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Air Ion Concentrations under Overhead High-Voltage Transmission Lines

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Abstract

This paper reports air ion concentration monitored at 41 sites under overhead high voltage ac power lines in and around an urban environment. The net ionic polarity under power lines was of both signs but mostly positive, and concentrations varied widely from 0 to 3300 ions cm^{-3}. Concomitant measurements of the vertical dc electric field at the ground confirmed the presence of a net positive charge above. Approximately 19% of the sites exhibited relatively high ion concentrations exceeding 1000 cm^{-3}. The mean value of all the sites was 776 cm^{-3}. Statistically, the mean for the transmission voltage (220-330 kV) line sites was significantly higher than that for the sub-transmission voltage (110-132 kV) line sites with means of 905 and 501 cm^{-3} respectively. These values were compared with the mean urban outdoor concentration well away from the lines which was about 400 cm^{-3} and of negative polarity. Overall, ion concentrations at approximately 76% of the power line sites exceeded the absolute mean urban outdoor value. The dc electric fields under the power lines showed a statistically significant relationship to the measured ion concentrations, although there was considerable scatter to indicate that electric field measurements do not necessarily reflect air ion concentrations at ground level.

Keywords: Atmospheric ions, atmospheric electric field, charged aerosols, power lines,

1. Introduction

Atmospheric air contains ions in the form of charged molecules and aerosol particles. In the absence of anthropogenic sources, ions originate from the interaction of cosmic rays on air molecules and the presence of trace radioactive materials in the environment to form molecular clusters bound together by charge (Iribarne and Cho, 1980). In clean environments, these, so-called ‘small ions’ occur in number concentrations of a few hundred cm^{-3} (Reiter, 1992). In populated areas, small ions are also produced by several anthropogenic sources such as electrical installations, motor vehicles, industrial processes and air conditioners and these may elevate ambient ion concentrations. Once produced, small ions quickly attach to aerosol particles in the air, producing ‘large ions’ in the same size range as aerosols, roughly 1 nm to 1 μm in diameter. Small ions have a higher mobility than large ions and are affected more by the presence of local electric fields. Large ions are not easily disturbed by electric fields but can be transported further by the wind.

High voltage transmission lines generate corona, giving rise to small ions that tend to migrate towards the surface of the earth where they enhance the air ion concentrations close to ground level. Elevated small ion concentrations have been found in the air close to ground level near overhead transmission lines (Carter and Johnson, 1988). Large ions can be carried further in the wind and may be detected by monitoring the static dc electric fields on the ground downwind of the lines. Concentrations of space charge, consisting of both small and large ions, may be measured directly using ion monitors. Levels of space charge concentrations produced by overhead high voltage transmission lines can be significantly higher than background levels well away from ion sources. For example, Suda and Sunaga (1990) measured large ion concentrations near a high voltage dc test line and found concentrations of about 10^4 ions cm^{-3} at a distance of 200 m downwind of the line when it was energized by a voltage of 750 kV. Carter and Johnson (1988) measured air ion concentrations near a 500 kV dc test line and found small ion concentrations of up to 1.5 x 10^5 cm^{-3} and large ion concentrations of a few tens of thousands cm^{-3}. Ion concentrations produced by ac high voltage lines are generally lower than from dc lines. Grabarczyk and Berlinski (2004), using a Gerdien-type intermediate/large ion counter near high voltage ac lines, reported concentrations of the order of 10^3 cm^{-3} near 110 and 220 kV lines and of the order of 10^4 cm^{-3} near a 400 kV line.

The atmospheric electric field occurs due to charged particles and ions in the air that generally tend to have a net positive charge under fair weather conditions. Thus, the field is directed vertically downwards and has a value of 100 to 200 V m^{-1} at the ground (Reiter, 1992). The field decreases rapidly with increasing altitude and at 5 km it is about 10% of its value at ground level. The value of the electric field at the ground, therefore gives an indication of the total net space charge within the column of air above the measurement point. Its magnitude and direction can be significantly affected by the formation of thunderclouds above or the presence of local space charge from sources such as overhead power lines. Corona generated ions from power lines, as they are carried by the wind, cause fluctuations in the electric fields measured at ground level. Fews et al, (1999, 2002) used a fieldmeter to measure changes in the earth's vertical electric field to estimate the ion concentrations near several overhead 132 and 400 kV transmission lines. They used a dispersion model to estimate the enhanced ion concentrations at ground level and found values from 250 to 7000 charges cm^{-3} with an average value of 3000 cm^{-3}. Both positive and negative space charge clouds were detected with an excess of positive charge during fair weather conditions.

Free ions do not exist for long in air, being easily attached to aerosol particles. The concentration of aerosols may be affected by factors such as gravitational settling, dispersion by wind and coagulation. In these respects, charged particles may behave differently to uncharged particles. It is, therefore, important to determine ion concentrations in different environmental situations. This information is needed for a better understanding of the dynamics of atmospheric processes and for human exposure assessment. The present study was conducted with the aim of measuring air ion concentrations under several overhead transmission lines in a large urban environment and to assess excess ion concentrations in relation to the urban outdoor.

2. Methods

2.1 Study area

The study was conducted in an area within a radius of about 18 km from the centre of a large urban area in Australia. This is a high population density area with undulating terrain. The area contains several high voltage substations linked by a network of transmission and sub-transmission voltage overhead ac transmission lines. In this paper, transmission voltage levels are defined as between 220 and 330 kV and sub-transmission voltage levels as between 110 and 132 kV. Most of the lines are double circuit, strung on steel lattice towers, and run along creek valleys, open parkland and cleared pathways through forest and bush land. Quite a few lines are located in close proximity to residential areas. Line heights vary from 10 to 25 m.

