

MEASUREMENT OF ION MOBILITY SPECTRA FOR RAIN
AND RELATIVE HUMIDITY INDUCED ION
PHENOMENA UNDER 400 KVAC TRANSMISSION LINES

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I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.



Signature of Candidate

5th day of May 1968

ABSTRACT

An ion mobility scanning ion chamber has been developed for field use and the ion concentrations over the mobility range $2,77 - 0,004 \times 10^{-4} \text{ m}^2/\text{V}\cdot\text{sec}$ have been measured for both rain induced ion phenomena and for relative humidity induced ion phenomena under 400 kVAC transmission lines.

The rain induced ion phenomena produced ion concentrations in excess of $1,8 \times 10^{12} \text{ ions/m}^3$, which was the saturation level of the ion chamber. Such a concentration moved by the wind would induce a potential of about 8000 v. in an insulated object of 100 pF capacitance.

The relative humidity induced phenomena shows preferential ion mobilities, and thus molecular clusters, with ion concentrations greater than 10^{11} ions/m^3 . A curve fit relating ion concentration and relative humidity has been obtained with a correlation coefficient better than 84% and the possible water vapour clusters have been identified.

The ion mobility scanning ion chamber is described and also a small potential free spherical probe, with a low perturbing effect on the electric field, used for the measurement of A.C. electric fields, and especially around irregular structures.

IV

FOR MY WIFE
ERICA
WHO ENDURED MY ABSENCE

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CONTENTS

	Page
Declaration	ii
Abstract	iii
Dedication	iv
Acknowledgements	v
Contents	vi
List of Figures	viii
Section 1	ix
Section 2	x
Appendix A	x
Appendix B	x
List of Tables	xi
Section 1	xi
Section 2	xi
Appendix A	xi
Appendix B	xi
List of Symbols	xii
1. Introduction	i
2. Section 1: Rain Induced Ion Phenomena under 400 kVAC Transmission Lines	3
2.1 Introduction	4
2.2 Theoretical Aspects	4
2.3 Effect of Rain	6
2.4 Effect of Wind	8
2.5 Effect of Temperature	9
2.6 Radio Interference (RI)	9
2.7 Audible Noise (AN)	10
2.8 Potential Gradient	10
2.9 Atmospheric Pressure	11
2.10 Discussion	11
2.11 Conclusion	15
2.12 References	16
3. Section 2: Humidity Effects on Ionisation of the Atmosphere Around 400 kVAC Transmission Lines	35
3.1 Introduction	36
3.2 Effect of Relative Humidity on Ion Concentrations	36
3.3 Effect of Air Pressure	37
3.4 Effect of Temperature	37
3.5 Effect of Precipitation	37
3.6 Effect of Wind	38

	Page
3.7 Radio Interference (RI)	38
3.8 Audible Noise	38
3.9 Potential Gradient	39
3.10 Ion Mobility Spectra and Space Charge	39
3.11 Electrical Charges on Mist and Clouds	40
3.12 Ion Mobility	43
3.13 Conclusion	52
3.14 References	54
Appendix A	
Ion Mobility Scanning Ion Chamber	77
Introduction	78
Ion Chamber Construction	79
Air Velocity	83
Ambient Temperature	83
Calibration Tests	84
Relative Humidity and Water Spray Tests	85
Field Results in Rain	86
General	86
References	88
Appendix B	
Spherical Probe for Electric Field Measurements	98
Introduction	99
Spherical Probe	99
Probe Battery Voltage Monitoring	106
Calibration and Results	110
Conclusion	114
References	115

viii

List of Figures
Section 1

Rain Induced Ion Phenomena Around 400 kVAC Transmission Lines

		Page
Figure 1	Test Site	17
Figure 2	Corona Power Loss at Test Site	17
Figure 3	Rainfall	18
Figure 4	+ve Ions Fair Weather Mobility Spectrum Scan 156	19
Figure 5	-ve Ions Fair Weather Mobility Spectrum Scan 156	19
Figure 6	Spacecharge Fair Weather Mobility Spectrum Scan 156	19
Figure 7	+ve Ions Rain Mobility Spectrum Scan 159	20
Figure 8	-ve Ions Rain Mobility Spectrum Scan 159	20
Figure 9	Spacecharge Rain Mobility Spectrum Scan 159	20
Figure 10	+ve Ions Rain Mobility Spectrum Scan 165	20
Figure 11	-ve Ions Rain Mobility Spectrum Scan 165	21
Figure 12	Spacecharge Rain Mobility Spectrum Scan 165	21
Figure 13	+ve Ions Rain Mobility Spectrum Scan 170	22
Figure 14	+ve Ions Rain Mobility Spectrum Scan 170	22
Figure 15	Rain Mobility Spectrum Scan 170	22
Figure 16	Rainfall	23
Figure 17	+ve Ions Rain Mobility $2.77 - 1.0 \times 10^{-4} \text{ m}^2/\text{V.sec}$	24
Figure 18	-ve Ions Rain Mobility $2.77 - 1.0 \times 10^{-4} \text{ m}^2/\text{V.sec}$	24
Figure 19	+ve Ions Rain Mobility $0.85 - 0.6 \times 10^{-4} \text{ m}^2/\text{V.sec}$	25
Figure 20	-ve Ions Rain Mobility $0.85 - 0.6 \times 10^{-4} \text{ m}^2/\text{V.sec}$	25
Figure 21	+ve Ions Rain Mobility $0.037 - 0.02 \times 10^{-4} \text{ m}^2/\text{V.sec}$	26
Figure 22	-ve Ions Rain Mobility $0.037 - 0.02 \times 10^{-4} \text{ m}^2/\text{V.sec}$	26
Figure 23	Spacecharge Sum Scans 200-225	27
Figure 24	Wind Direction	28
Figure 25	Wind Direction	29
Figure 26	Wind Velocity	29
Figure 27	Wind Velocity	29
Figure 28	Temperature	30
Figure 29	Temperature	30
Figure 30	Radio Interference	31
Figure 31	Radio Interference	31
Figure 32	Audible Noise	32
Figure 33	Audible Noise	32
Figure 34	Potential Gradient	33
Figure 35	Potential Gradient	33
Figure 36	Atmospheric Pressure	34

List of Figures
Section 2
Humidity Effects on Ionisation of the Atmosphere Around
400 kVAC Transmission Lines

	Page
Figure 1 -ve Ions Rain Mobility $2.77 - 1.0 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	56
Figure 2 +ve Ions Rain Mobility $0.847 - 0.60 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	57
Figure 3 +ve Ions Rain Mobility $0.54 - 0.4 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	58
Figure 4 +ve Ions Rain Mobility $0.35 - 0.2 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	59
Figure 5 +ve Ions Rain Mobilit. $0.186 - 0.1 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	60
Figure 6 +ve Ions Rain Mobility $0.098 - 0.08 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	61
Figure 7 +ve Ions Rain Mobility $0.079 - 0.06 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	62
Figure 8 +ve Ions Rain Mobility $0.059 - 0.04 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	63
Figure 9 +ve Ions Rain Mobility $0.037 - 0.02 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	64
Figure 10 +ve Ions Rain Mobility $0.019 - 0.01 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	65
Figure 11 +ve Ions Rain Mobility $0.0098 - 0.008 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	66
Figure 12 +ve Ions Rain Mobility $0.0079 - 0.006 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	67
Figure 13 +ve Ions Rain Mobility $0.0059 - 0.004 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	68
Figure 14 -ve Ions Rain Mobility $0.186 - 0.1 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	69
Figure 15 Relative Humidity	70
Figure 16 Air Pressure	70
Figure 17 Temperature	71
Figure 18 Rainfall	71
Figure 19 Windspeed	72
Figure 20 Radio Interference	72
Figure 21 Audible Noise	73
Figure 22 Electric Field	73
Figure 23 Mobility Spectrum +ve Ions, Scan 156-250	74
Figure 24 Mobility Spectrum -ve Ions, Scan 156-250	74
Figure 25 Mobility Spectrum Spacecharge Scan 156-250	74
Figure 26 Stokes Law Mobility versus Molecule Radius with Langevin's Law Computed for $\text{N}(\text{H}_2\text{O})$ Molecules	75
Figure 27 Curve Fit Ions versus Relative Humidity Mobility $0.85 -$ $0.6 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	76
Figure 28 Curve Fit Ions versus Relative Humidity Mobility $0.54 -$ $0.4 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$	76

