun Hwang, June-Ho Park, Chartier, V.L, ”New formulas for predicting audible noise from overhead HVAC lines using evolutionary computations”, IEEE Transactions on Power Delivery, Volume 15, Issue 4, Pages 1243-1251, October 2000.

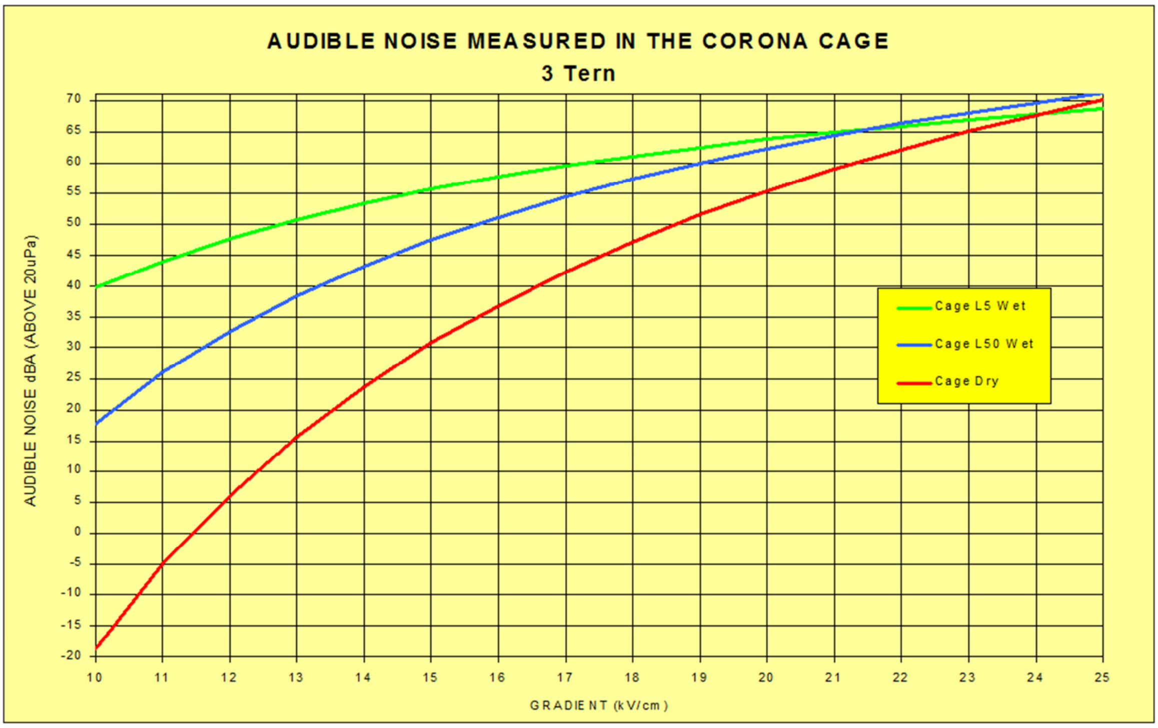
[49] Shankle D. F, Griscom S. B,. Taylor E. R, Schlomann R. H., ”The Apple Grove 750-kV Project-Equipment Design and Instrumentation” IEEE Transactions on Power Apparatus and Systems, Volume 84, Issue 7, Pages 541-550, July 1965.

[50] Altitudes, not mentioned in the relevant references, were obtained using Google Earth

Appendix A

12 dB Noise Difference between Dry and Wet Levels at 16.5 kV/cm

Unrelated to the main research, a 12 dB difference was measured between the dry and wet audible noise levels under a 400 kV line (at two different altitudes). The conductor on the line is a triple Tern (27mm diameter) bundle with an operating gradient of 16.5 kV/cm. Measurements performed by the author on a 3 Tern conductor bundle in the large Eskom corona cage [34] are depicted below. The difference between the dry and L50 wet levels at a gradient of 16.5 kV/cm is also 12 dB. This is a by-product of the research and is recorded for interest.



Audible noise measurements of a 3 Tern conductor bundle in a corona cage (3.5 m radius).