2.2 Instrumentation

Small ion concentrations were measured with an Alphalab air ion counter. This is a battery-operated instrument that samples atmospheric air at a rate of 800 $cm^3\ s^{-1}$. The air is drawn through a parallel plate assembly with an air gap of 4 mm and a polarization field of 1 kv m^{-1}. Negative and positive ions are detected separately by selecting a polarity switch. The instrument has a dynamic range of 10 – 10^6 ions cm^{-3} with a minimum detectable charge concentration of 10 ions cm^{-3}. Nominal response time is about 1 s. The instrument was factory calibrated just prior to the measurement campaign.

The vertical dc electric field at ground level was measured with a JCI 140 electric fieldmeter. This is a compact, battery-operated instrument that uses a rotating chopper to alternately expose and shield a conductor plate to the electric field. The resulting induced current induced on the plate is a measure of the dc electric field. The instrument has a time response of 50 ms and a resolution of 10 V m^{-1}. The instrument was pre-calibrated in the laboratory using two large, flat, parallel plates connected to a variable voltage supply to simulate a known electric field.

2.3 Measurement technique

At each site, the two instruments were affixed to a camera tripod and placed at a height of about 0.5 m above the ground. The fieldmeter was held with its face upwards to measure the vertical electric field. The ion counter was held well away from its support and nearby objects. From switch-on, the time taken to achieve a steady reading was typically about 1 min. The two instruments were provided with analogue outputs which could be digitised and fed into a portable computer that logged the data in real time. Wind direction was monitored with a portable wind vane.

Owing to fringing effects, the earth's vertical electric field is significantly affected by nearby structures such as buildings and tall trees. It is generally measured at an unobstructed site which is at a distance of at least three times the height of a nearby object that may affect it. In this study, the background dc electric field was measured in an open park, on level ground, well away from all objects that may have affected it. However, the use of a fieldmeter under a power line that is not energized, or a supporting pylon, would give an electric field value that was less than background. When the line was energized and emitting corona ions, the reading obtained in this manner could only be used to give an indication, and not a reliable value, of the ion concentration produced by the line.

At each measurement site, the instruments were positioned directly under the lines. Some readings were obtained under support pylons. The ion concentration measurements at ground level seldom reflect the total ion concentrations emitted by the lines above. Electric field measurements have shown that these ions are carried in the wind and may not reach the ground for some distance away from the lines (Fews et al, 1999). This distance is a function of the wind speed and direction. As the main aim of this study was to compare the ion concentrations at a range of power line sites, it was decided to place the instruments directly under the lines, instead of adding further variables into the equation by placing them at various distances downwind of the lines. However, at one of the sites, denoted ‘Site A’, in addition to the normal measurements, investigations were carried out over a longer period of time, whilst also measuring meteorological parameters such as the wind speed and direction. This site was mid-span under a set of three parallel double-circuit power lines – two transmission voltage and one sub-transmission voltage. The ion counter was positioned about 0.5 m above ground level at a point 5 m away from the point on the ground directly beneath the sub-transmission voltage line. The two transmission voltage lines were 32 and 68 m away from the instrument. Measurements were obtained over a period of six hours, from 10:30 to 16:30 hrs.

2.4 Line characteristics

All the sites investigated contained 1 to 3 parallel sets of double circuit ac transmission and sub-transmission voltage lines. Operating characteristics of the lines, such as the operating voltage and the peak current at the time of each measurement, were not available. The lines were assumed to be energized during all measurement periods.

2.5 Statistical Methods

Mean values of the same parameter obtained under different conditions, for example the air ion concentrations at outdoor sites and power line sites, were compared using a two-sample t-test ($\alpha = 0.05$). Relationships between two different parameters, for example the ion concentration and the electric field, were tested using a simple linear regression analysis ($\alpha = 0.05$). A P-value of less than 0.05 was taken as an indication that there was a significant linear relationship between the two parameters.

3. Results and Discussion

3.1 Urban outdoor ion concentrations

In order to derive the urban outdoor ion concentration, ion counter readings were logged at 1 s intervals for a period of 30 min at each of three urban locations. These were (1) within the City Gardens (CG), (2) near a busy intersection in the Central Business District (CB) and (3) in an outdoor car park (CP) near the centre of the city. All three sites were situated well away from known high voltage electrical installations within the study area. Fig 1(a) shows the time series obtained at the CG site, on a relatively calm day. The sky was free of clouds and there was a low breeze gusting to no more than about 3 m s^{-1}. The mean value and standard deviation of the ion concentration was (387 ± 142) cm^{-3}. Fig 1(b) shows a similar observation at the CB site. The mean value and standard deviation of the ion concentration was (399 ± 144) cm^{-3}. Note the relatively larger frequency of spikes of both signs observed here over the CG site. The sharp spikes coincided with the passage of pedestrians within a few metres of the instruments. Fig 1(c) shows the measurements obtained at the CP site. The mean value and standard deviation of the ion concentration in this case was (407 ± 107) cm^{-3}. Note the relative absence of sharp peaks in this dataset. There were fewer disturbances from external sources such as passing pedestrians at this location. The mean value of these three sets of observations was 398 ions cm^{-3} and a rounded-off value of 400 ions cm^{-3} was assumed for the mean urban outdoor concentration.

An important observation is that the net outdoor ions were of negative polarity at all locations. The general slow variation of around 100-200 ions cm^{-3} was well within the range of normally observed fluctuations in atmospheric ion concentrations (Bracken, 2005).