List of Figures
Appendix A
Ion Mobility Scanning Ion Chamber

	Page
Figure 1 Multiple Plate Ion Chamber	80
Figure 2 Multiple Plate Circuit Diagram	80
Figure 3 Positive Ion Mobility Spectrum	89
Figure 4 Negative Ion Mobility Spectrum	90
Figure 5 Spacecharge Mobility Spectrum	91
Figure 6 Rainfall	92
Figure 7 Positive Ion Mobility Spectrum	93
Figure 8 Negative Ion Mobility Spectrum	94
Figure 9 Spacecharge Mobility Spectrum	95
Figure 10 Construction of Multiple Collector Plate	96
Figure 11 Ion Chamber	97

Appendix B
Spherical Probe for Electric Field Measurements

Figure 1 Principle of Capacitive Spherical Probe	100
Figure 2 Transmitter and Receiver Characteristics	101
Figure 3 Forward Bias Characteristics : Transmitter & Receiver	102
Figure 4 Equivalent Transmitter Circuit	103
Figure 5 Effect of Probe Battery Voltage on Calibration Accuracy	105
Figure 6 Electronic Solution Equation 5	106
Figure 7 Compensated Temperature Error	109
Figure 8 AC Field Meter Calibration	111
Figure 9 Equipotential Plot	112
Figure 10 Spherical Probe	115

List of Tables
Section 1
Rain Induced Ion Phenomena Under 400 kVAC Transmission Lines

		Page
Table 1	Potential Gradient and Ion Current Density	13
Table 2	Current Density Scan 159	14
Table 3	Current Density Scan 165 and 170	14

Section 2
Humidity Effects on Ionisation of the Atmosphere
Around 400 kVAC Transmission Lines

Table 1	Ion Concentration and Ion Mobilities for Environmental Chamber Water Sprays	42
Table 2	Decay Half Lives for Water Vapour	43
Table 3	Ion Mobilities	46
Table 4	Radius of Ion Calculated from Stoke's Law at 288°K, 760 Torr (1.013×10^5 Pascal)	48
Table 5	Values of Mean Velocity $\bar{v}$, Molecular Diameter D , Mean Free Path λ and the Collision Frequency ν calculated from the Kinetic Theory for Gases, 15°C (288°K) and 760mm Hg.	49
Table 6	Curve Fit for Positive Ion Concentration versus Relative Humidity	50
Table 7	Projected Ion Concentrations from Equation 15	51
Table 8	Possible H ₂ O Clusters	52

Appendix A

Table 1	Multiple Plate Ion Chamber Mobility Values $\times 10^{-4}$ m ² /V.sec	81
Table 2	Temperature Stability of Electrometer Module using $10^{11} \Omega$ Resistor	84
Table 3	Decay Half Lives for Water Vapour	85

Appendix B

Table 1	Calibration of Spherical Probe	111
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List of Symbols

Mobility (ion)	$(m^2/V.sec)$	κ
Applied frequency (Hz)		f
Relative air density		δ
Atmospheric pressure (Pascals)		P
Conductor radius		a or r
Absolute temperature ($^{\circ}K$)		T
Separation between centres of conductor bundle		S
Voltage to ground (RMS)		V_e
Corona inception voltage		V_o
Corona power loss (Fair weather)		P_{FW}
Corona power loss (Rain)		P_R
Potential gradient		E
Current density (A/m^2)		J
Ion concentration (ions/ m^3)		n
Charge on electron		e
Decibel		dB
Charge (Coulombs)		Q
Coulombs		C
Diffusion coefficients with polarity		D^-, D^+
Relative humidity (%)		RH
Gas density		ρ
Mean free path (ions)		λ
Permittivity of free space		ϵ

INTRODUCTION

This dissertation reports the observations made in the field under 400KVAC Transmission Lines of the ionisation of the atmosphere from two different climatic conditions: rain and relative humidity. The ion concentrations over a range of ion mobilities, from 2,7 to $0,004 \times 10^{-14} \text{ m}^2/\text{V.sec.}$, have been measured in a series of experiments which are believed to be the first time the ion mobility spectra under a high voltage transmission line has been obtained.

To be able to make these measurements, it was necessary to build a mobility scanning ion chamber, to test it under simulated field conditions, to build a weather station and to programme a data acquisition system, such that the whole instrumentation could be left in the field for a number of days (14) unattended, during which time near simultaneous measurements of positive and negative ion concentrations are obtained for one of 13 ion mobilities. The near simultaneous time between the positive and negative ion measurements is one minute: the time of one scan of positive and negative ion concentrations at the 13 ion mobilities takes 30 minutes inclusive of two readings of climatic and other data during that period.

Section 1 of the dissertation deals with the rain induced ion phenomena. This takes place when rain wets the energised conductors of the transmission line and corona power loss occurs: in the field condition this would be about 170kW/km for rainfall of 60mm/hour. The ion clouds so generated are an abrupt phenomena coincident with the rainfall, but existing for long periods of time after the rain has ceased. Section 2 deals with the humidity effects on the ionisation of the atmosphere. This is a more subtle effect since the relative humidity built up on a daily cycle to a point where fog occurred. At this point where the relative humidity is high the ion concentrations increased with a marked preferential ion mobility, which is an indication of the preferential clustering of the water vapour molecules. From these observations a curve fit has been obtained for ion concentrations versus relative humidity with a correlation coefficient of better than 80%.

The two appendices describe the essential instrumentation. Appendix 1 describes the mobility scanning ion chamber, the testing of the ion chamber and the ion mobility spectra obtained from the ion chamber from water spray induced ionisation in a closed atmosphere, and from rainfall in the field.

Appendix 2 describes an AC field meter. Such a meter was required to record the AC field under the transmission lines and the effects that ion clouds would have upon the reading. The instrument described in Appendix 2 was developed from the field instrument: it is essentially potential free due to the very high insulation offered by the optical fibre transmission of data to ground level, it offers a minimal perturbation of the field because it is spherical and with a small diameter of about 60mm. The sphere, being powered by small coin size batteries, has an accuracy in high fields determined by the battery voltage, and consequently it is essential to know the battery voltage when the instrument is used for plotting equipotential points around irregular structures, such as conductor clamps. This has been achieved in a novel manner such that the battery voltage can be monitored continuously.

The four reports which comprise this dissertation are taken individually, since they investigate different aspects albeit of the same subject. For this reason each report is composed as an individual report with its own references, since it is hoped that by this means the subject is presented in a more clear and rational manner.

SECTION 1

RAIN INDUCED ION PHENOMENA UNDER 400 KV AC TRANSMISSION LINES

Abstract: The ion concentrations for 13 ion mobilities from 2.77 to $0.004 \times 10^{-4} \text{ m}^2/\text{V} \cdot \text{sec}$ have been measured in rain conditions under a 400 kV AC transmission line. Ion concentrations greater than $1.8 \times 10^{12} \text{ ions/m}^3$ have been found.

Introduction

The measurement of the ion current density under HV DC transmission lines has been investigated [1] [2] [3] in fair weather conditions where the DC corona effects are the worst case, whereas the AC corona effects are the worst case during rain [11].

The ion mobility values generally found in fair weather conditions are [1], for positive ions, $1.99 \times 10^{-4} \text{ m}^2/\text{V}\cdot\text{sec}$ and negative ions, $1.4 \times 10^{-4} \text{ m}^2/\text{V}\cdot\text{sec}$, although more recent work [2] suggests that both positive and negative ion mobilities of $1.7 \times 10^{-4} \text{ m}^2/\text{V}\cdot\text{sec}$ could be used. Laboratory measurements [3] suggest $2.1 \times 10^{-4} \text{ m}^2/\text{V}\cdot\text{sec}$ for positive ions and $1.36 \times 10^{-4} \text{ m}^2/\text{V}\cdot\text{sec}$ for negative ions in dry air.

This paper presents the results of measuring the ion concentration for ion mobilities of $2.77 \times 10^{-4} \text{ m}^2/\text{V}\cdot\text{sec}$ to $0.004 \times 10^{-4} \text{ m}^2/\text{V}\cdot\text{sec}$ [4] during rain conditions under 400 kV AC.

Theoretical Aspects

The AC corona power loss in fair weather is found from Peek's equation [5]. The geometry of the line influences the surface potential around the conductors which determines the corona inception potential, and the corona power loss is inversely proportional to the relative air density.

$$P = \frac{241}{\delta} (f + 25) \sqrt{\frac{a}{S}} (V_e - V_0)^2 10^{-5} \text{ kW/km} \quad (1)$$

where f is the applied frequency, δ = relative air density ($= 2.941 \times 10^{-3} \frac{P}{T}$, where P = atmospheric air pressure in Pascals and T is absolute temperature), a = conductor radius, S the separation between the centres of the conductor, V_e is the RMS voltage to ground and V_0 is the corona inception voltage. This latter is given as 21.1 kV/cm by Cobine [5] and 19.7 kV/cm elsewhere. [1].