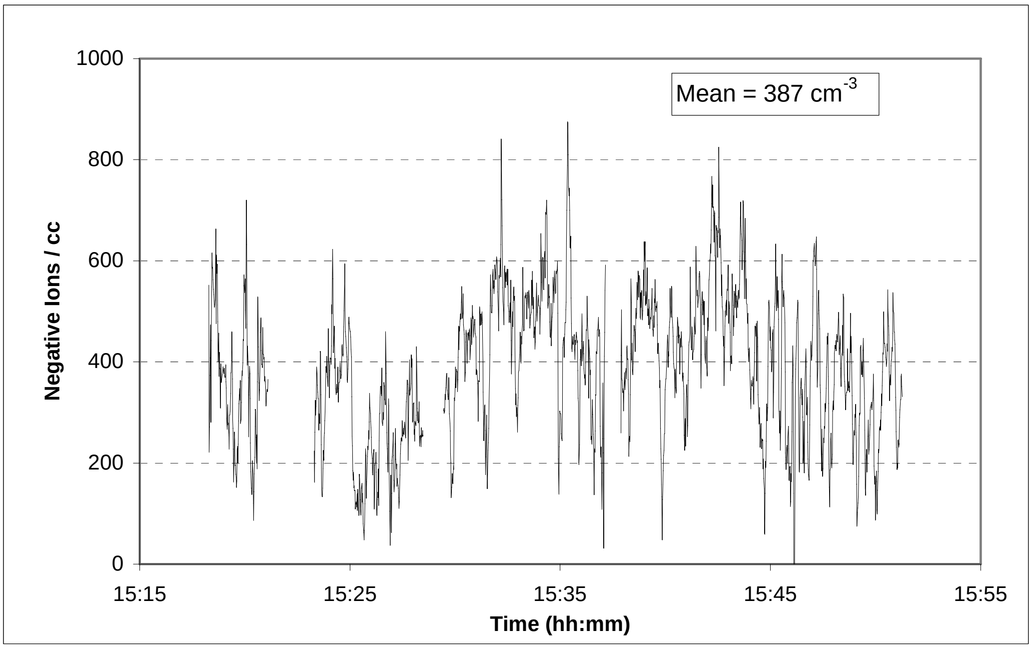

Fig 1(a): Ion concentration measured in the City Gardens.

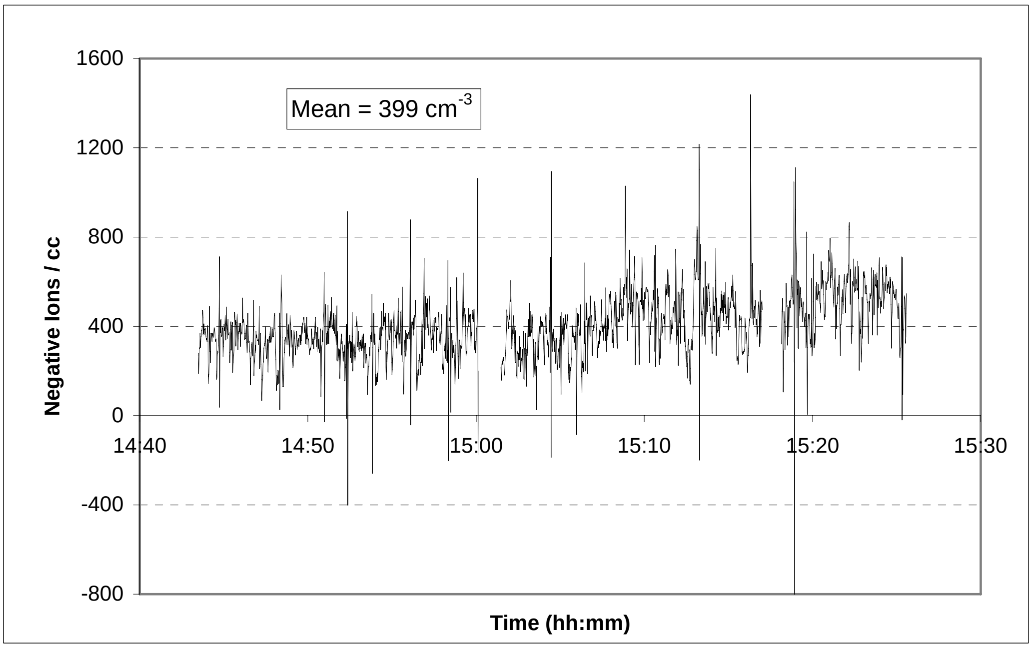

Fig 1(b): Ion concentration measured at the central business district site.

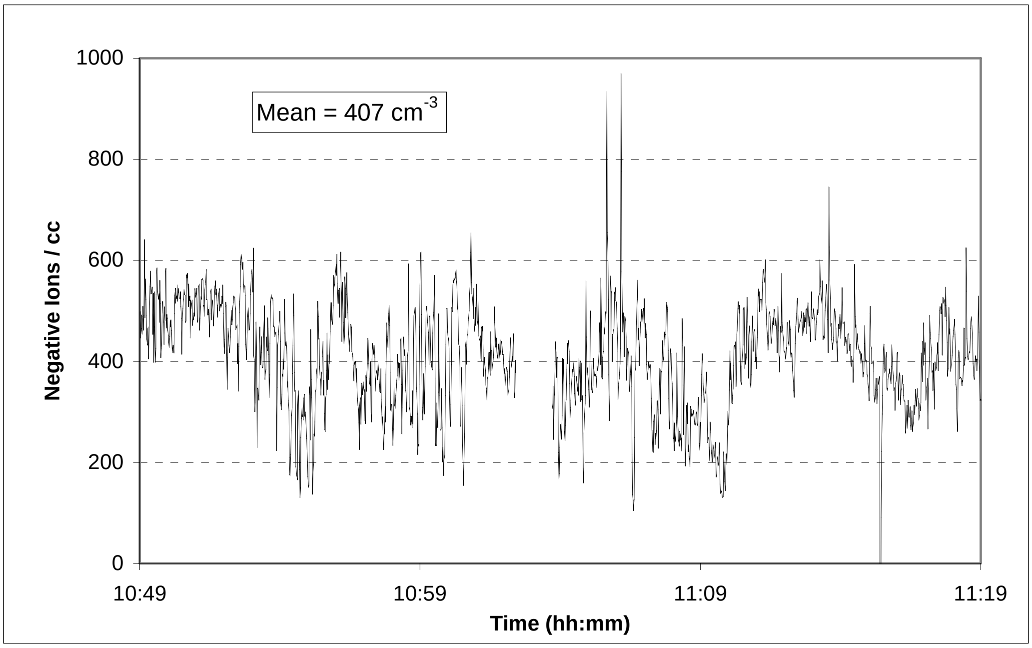

Fig 1(c): Ion concentration measured in the outdoor car park site.

3.2 Ion measurements under power lines

These measurements were all carried out in close proximity to the overhead lines. At the power line sites, the mean of the measured ion concentrations was significantly higher than at the three urban outdoor locations. Both signs of charge were observed. Of the 41 power line sites investigated, 25 showed a net positive charge and 16 showed a net negative charge. Figure 2 shows the measured ion concentrations at all the sites, ordered left to right from most negative to most positive. Also shown is the mean urban outdoor ion concentration of -400 cm^{-3}. There was no evidence indicating any relationship between the observed polarity and meteorological conditions such as wind and humidity and specified line voltages. Actual line voltages at the times of measurement and other line characteristics, such as the peak current, were not known.

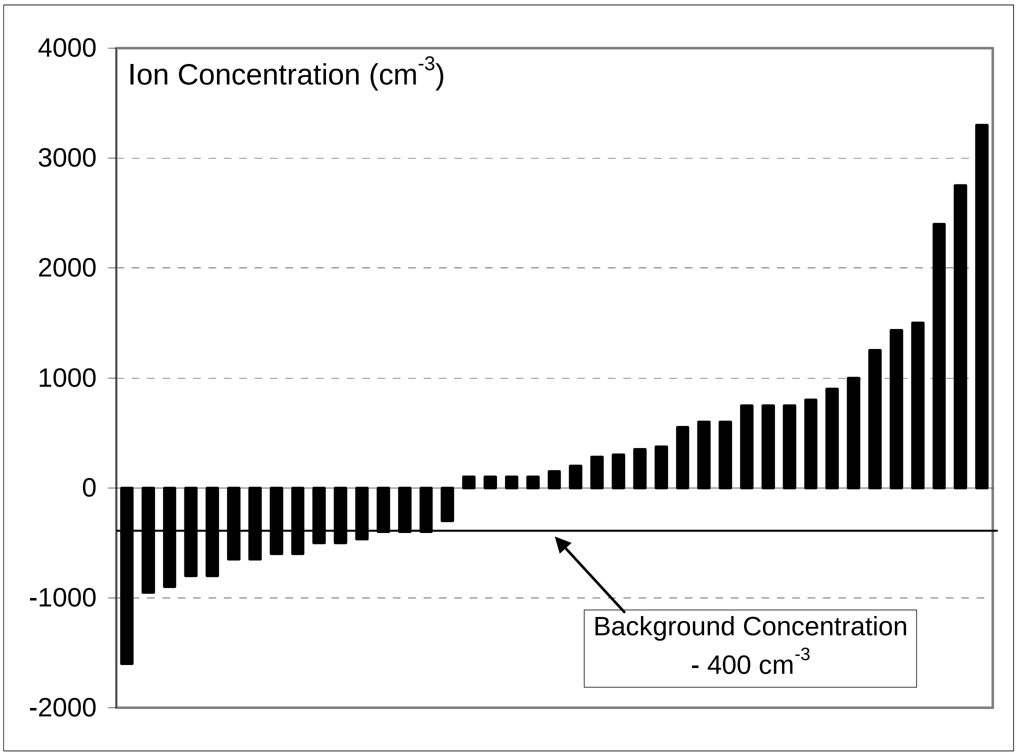

Fig 2: Measured Ion Concentrations at the 41 power line sites investigated.

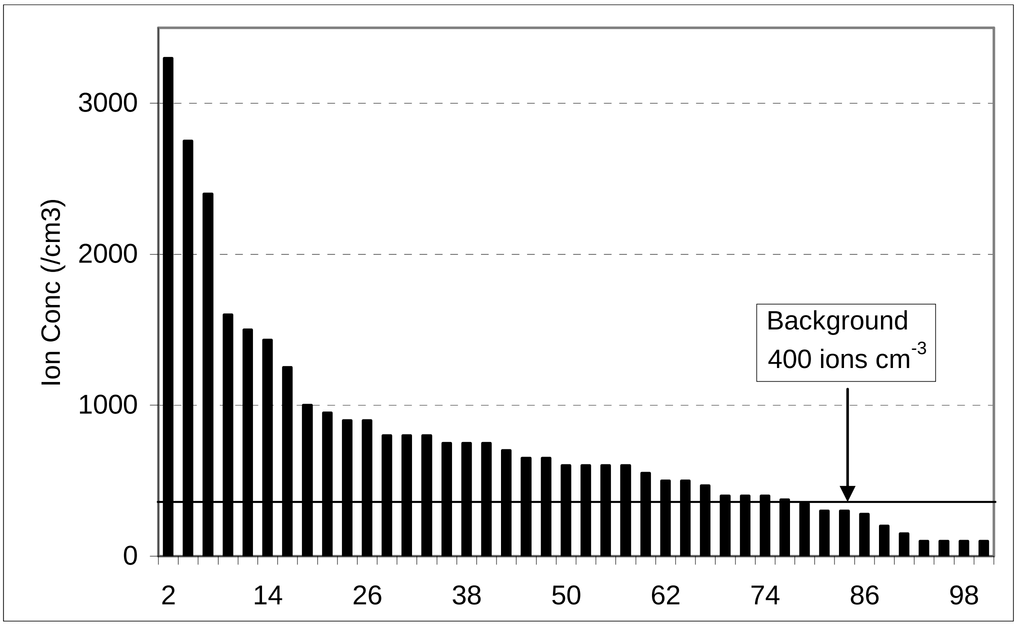

Fig 3: Absolute ion concentrations measured at each site plotted against the percentage number of sites with ion concentrations greater than the value at that site.