The corona loss in rain is proportional over most normal rates to the logarithm of the rainfall rate [6].

$$P_R = P_{FW} + \left[\frac{V}{\sqrt{3}} J r^2 \ln(1 + KR) \right] \sum_{i=1}^n (E_i^m) \quad (2)$$

where P_{FW} = corona power loss for fair weather, V = phase to phase voltage in kV, r = radius of conductor in cm, n = total number of conductors, E = potential gradient of the underside of each conductor, kV/cm, m = an exponent = 5, K = a wetting coefficient = 10 if R is in mm/hour, R = rainfall rate, J = loss-current constant. $J = 5.35 \times 10^{-10}$ for 500 kV and 700kV, = 7.04×10^{-10} for 400 kV configurations. The term $\sum [E_i^m]$ requires that each of the n conductors of the line are treated separately, the gradient on the underside of the conductor is raised to the fifth power and the results are summed.

Figure 1 shows a sketch of the site where the ion measurements were made. There are three 3 phase lines spaced 30 m centre wire to centre wire. Each conductor bundle forms an equilateral triangle of side 38.1 cm using aluminium conductors of 35.5 mm diameter. The phase to phase spacing is 10.8 m. The ion chamber is situated 21 m from the centre line of the central line and an audio noise monitor and electric field monitor are situated under the centre line. 800 m to the west is a 400 kV switchyard and the area is rural with motor vehicles only in the morning and evening going into the switchyard from the western entrance. Figure 2 shows the corona power loss computed from the Bonneville Power Administration computer programme. From the same programme, the radio interference (RI) is given as:

Fair L50, 39 dB : Rain L50, 56 dB.

The audible noise (AN) is given as:

Fair L50 16 dB : Rain L50 41 dB.

The ion chamber completes a scan of 13 positive and 13 negative ion concentration measurements for each of the 13 ion mobility values in 30 minutes. The negative ion concentration is measured by the same ion chamber one minute after the positive ion measurement so they are essentially simultaneous. Climatic and other parameters are measured twice for each 30 minute scan.

Effects of Rain

The rainfall was measured by a tipping bucket system and the climate conditions were somewhat abrupt thunderstorms where there was a heavy rainfall preceded by fair weather.

Figure 3 shows the rainfall measured. The total rainfall is 56.8 mm over scans 158-161 which represent 90 minutes giving a rainfall rate of 37.87 mm/hour which from Figure 2 indicates a corona power loss of about 148 kW/km.

The fair weather ion spectra for scan 156 are shown in Figure 4, +ve ions, Figure 5, -ve ions, and Figure 6 the spacecharge being the negative ions subtracted from the positive ions for the related ion mobility. Positive ions ($280 \times 10^6/\text{m}^3$) predominate for the light ions (O_2^+ , N_2^+ , CO_2^+) and there are also +ve ions in the $0.037 - 0.01 \times 10^{-4} \text{ m}^2/\text{V} \cdot \text{sec}$ mobility range. The ion chamber is not specifically designed for natural background ion levels, where these levels represent an ion current of about 10^{-13} amperes, and about 1 mV output. The ion chamber reads a maximum of 10^{-9} amperes representing 10V output, and this corresponds to 1.56×10^{12} ions/ m^3 .

Ion mobility spectra taken for scan 159, at which point some 49 mm of rain has fallen, are shown in Figure 7 (+ve), 8 (-ve) and 9 (spacecharge). From these it can be seen that the ion chamber has saturated at about 2×10^{12} ions/ m^3 in one instance for positive ions and two instances for negative ions. These are reflected in the spacecharge spectra where the overall effect appears to be negative. It should be pointed out that if the ion current density measurements had been done with a "Wilson plate" method [7] [8] the value would represent the integral of the positive and negative ion concentrations, since the current density J , is given by [9] [10].

$$J = ne k \tilde{E} \quad (3)$$

where n is the ion concentration, e the electronic charge, k the ion mobility and $\tilde{E}$ the potential gradient.

Figures 10 (+ve), 11 (-ve) and 12 (spacecharge) for scan 165 shows the mobility spectra when the rain has almost ceased and 4.5 hours after the rain commenced (y scans at 30 min. per scan). Here, the positive ions predominate with the ions $> 2 \times 10^{12}$ ions/m³ over the mobility range $0.85 - 0.2 \times 10^{-4}$ m²/V.sec, with only the initial mobility range of $2.77 - 1.0 \times 10^{-4}$ m²/V.sec showing a saturated negative ion peak. These show in the spacecharge spectra that the integrated ion current density would have been positive.

Figures 13 (+ve) 14 (-ve) and 15 (spacecharge) for scan 170 shows the spectra for scan 170, which is 6.5 hours after the initial rainfall, and the spacecharge spectrum is essentially that for Figure 12. (Note that the spacecharge figures are lines, whereas the figures for +ve and -ve ions are logarithmic in scale).

From these spectra it can be seen that the important ion mobility values for rain are the first two, being $2.77 \times 1.0 \times 10^{-4}$ m²/V.sec, $0.85 - 0.6 \times 10^{-4}$ m²/V.sec, and also that for $0.037 - 0.02 \times 10^{-4}$ m²/V.sec there appears to be a shift from the light ions to the next lower spectral value and a special ion concentration in the latter ion mobility value. This must be due to preferential H₂O clusters (+ve ion groups) and attachments (-ve ion groups) with a grouping of N (H₂O) for the +ve ion peak at mobility $0.037 - 0.02 \times 10^{-4}$ m²/V.sec where N is an integer representing the number of molecules. Figure 16 shows a long time period with five incidents of rain, one of which reaches 48 mm at scan 225. The period of 50 scans covers a time of 25 hours. Figures 17 and 18 show respectively the +ve and -ve ion concentrations for the mobility range $2.77 - 1.0 \times 10^{-4}$ m²/V.sec and the long period (6.5 hours) of saturation ($> 2 \times 10^{12}$ ions/m³) for -ve ions following on the heavy rainfall period commencing with scan 224.

Figures 19 and 20 show the ion concentration for the mobility range $0.85 - 0.6 \times 10^{-4}$ m²/V.sec, and here the +ve ions saturate in a gradual build up from scan 209 where no rain is indicated in Figure 16, Figures 21 and 22 show the ion concentrations over the mobility range $0.037 - 0.02 \times 10^{-4}$ m²/V.sec, and these, whilst showing concentrations $> 10^{11}$ ions/m³ are not large enough to saturate the ion chamber. The evidence indicates that the heavy rainfall commencing on scan 224 terminates the light positive ions (Figure 11) and

initiates the very large ion concentration (Figure 15). No such coincidence is shown in Figures 19 and 20, but Figure 22 shows the -ve ions being terminated with the period of heavy rainfall.

Figure 23 shows the spacecharge sum for the scans 210 to 225 being the sum of ion concentrations of all ion mobility for each scan from the rainfall which commenced in scans 202 - 204. This spacecharge shows an increasing positive spacecharge which becomes negative at the commencement of the heavy rainfall.

Effects of Wind

Figures 24 and 25 show the wind direction relating to the ion measurements of Figures 3 - 15 and Figures 10 - 23 respectively. For the same period, Figures 27 and 28 show the wind velocity.

The wind direction is shown on a linear scale with north at 360° and at 0° , 180° is south.

Over the periods for the ion spectra for scans 156 - 159, 165 and 170, the wind direction was north, with scan 165 and scan 170 in an easterly direction.

Consequently, scan 156 is representative of the corona from the northernmost line, whereas 165 and 170 could be representative of a wind blowing along the lines towards the ion chamber from the east: this would perhaps explain the very high concentrations present.

The wind velocities for the scans 156, 159, 165 and 170 was low, of the order of 1 m/sec (3.6 km/hour) as shown in Figure 26. For scans 200-250, the wind direction was relatively steady from the northwest until scan 220 where it was generally easterly, and then became northerly thereafter. The wind velocity was generally light; 0.3 m/sec. except for a peak of 9 m/sec (32.4 km/hour) coincident with the heavy rain at scan 225. The very large +ve ion concentrations do not appear to fit the wind pattern, except the -ve ions of Figure 19 and Figure 20 fall into the east wind period. However, the light mobility ions coincide with the high wind velocity: +ve ions cease, -ve ions commence as shown in Figures 17 and 18.