Figure 3 shows the absolute values of the mean ion concentration measured at each site plotted against the percentage number of sites with ion concentrations greater than that value. This enabled a comparison of the ion concentrations at the various sites. For example, it can be seen from the figure that approximately 19% of the sites had a mean ion concentration greater than 1000 cm^{-3}. The mean value of all the sites was 776 cm^{-3} which statistically is significantly greater than the absolute urban outdoor concentration of 400 cm^{-3}, shown by the horizontal line. This line also shows that the ion concentrations at approximately 76% of the power line sites exceeded the absolute mean urban outdoor value. Although, the net sign of space charge observed was not related to the line voltage, the magnitude of the space charge concentration was significantly greater under the transmission lines than under the sub-transmission lines, with mean values of 905 and 501 cm^{-3} respectively. A statistical analysis using all observations showed that the mean value under the transmission line sites was significantly greater than under the sub-transmission line sites at a confidence level of 90%. There was one sub-transmission line site which showed an unusually high ion concentration of 2400 cm^{-3}. This measurement point was located downwind of three widely spaced sub-transmission lines, which may have had a cumulative effect. When this point was removed from the analysis, the mean ion concentrations observed at the transmission and sub-transmission line sites were significantly different at a confidence level in excess of 99%.

The opposite polarity of charge found between most of the power line sites and the urban outdoor suggests that the ion concentrations attributed to the power lines were affected by the outdoor concentration of approximately 400 negative ions cm^{-3}. Negative ion concentrations measured in the environment near power lines would be higher than the concentration emitted by the lines, while positive ion concentrations measured would be lower than the concentration emitted. This is also reflected in the number of power line sites, about 24% (Fig 3), that showed ion concentrations *lower* than that observed at the urban outdoor sites. This was only possible if the lines were emitting positive ions that may have neutralized some of the negative charges in the normal background air.

It should be noted that there was no relationship between the magnitude and sign of the observed space charge. The highest concentration found was 3300 cm^{-3} at a site with three parallel sets of double-circuit transmission lines. It is hypothesized that a separating spacer on one of these lines had a high corona-emitting point, possibly due to the breakdown of insulation with age. This was evidenced by an audible crackling hiss from this separator. With the wind blowing parallel to the lines, further readings were obtained at points upwind and downwind of the spacer. The ion concentration reading downwind of this spacer was about three times higher than upwind. Note that, in this instance, since the wind was blowing parallel to the lines, both these upwind and downwind sites were located under the power lines. The value assigned to this site is the average of the upwind and downwind readings. Maximum values downwind of the spacer showed spikes of up to 25,000 cm^{-3} that lasted for very short times of the order of 1 s.

The second and fourth highest absolute values in Fig 3 (+2750 and -1600 cm^{-3}) were obtained near two different high voltage substations. It is interesting to note that, although the magnitudes were both extremely high, the polarities were opposite. It could not be established which one or more of the electrical components within the substation – transformers, insulators, lines or pylons, were responsible for the corona discharges that may have provided the observed ions and whether this had a bearing on the different signs of charge observed.

Corona discharges from an ac power line can produce ions of both signs. However, the physics of positive and negative coronas are very different. During the positive half cycle, electrons near the line are removed from atoms forming positive ions. During the negative half cycle, electrons are ejected mainly due to the photoelectric effect. Negative ions generally have a higher mobility than positive ions in air, and are consequently able to get further away from the line during the corresponding half-cycle and undergo a higher degree of ionising inelastic collisions than the more massive positive ions (Fews et al, 1999). The discharge processes of each sign may vary according to the magnitude of the line voltage. Two principal corona modes are the glow mode and the streamer mode. The main factors that determine the occurrence and characteristics of these modes are the polarity and magnitude of the voltage, the geometry of the lines and ambient weather conditions (IEEE, 1991). Positive corona can occur in the form of burst corona and onset streamers that are essentially highly repetitive pulses of small amplitude. Positive glow is a stable, steady discharge of constant luminosity. With an ac voltage, positive onset streamers are suppressed by space charge created during the negative half cycles, so that the positive glow is the first corona mode observed as the applied voltage is raised. Negative glow may be difficult to observe because of the predominance of Trichel streamers, which are negative pulses of high frequency. At higher fields, both polarities can give rise to pre-breakdown streamers which occur as low frequency, high amplitude pulses. Thus, the net ion concentration that is released to the atmosphere from high voltage power lines in corona may be of either sign, depending on a myriad of factors and processes. Furthermore, the mobilities of positive and negative ions are affected differently as the ambient humidity changes (Fujioka et al, 1983). This may result in different concentrations of the two types of ions with distance to the lines. Therefore, the net polarity of charge present near a power line is dependent on many known and unknown factors and such an investigation is beyond the scope of this paper.

Fig 4(a) and (b) show two time series of the ion concentration measured at Site A. This power line site showed a relatively higher ion count over most of the other sites. Fig 4(a) presents a 1-hour segment when there was a steady wind of about 1-3 m s^{-1} blowing at an angle of about 45° to the lines, towards the sampling site, throughout. The sky was clear of any clouds and the air temperature and relative humidity were about 24°C and 55% respectively. The mean ion concentration measured during this segment was (1544 ± 216 cm^{-3}). The uncertainty is the standard deviation about the mean. Fig 4(b) shows another 1-hour segment at the same site during the afternoon of the same day. The wind had now picked up to about 4-6 m s^{-1} albeit in roughly the same direction as during the morning. The air temperature and relative humidity were about 27°C and 45% respectively. The mean value of ion concentration over this period had increased to (2106 ± 1950) cm^{-3}. This may be attributed to a combination of an increased emission of corona ions from the lines and an increased transportation rate of ions away from the lines towards the measurement point due to the higher wind speed. Note the higher variability in the increased standard deviation about the mean. Rapid short term fluctuations of ion concentrations near overhead ac power lines during wind are not uncommon (Bracken et al, 2005).