The effect of high wind velocities at the advent of a storm would give turbulent mixing of the ions. Why this should initiate or stop ions of one polarity is not clear.

Effect of Temperature

The rainfall is coincident with the relatively abrupt temperature drops of Figures 28 and 29. In general, the temperature drops from 28°C to 15°C. This change of 13°C could be expected to change the vertical height of the transmission line conductors, especially with rain falling upon them, and therefore the potential gradient. There does not appear to be any coincidence with the temperature, although equation (1) implies a degree of direct proportionality. The effect is no doubt masked by the more intense effect of the rain.

Radio Interference RI

Radio interference is a direct result of corona: whether this is due to the conductor, or to the insulators. Cap arcs are a strong radio noise source, and these can arise from imperfect connections, or from a foreign body on the line. Figures 30 and 31 show the relevant RI values obtained at 850 kHz and 20 dBs attenuation. The fair weather level is about 67 dBs (relative to 1μV), which is 26 dBs greater than that predicted. The rain values are; for Figure 30 at scan 159, 70 dB, being 16 dBs greater than predicted for the L50 rain value. This peak does, however, coincide with the rainfall.

The rainfall peaks of scans 225 and 230 produce very small increases in RI, being 14 dBs greater than predicted.

The inference here is that there is a gap noise source providing some 26 dBs of RI in fair weather, although such noise usually diminishes with rain and this is indicated by the RI being only 14-16 dBs higher than the predicted value for rain.

Audible Noise (AN)

The BPA prediction for audible noise is exceeded by the measured values shown in Figures 32 and 33. These figures are not A weighted.

The lowest value of some 48 dB is 32 dBs greater than the fair weather L50 prediction of 16 dB. The rain predicted value L50 is 41 dB. Figure 32 does show an increase in AN coincident with the inception of rain at scan 158 and Figure 33 shows two AN peaks coincident with rain fall at scans 204, 224, 230 and 245. However, there does not appear to be a general AN increase coincident with ion concentration, and it is thought that this is masked by the gap noise and that the AN peaks are storm related rather than corona related.

Potential Gradient

The remotely read potential gradient meter does not show a rain related peak in Figure 34. However, the potential gradient in Figure 35 does show the two heavy rainfall peaks of scans 224 and 230. The fluctuations in Figure 34 are thought to be due to ion clouds, but the large change in Figure 35 from 1.4 kV/m to 0.6 kV/m at scan 218, which then reverses at scan 250 does not seem to be related to the ion clouds. However, the potential gradient instrument is about 21 m from the ion chamber so there could have been an intense ion cloud at that point which was not measured at the ion chamber.

This large drop in potential gradient does commence with the wind direction change (see Figure 25) but it does not terminate with a similar wind direction change, and wind movement of the instrument can be ruled out.

The potential gradient meter would show a reading of about 20 kV/m if the body of the instrument, or one of the electrodes, became connected to earth. This would then be the potential at that point in space. This does not explain the two peaks at scan 224 and 230.

The instrument, which is an AC reading unit, is switched on via an optical fibre system just prior to a measurement. The reading of the instrument for

the data acquisition system takes approximately 5 seconds. There is a possibility that there was lightning close by which caused these peaks.

The BPA prediction was 1.4 kV/m at the instrument site at a height of 1.8m. The instrument reads initially (before rain) 1.2 kV/m which is in good agreement.

Atmospheric Pressure

The air pressure variations of Figure 36 range from 0.846×10^5 P at 28°C to 0.825×10^5 P at 18°C. The relative air density, δ , varies only from 0.827 to 0.834 giving rise to a change in the first term of equation (1) of 0.83%. This effect in the fair weather corona is imperceptible in relation to the extreme reactions in corona due to rain.

There appears no change in the ion concentrations for the low pressure depression between scans 210 and 240.

Discussion

The ion concentrations described in this paper are the spacecharge densities for different mobilities. Where the net spacecharge, being the sum of all the spacecharges, is remote from an electric field, or where that field, E V/m, provides a velocity, V m/sec, which is small compared to the wind velocity, w , then the convection current J_C amps/m², is given by [9]:

$$J_C = w Q \text{ amps/m}^2 \quad (4)$$

when

$$w > v = k E^2 \text{ m/sec}$$

and $Q = n e$ coulombs, the total unipolar ion concentration multiplied by the electronic charge.

For an insulated conducting object with a capacitance C farads to ground, then

the potential to which it will rise depends only upon

$$V = \frac{1}{C} \int J_C dt \quad (5)$$

This requires that the wind is stable and non-turbulent so that the ion cloud is driven at a steady velocity into the conducting object.

For a wind velocity of 1 m/sec, the convection current for the spacecharge of Figure 9 would be -6.08×10^{-7} amps/m²/sec and for Figure 12, $+8.64 \times 10^{-7}$ amps/m²/sec, and these would induce a potential of - 6080 volts and 8640 volts respectively into the 100 pF capacitance.

Where the electric field provides a dominant effect over the wind velocity, then the ion concentrations at different mobilities provide the ion current density as given in equation (3).

To equate the present findings with those obtained from high voltage DC transmission lines is difficult because the conductor potential change in the AC case causes the ions to move in opposite directions in each half wave. Further, the ion current density refers to the vertical component.

Table 1 shows the 75 percentile values [12] obtained under fair, fog and rain weather conditions: to arrive at the ion concentration the problem is what ion mobility should be used.

The ion concentration was calculated using the generally accepted values for fair weather ion mobilities. The rain value for the ion mobility is $\sim 0.7 \times 10^{-4}$ m²/V.sec as shown in Figure 19, and the ion concentrations required to provide the same ion current density under rain are therefore much greater.

Similar ion current densities for fair weather have been found by Maruvada [13]: the maximum values at the 99% cumulative probability level were about -850 nA/m² and $+650$ nA/m² with an electric field of 45 kV/m. This gives an ion concentration of 6.56×10^{11} ions/m³ for negative ions and 6.45×10^{11} ions/m³ for positive ions using the fair weather ion mobilities of 1.8×10^{-4}

$\text{m}^2/\text{V}.\text{sec}$ for negative ions and $1.4 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$ for positive ions. From Figure 9 the spacecharge for scan 159, the ion current density would be the scan of the currents due to the different ion mobilities. This applies also to the spacecharges found for scans 165 and 170.

Table 1 Potential Gradient and Ion Current Density
400 kV DC 12.1m Pole spacing 10.7 m Line height

	Fair	Fog	Rain	
Electric Field				
kV/m				
+ve	22.5	22.5	30	
-ve	20	28	28	
Non-Current Density				
$\times 10^{-9} \text{ A/m}^2$				
+ve	60	80	100	
-ve	40	100	100	
Ions $\times 10^{11}/\text{m}^3$				
+ve	1.19	1.59	1.49	$k = 1.4 \times 10^{-4} \text{ m}^2/\text{V}.\text{se}$
-ve	0.69	1.24	1.24	$k = 1.8 \times 10^{-4} \text{ m}^2/\text{V}.\text{se}$
+ve	-	-	2.98	$k = 0.7 \times 10^{-4} \text{ m}^2/\text{V}.\text{se}$
-ve	-	-	3.19	$k = 0.7 \times 10^{-4} \text{ m}^2/\text{V}.\text{se}$

The electric field external to the ion chamber is 1.4 kV/m (at 50 Hz). Table 2 shows the ion current densities for scan 159 and Table 3 shows the ion current densities for scans 165 and 170 for these are virtually identical.

These two tables show the effects of different ion mobilities, and these would be the currents induced into an insulated conducting object at that point in the electric field. The current found in Table 2 would produce -813 volts across an object of 100 pF. The true values of the ion concentration are unknown and the ion mobility spectra represent 30 minutes between the first

and last mobility measurements, so although the ion concentrations at the same mobility for positive and negative ions represent a time difference of only one minute, this does not necessarily represent a true spectra since at the

Table 2 Ion Current Density Scan 159

Mobility $\times 10^{-4} \text{ m}^2/\text{V} \cdot \text{sec}$	Ions $\times 10^{12}/\text{m}^3$	+ J $\times 10^{-8} \text{ A}/\text{m}^2$	-J $\times 10^{-8} \text{ A}/\text{m}^2$
1.8	1.8		7.26
0.7	1.8		2.82
0.5	1.8	2.02	
0.03	1.0		0.067
$\int J$		2.02	10.147
$J^+ - J^-$			$-8.128 \times 10^{-8} \text{ A}/\text{m}^2$

Table 3 Ion Current Density Scans 165 and 170

Mobility $\times 10^{-4} \text{ m}^2/\text{V} \cdot \text{sec}$	Ions $\times 10^{12}/\text{m}^3$	+ J $\times 10^{-8} \text{ A}/\text{m}^2$	- J $\times 10^{-8} \text{ A}/\text{m}^2$
1.8	1.8		7.26
0.7	1.8		
0.5	1.8	2.82	
0.3	1.8	2.02	
0.03	1.8	1.21	
$\int J$		6.171	7.26
$J^+ - J^-$			$-1.09 \times 10^{-8} \text{ A}/\text{m}^2$

final mobility measurement the values measured at the initial mobility were taken 30 minutes previously. In the field under storm conditions the wind direction and velocity could have changed the ion concentration.

Conclusion

Very large ion concentrations have been measured under 400 kV AC transmission lines as a result of rain. These concentrations would appear to exceed by an order of magnitude those measured around HV DC transmission lines, but it is thought that the ion spectra has been shown for the first time.

The saturation of the ion chamber is due to the very high corona loss under heavy rain. What is of great interest is the long length of time that the ion clouds exist, and also the abrupt changes in the ion cloud polarity.

These changes of ion cloud polarity are not easily explained by electric field or ionisation factors. The most probable reason is turbulent wind mixing.

Whilst a unipolar ion cloud will exist under conditions where the wind velocity has a greater effect on the direction of the ion cloud than the electric field, in the immediate area around the transmission line the ion mobility spectra determines the ion current density which would charge an insulated conducting object. With the presence of both positive and negative ions, this ion current density varies greatly.

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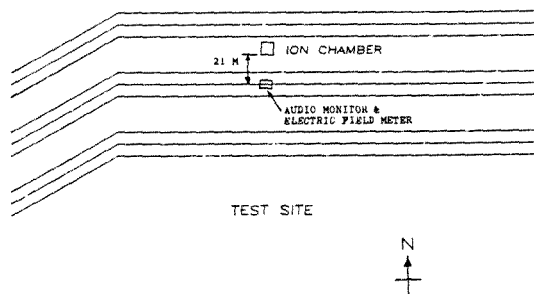


Figure 1
Test Site

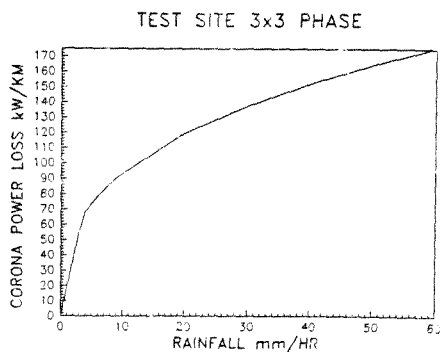
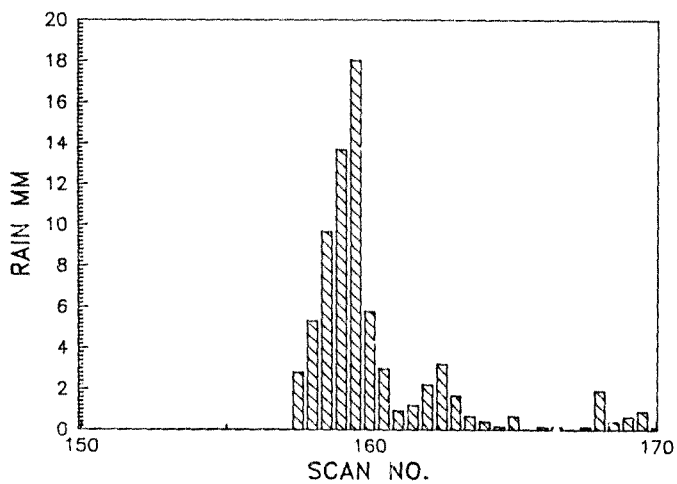


Figure 2
Corona Power Loss at Test Site

Figure 3
Rainfall



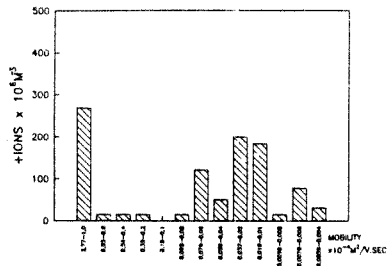


Figure 4

+ve Ions, Fair Weather, Mobility Spectrum Scan 156

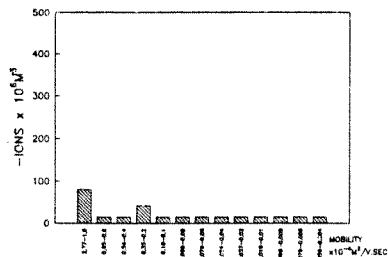


Figure 5

+ve Ions, Fair Weather, Mobility Spectrum Scan 156

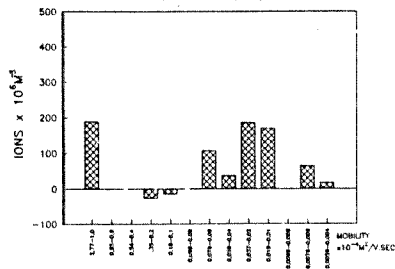


Figure 6

Spacecharge, Fair Weather, Mobility Spectrum Scan 156

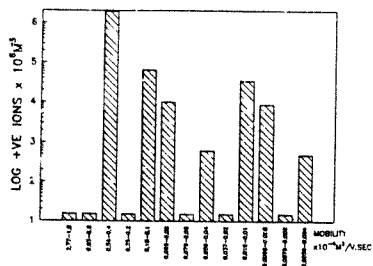


Figure 7

-ve Ions, Rain, Mobility, Spectrum Scan 159

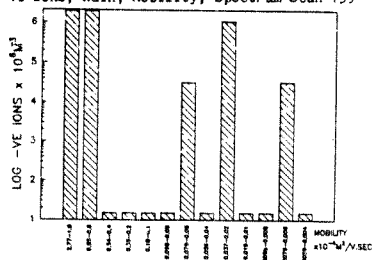


Figure 8

-ve Ions, Rain, Mobility Spectrum Scan 159

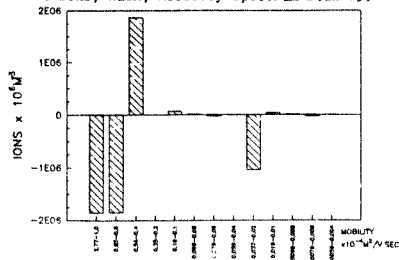


Figure 9

Spacecharge, Rain, Mobility Spectrum Scan 159

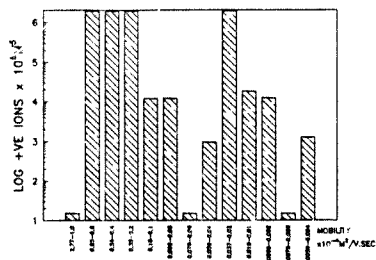


Figure 10

+ve Ions, Rain, Mobility Spectrum Scan 165

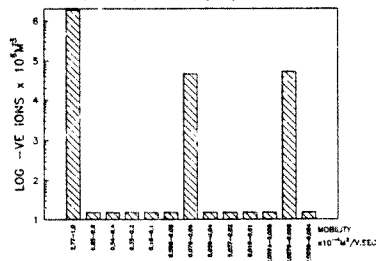


Figure 11:

-ve Ions, Rain, Mobility Spectrum Scan 165

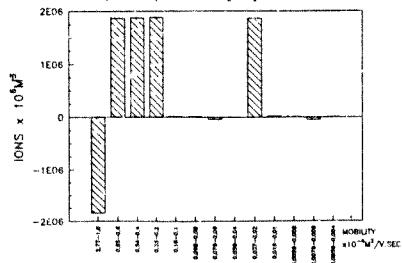


Figure 12

Spacecharge, Rain, Mobility Spectrum Scan 165

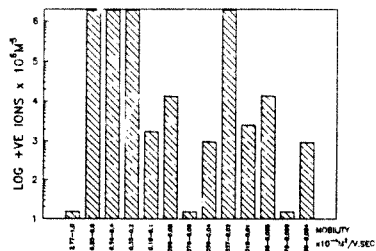


Figure 13

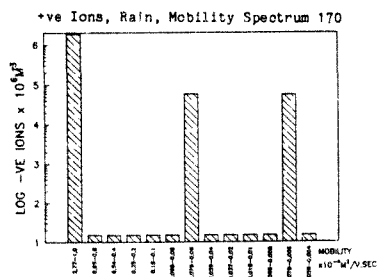


Figure 14

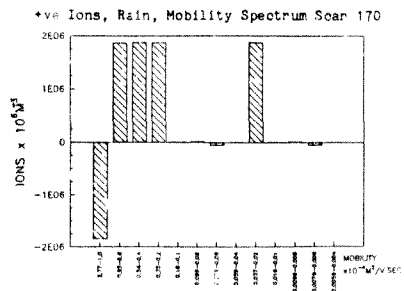


Figure 15

Rain, Mobility Spectrum Soan 170

PRECIPITATION

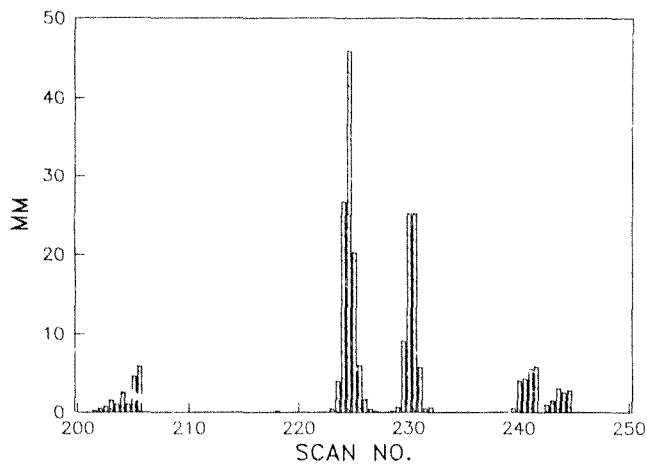


Figure 16
Rainfall

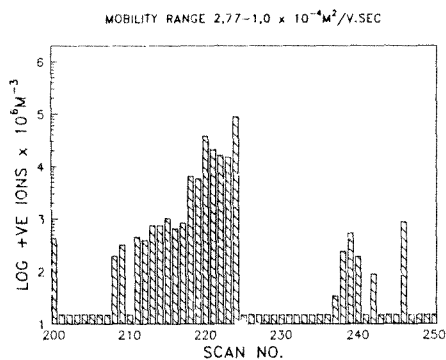


Figure 17

+ve Ions, Rain, Mobility $2.77 - 1.0 \times 10^{-4} \text{ m}^2/\text{V.sec}$

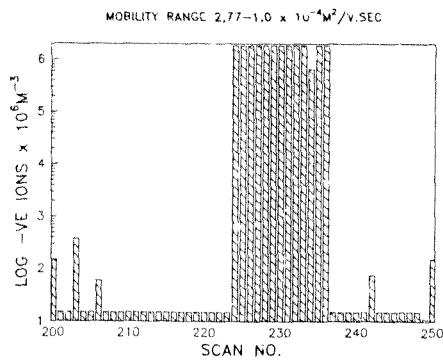


Figure 18

-ve Ions, Rain, Mobility $2.77 - 1.0 \times 10^{-4} \text{ m}^2/\text{V.sec}$

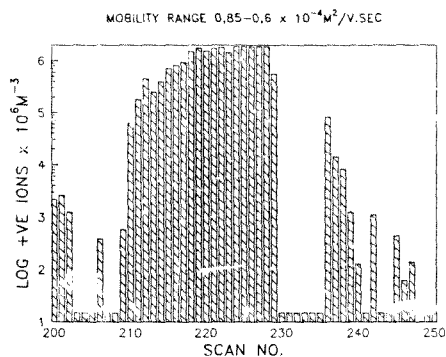


Figure 19

+ve Ions, Rain, Mobility $0.85 - 0.6 \times 10^{-4} \text{ m}^2/\text{V.sec}$

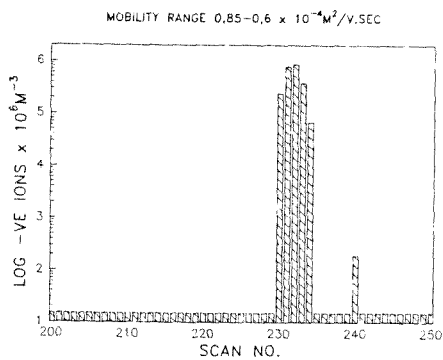


Figure 20

-ve Ions, Rain, Mobility $0.85 - 0.6 \times 10^{-4} \text{ m}^2/\text{V.sec}$

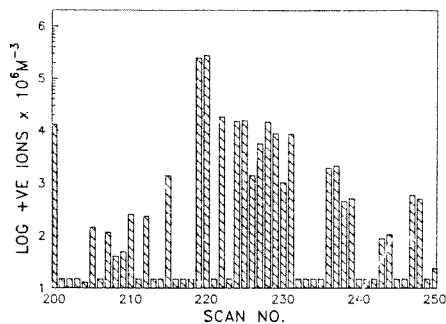
MOBILITY RANGE $0.037 - 0.02 \times 10^{-4} \text{ m}^2/\text{V} \cdot \text{SEC}$ 

Figure 21

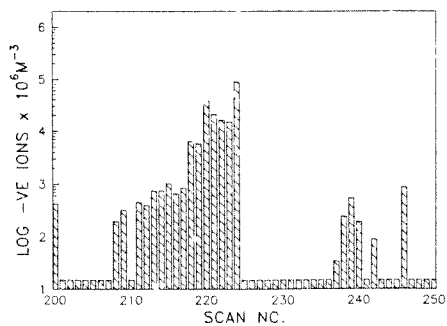
+ve Ions, Rain, Mobility $0.037 - 0.02 \times 10^{-4} \text{ m}^2/\text{V} \cdot \text{sec}$ MOBILITY RANGE $0.037 - 0.02 \times 10^{-4} \text{ m}^2/\text{V} \cdot \text{SEC}$ 

Figure 22

-ve Ions, Rain, Mobility $0.037 - 0.02 \times 10^{-4} \text{ m}^2/\text{V} \cdot \text{sec}$