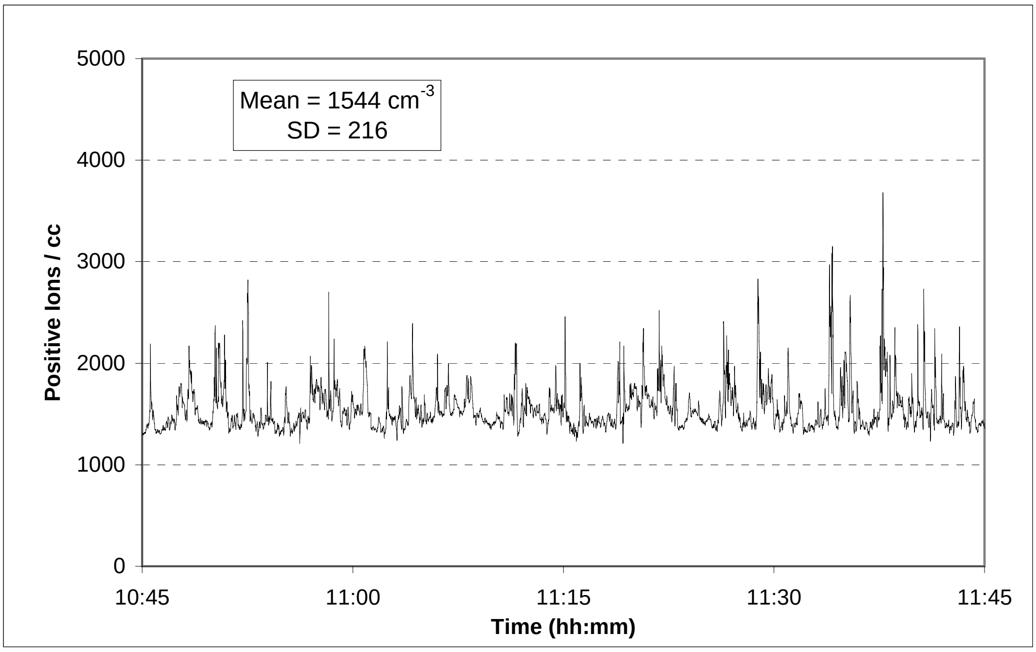

Fig 4(a): Ion concentration measured under the transmission voltage power line at Site A. Windspeed 1-3 m s^{-1}.

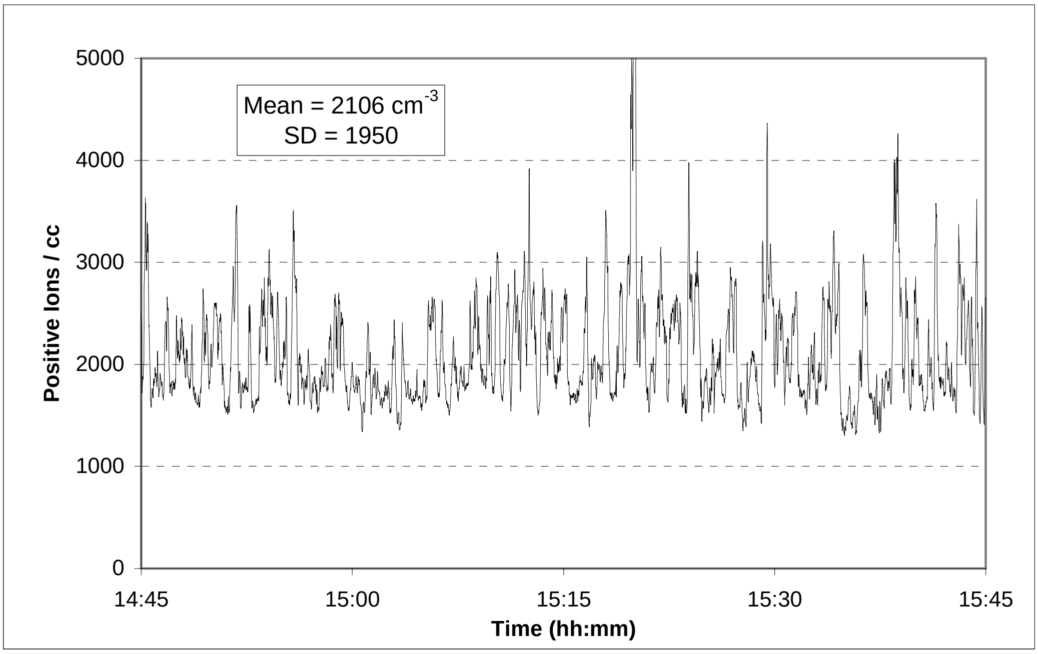

Fig 4(b): Ion concentration measured at Site A as above, but at a higher windspeed of 4-6 m s^{-1}.

There are three important differences between the urban outdoor data in Fig 1 and the data obtained under the power lines shown in Fig 4. First, the mean value under the power lines was significantly higher than the urban outdoor. The difference was statistically significant at a confidence level of 95%. As stated earlier, this relatively higher value was not typical of all power line sites. Secondly, the peak ion concentrations under the power lines showed larger fluctuations than at urban outdoor sites. This was typical of all power line sites. Urban outdoor sites rarely showed such high fluctuations from the mean. This is illustrated more clearly in Fig 5 where, for each of the three cases – power line site with wind speeds 4-6 m s^{-1} (Fig 4(b)), power line site with wind speeds 1-3 m s^{-1} (Fig 4(a)) and the urban outdoor site (Fig 1(a)), the ion concentration readings are ranked from lowest to highest and plotted against the percentage number of points below the ordinate. Note the practically flat nature of the curve at the outdoor site. Very few points deviate far from the mean. At the power line site, at both wind speeds, the curve is still relatively flat, indicating that most of the points lie within a narrow range. However, the number of points deviating from the mean, illustrated at the far right of the graph, is noticeably higher than in the outdoor, and it increases with wind speed. This is also evidenced by the relative values of the three standard deviations given earlier.

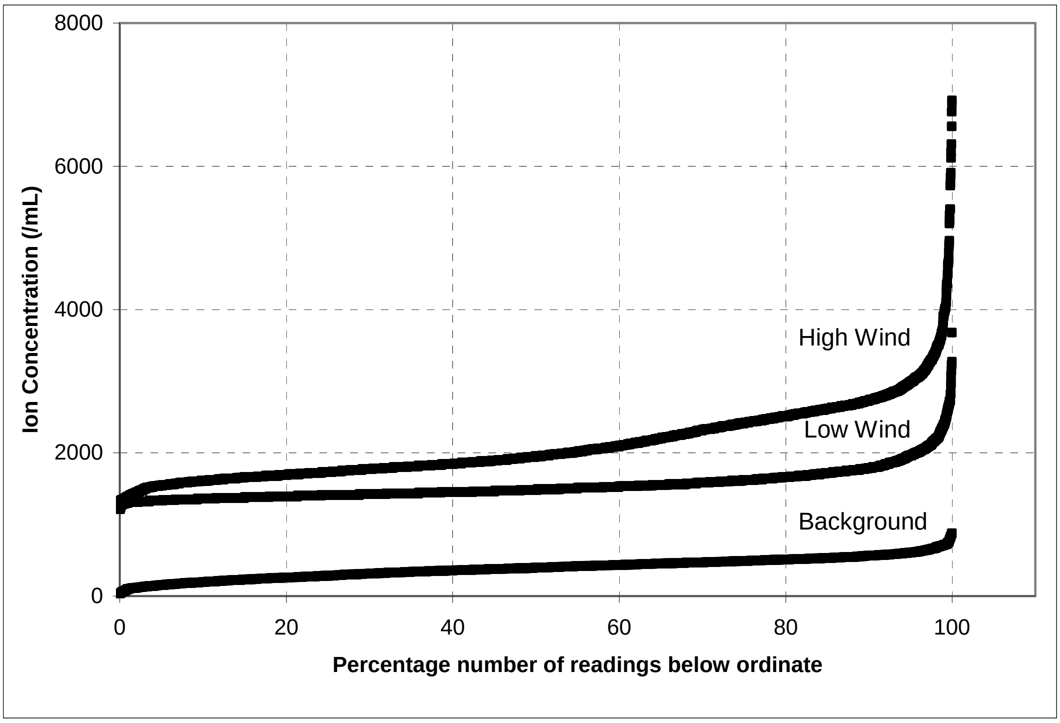

Fig 5: The ion concentration readings obtained in the urban outdoor site (CG) and at the power line 'Site A' at low wind speed (1-3 m s^{-1}) and at high wind speed (4-6 m s^{-1}) plotted against the percentage number of readings below the ordinate (see text for details).

A third important difference between the two types of sites is that, while all urban outdoor sites showed negative ion concentrations, most of the power line sites showed positive values. This is in agreement with other studies near overhead ac power lines, that have showed an excess of positive space charge (Fews et al, 2002; Grabarczyk and Berlinski, 2004, 2005; Bracken, 2005). However, there are some studies showing a net negative space charge near ac power lines. Fews et al. (1999) made measurements of dc electric fields downwind of 132, 275 and 400 kV lines at 14 sites and found fields corresponding to a net negative charge at all locations. Fews et al (2002) extended these measurements to 17 other sites and found a net negative charge at only 3 locations with net positive charge at the other 14 locations. Grabarczyk and Berlinski (2005) found a net positive charge downwind to a distance of 100 m from an ac line after which it reversed to net negative charge. Fews et al (2002) noted that the three cases with excess negative charge occurred during overcast and humid conditions and drew a parallel with the early work by Chalmers (1952) who reported the association of negative charge with periods of mist and fog. However, this does not explain the negative charges found by other workers, including Fews et al (1999). Fews et al (2002), quite rightly, state that the reasons for the preponderance of space charge with a bias towards one polarity, as opposed to another, are not fully understood.

3.3 Electric field measurements

The mean value of the background dc electric field obtained over all power line measurement days was 150 V m^{-1}. As stated earlier, under the power lines, this outdoor electric field was shielded and altered by the presence of the lines and pylons above the points of observation, and it was not possible to determine its actual value. Therefore, the values reported are only an indication of the net charge present above the instrument. In spite of this restriction, some interesting observations were noted. Fig 6 shows a bar graph of the measured dc electric fields at all the power line sites investigated. This graph bears a strong resemblance to the ion concentration graph shown in Fig 2. Also shown is the background field of +150 V m^{-1}. A positive field denotes a downward-directed dc field, indicating the presence of a net positive charge above. Similarly, a negative field denotes an upward directed field, indicating the presence of a net negative charge above.