SPACE CHARGE SUM

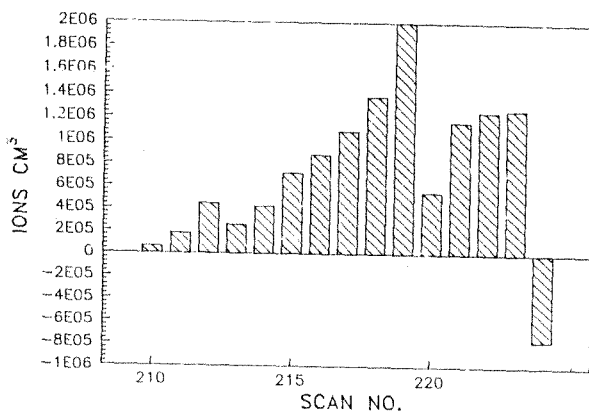


Figure 23

Spacecharge Sum. Scans 200-225

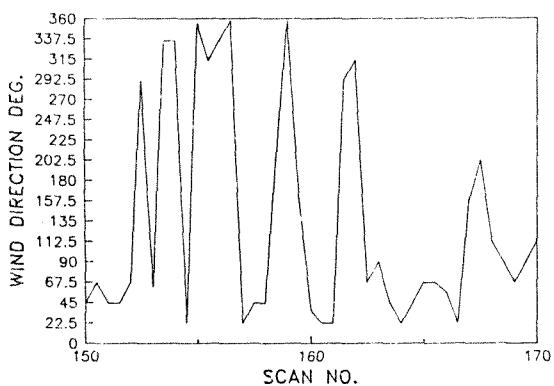


Figure 24

Wind Direction

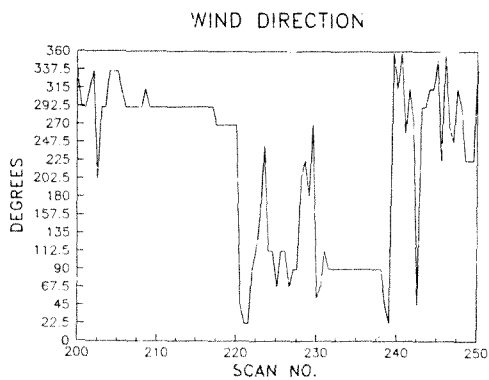


Figure 25

Wind Direction

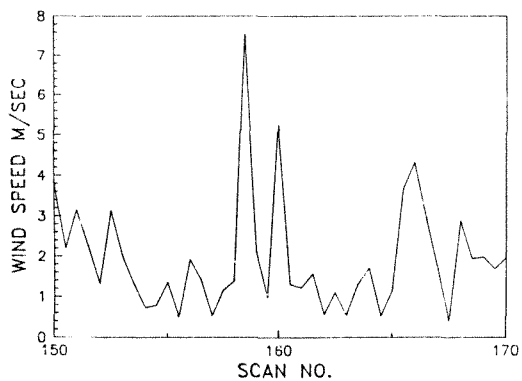


Figure 26

Wind Velocity

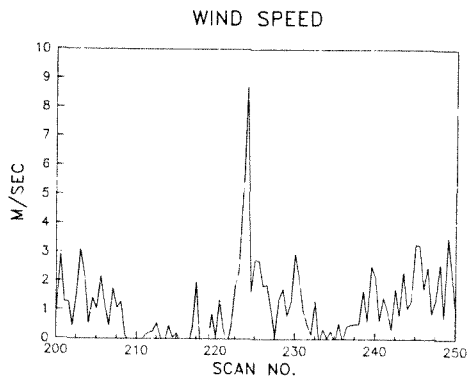


Figure 27

Wind Velocity

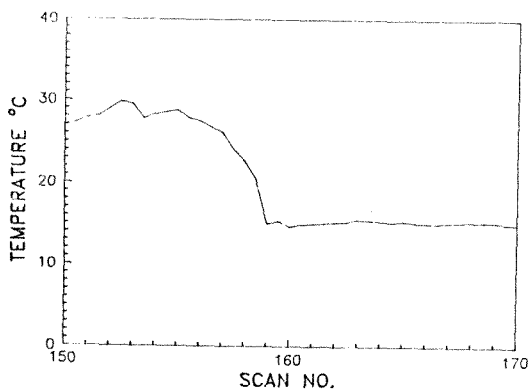


Figure 28

Temperature

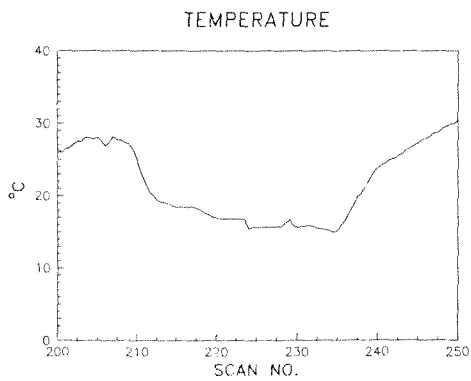


Figure 29

Temperature

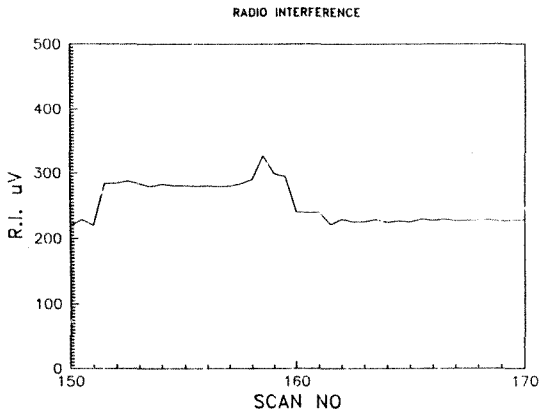


Figure 30

Radio Interference

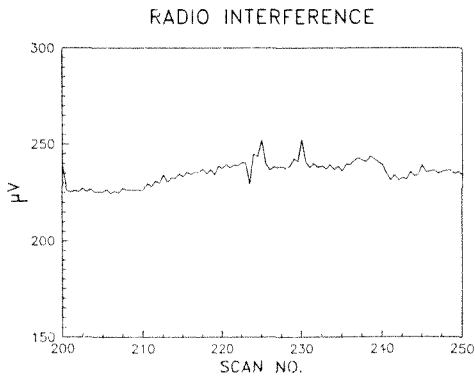


Figure 31

Radio Interference

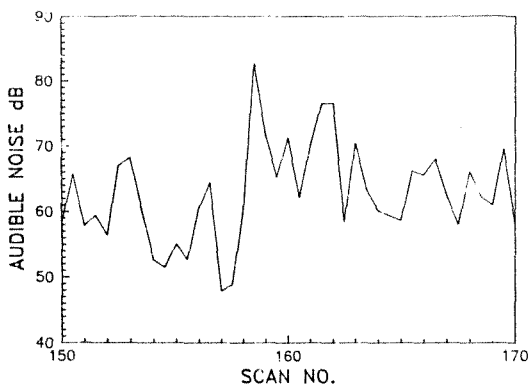


Figure 32

Audible Noise

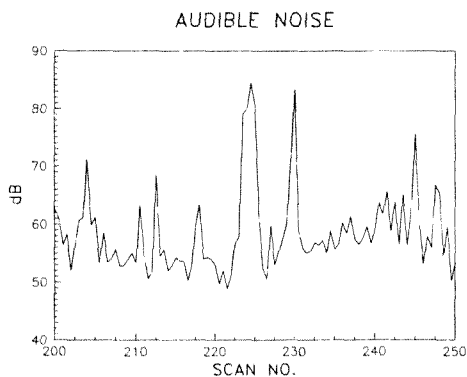


Figure 33

Audible Noise

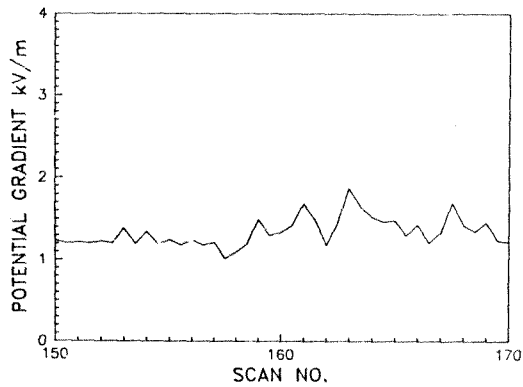


Figure 34

Potential Gradient

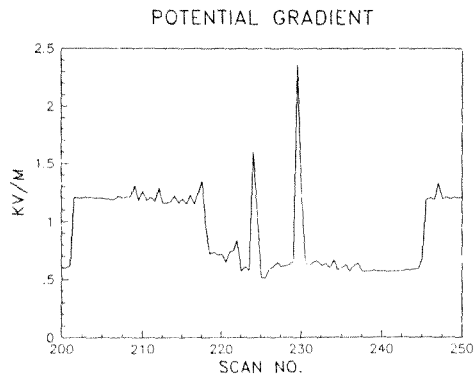


Figure 35

Potential Gradient

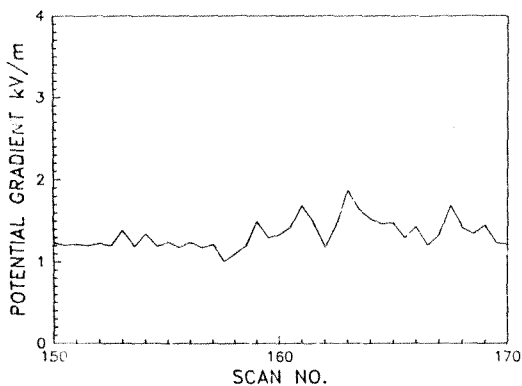


Figure 34

Potential Gradient

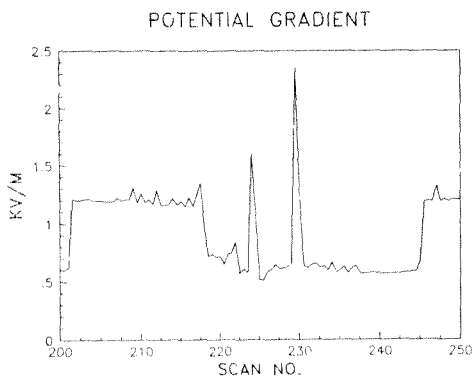


Figure 35

Potential Gradient

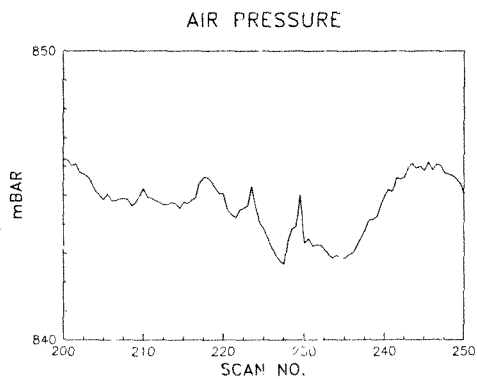


Figure 36

Atmospheric Pressure

SECTION 2

HUMIDITY EFFECTS ON IONISATION OF THE ATMOSPHERE AROUND 400 KV AC TRANSMISSION LINES

Abstract: Using a multiple plate aspirated ion chamber the ion concentrations for ion mobility from 2.77 to $0.004 \times 10^{-4} \text{ m}^2/\text{V} \cdot \text{sec}$ have been measured during a period when the relative humidity varied from nearly 100% to 40% on a daily basis. Concentrations greater than $1.5 \times 10^{12} \text{ ions/m}^3$ have been found. The average spacecharge density is shown to be positive for a section of the time with individual ion concentrations in excess of $2 \times 10^{11} \text{ ions/m}^3$. The curve fit for certain ion mobilities has a correlation coefficient of better than 80% for ion concentration versus relative humidity. Some possible H_2O molecular groups are identified from the ion mobility spectra.