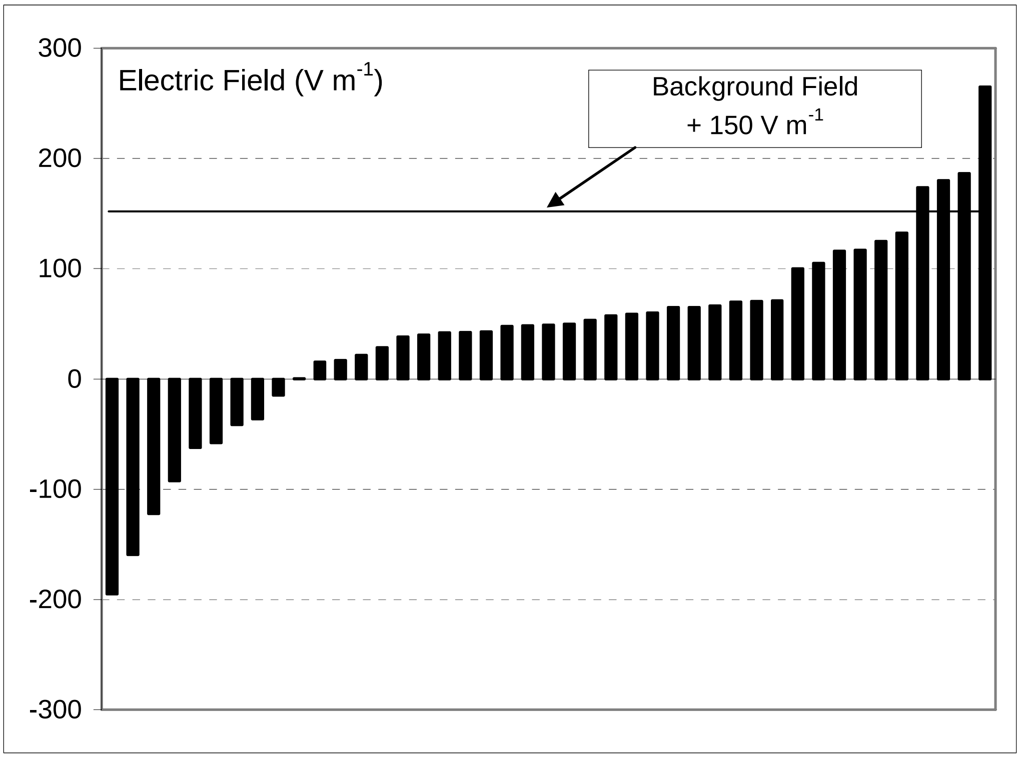

Fig 6: Measured dc electric field values at all power line sites investigated.

Electric field measurements were obtained at 43 power line sites. These are all shown in Fig 6. Only four of these sites showed a dc electric field that was more positive than outdoor, suggesting that in the large majority of cases, the net ion concentration produced by the power lines was negative. However, this conclusion is not realistic because, as stated earlier, the positive electric field of the earth at ground level is significantly decreased due to shielding by overhead power lines and pylons. As the lines were always energized, it was not possible to estimate the true background fields at the measurement sites at ground level. However, note that, in Fig 3, roughly 76% of the sites showed an ion concentration greater than the urban outdoor value. Comparing the data in Fig 6 with the ion concentration distribution in Fig 3, and making a general assumption that 76% of the sites must have electric field magnitudes that are greater than background, it may be estimated that the background electric field under the lines was approximately 50 V m^{-1}.

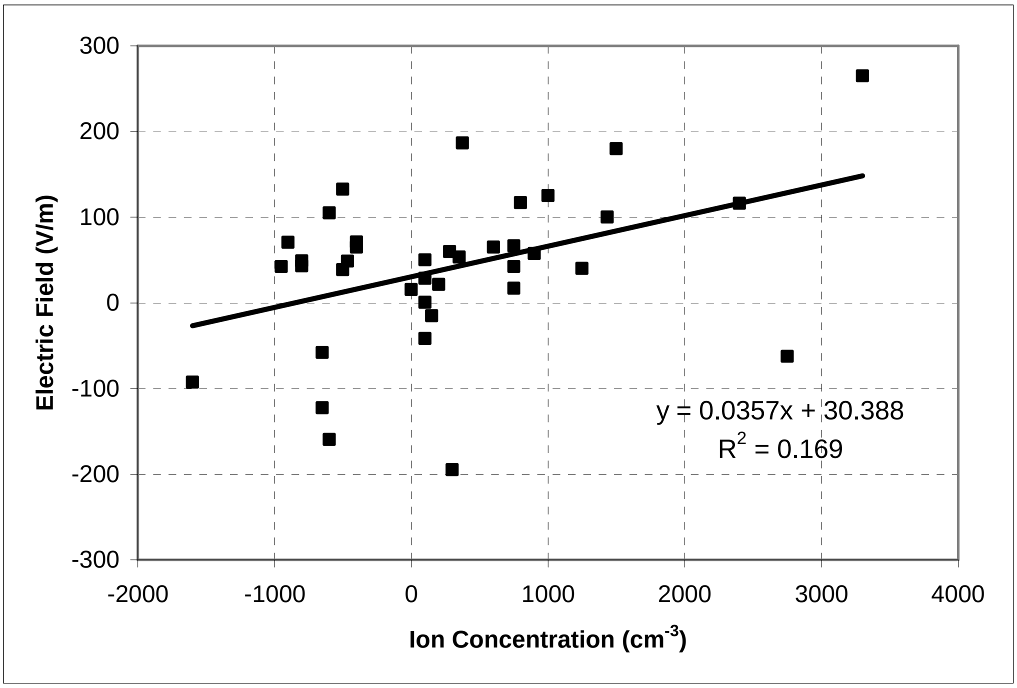

Fig 7: Measured dc electric field vs the ion concentration at the power line sites.

In Fig 7, the measured dc electric field is plotted against the measured ion concentration. Each point is a pair of measurements obtained at a given site. A linear regression analysis showed a statistically significant relationship ($p=0.01$) between the two parameters. A direct correlation is not unexpected because the electric field is dominated by the ambient ion concentration. However, there is a likely reason for the large scatter seen in Fig 7 ($R^2=0.17$): whilst the ion counter measures the ion concentration at a point near the ground, the fieldmeter records the electric field due to all ions above the measurement point. Corona ions are not emitted continuously in time and they are also swept around in the wind, so the instantaneous ion concentration at the ground is often very different to that at higher elevations. This observation suggests that electric field measurements do not necessarily reflect the true air ion concentrations at ground level.

4. Conclusions

This study, carried out in a large urban environment, shows that, while the urban outdoor air ion concentration is about -400 cm^{-3}, concentrations under overhead ac power lines are often higher (mean = +776 cm^{-3}). The values of the absolute ion concentrations at approximately 76% of the sites exceeded the absolute mean urban outdoor value. The mean value for transmission line sites (905 cm^{-3}) was significantly higher than that for sub-transmission line sites (501 cm^{-3}). Both signs of corona charge were observed but the majority of the lines gave rise to a net positive charge. Although this observation agrees with the literature, reasons for it are as yet uncertain. These observations were broadly confirmed by dc electric field measurements carried out concurrently.

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