Keywords: Transmission Lines; Ionisation; Relative Humidity; Ion Mobility.

SECTION 2

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Abstract: Using a multiple plate aspirate ion chamber the ion concentrations for ion mobility from 2.77 to $0.004 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$ have been measured during a period when the relative humidity varied from nearly 100% to 40% on a daily basis. Concentrations greater than $1.5 \times 10^{12} \text{ ions/m}^3$ have been found. The average spacecharge density is shown to be positive for a section of the time with individual ion concentrations in excess of $2 \times 10^{11} \text{ ions/m}^3$. The curve fit for certain ion mobilities has a correlation coefficient of better than 80% for ion concentration versus relative humidity. Some possible H_2O molecular groups are identified from the ion mobility spectra.

Keywords: Transmission Lines; Ionisation; Relative Humidity; Ion Mobility.

Introduction

The results given in this paper were obtained underneath three 3 phase 400 kV AC transmission lines using 35,5mm diameter aluminium conductors configured in a 3 bundle equilateral triangle of dimension 38,1cm. The phase to phase spacing is about 10.8m with 21m spacing between the three lines. The height of the conductors where the measurements took place was 22m. The line was not a standard span as it was the span to a strain tower where the line bent preparatory to entering a switchyard some 400m distant. The altitude is 1540m and these measurements were taken after an interval of heavy rainfall which had ended a long drought cycle and allowing the rain, fog (or low cloud) appeared on a daily basis. The area is rural farmland with some vehicle traffic.

Effect of Relative Humidity on Ion Concentrations

Figures 1 to 13 show the change in ion concentration for positive ions for different ion mobilities. Each scan comprised 13 measurements of positive ions and 13 measurements of negative ions with a one minute interval between the readings to provide a settling time for the ion chamber. Each of the 13 measurements were obtained from a sequential selection of ion chamber collector plates such that the ion mobility covers the range 2.77 to $0.004 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$. The ion chamber which makes the measurement has been described elsewhere [1]. Figure 1 is marked at the time of each midnight. The period covered in the figures is from 19 November to 2 December 1987. Each scan requires approximately 30 minutes and the figures cover a period of 12.84 days.

Figure 14 shows a single representation of the negative ions: they did not show a regular pattern as do the positive ions.

Figure 15 shows the variation of relative humidity, with a very large daily variation from 40% to 100%. Fog formed when the humidity level went above 80%. The correlation between the positive ion concentration and the relative humidity is very clear.

The variability of the ion level below 300×10^6 ions/m³ is due in part to the corresponding very low ion chamber current ($\approx 10^{-13}$ amperes) and also due to other external influences: wind direction and speed.

Effect of Air Pressure

The variation of air pressure is shown in Figure 16. This shows not only a daily variation but also a long term variation with a low pressure region centred between scans 280 - 400. This low pressure region is also apparent in the relative humidity pattern of Figure 15, and it is also apparent in the ion concentration. Thus, there is a reduction in the positive concentration during the same period in Figures 2, 3, 7, 9 and 12. There is also a very small indication of an increase in ions in Figures 5 and 10, which previously showed virtually no ion level. This would appear to demonstrate a small change in the ion mobility spectra.

The two spikes at scan 250 and scan 510 are due to a lightning strike along the transmission line which produced a trip, followed by an automatic reclosure of the protection circuit breakers. This had an effect on the 220V line voltage which supplied the equipment power supplies.

Effect of Temperature

The daily temperature variations are shown in Figure 17, and they vary from a low of 12°C to a high of 32°C. They are the inverse of the relative humidity as is to be expected and the continual low temperature during scans 460 - 570 produce a continuously high relative humidity. This really indicates the break up of the weather pattern of the previous period, and this is also apparent in the ion concentrations.

Effect of Precipitation

The rainfall during this period was slight as is shown in Figure 18. In general, these small rainfalls do not affect the ion concentration and that the lightning strike on the transmission line was distant is demonstrated by the absence of heavy rain on those lines. A local thunderstorm would give a rainfall of 40mm or more.

Effect of Wind

The wind direction during this period was variable, but generally between north, east and south. The transmission lines run east to west. The wind velocity, shown in Figure 19, is low except for some occasional high velocities. These higher velocities show a coincidence with disturbance of the ion levels, especially in Figures 1 and 2.

The periodic early morning calm periods, where the wind velocity falls below 1 m/sec, coincide in general with the high ion concentrations.

Radio Interference (RI)

The predicted levels, obtained from the Bonneville Power Administration Computer Programme, predicts L50, fair weather, to be 38 dB and L50 rain, to be 55 dB.

The radio interference of Figure 20 was obtained at 850 kHz and indicates an RI value of 55 dB referenced to 1 μ V with a fixed attenuation of 10 dB of the instrument added on. The sudden, large reductions of RI are coincident with the slight rainfall pattern of Figure 18.

The small variations of RI are coincident with relative humidity and ion concentrations. The RI is generally high with low humidity, and this is consistent with the RI coming from a gap source: arcing tends to reduce with rain and increase with low humidity. The effect on RI of corona power loss due to relative humidity as indicated by the small variations, is about 20 μ V in a general level of 170 μ V, a variation of about 12%.

Audible Noise

The predicted values for audible noise were: L50 fair, 14 dB; L50 rain, 41 dB. The measured values in Figure 21 (which are not A weighted, show levels some 50 dBs greater than expected for fair weather, and some 23 dBs greater than expected for rain. There seems no real pattern and the audible noise seems due to the gap source noise.

Potential Gradient

The potential gradient shown in Figure 22 indicates some very high peaks and troughs. The small fluctuations will be due to small changes in the transmission line potential and are to be expected. The large decreases in potential gradient are coincident with high ion concentrations, and these are especially noticeable in Figure 2. These would be due to ion clouds shielding the potential gradient detector, and consequently reducing the potential gradient. The very large increases of potential gradient are not easily explained, the two lightning pulses are due to the power supply change, not a direct reading of electrostatic voltage pulse. The instrument was remotely controlled via optical fibres and was switched on just prior to a measurement. The measurement requires only some 2 seconds to be entered into the data acquisition system, and the large increases in potential gradient occur over a number of scans and two measurements are made during each scan. Consequently, the peak at scan 110 for example, existed over 4 scans, being eight measurements and approximately 120 minutes duration. Such an increase cannot be explained by thunderstorms, which were absent. Neither can they be explained by excessively high temperatures affecting the transmission line conductor sag, especially as the span length is only about half a normal span.

Ion Mobility Spectra and Spacecharge

Figure 23 shows the average ion concentration versus ion mobility for positive ions over the scans 156 - 250. These, by reference to Figures 1 - 13, cover two cycles of humidity, and the data was restricted to the high humidity range which is $93\% \pm 3\%$. There is a factor of ten increase in ion concentration from the light ions, mobility $2.77 - 1.0 \times 10^{-4} \text{ m}^2/\text{V} \cdot \text{sec}$ to that for $0.847 - 0.6 \text{ m}^2/\text{V} \cdot \text{sec}$ and an increase in ion concentration of 20 times for mobility range $0.350 - 0.2 \times 10^{-4} \text{ m}^2/\text{V} \cdot \text{sec}$. Figure 24 shows the spectra for negative ions and the variability here was much greater, as was mentioned previously, referring to Figure 14. The spacecharge, being the negative ions subtracted from the positive ion concentration is shown in Figure 25. Each of these figures indicates a preferential mobility pattern with Figure 23 showing 5 mobility peaks.

The result is interesting since the expectation was that negative ions would predominate with high relative humidity, and an empirical formula has been given [18] such that;

$$\frac{D^-}{D^+} = \frac{k^-}{k^+} = 1.7544 - 0.131 (\log (RH\%)) \quad (1)$$

Where D^- , D^+ are the coefficients of diffusion of the ions, k^- , k^+ are the ion mobilities.

Since the ion concentration is related by:

$$\frac{N^-}{N^+} = \left(\frac{D^-}{D^+}\right)^2 = \left(\frac{k^-}{k^+}\right)^2$$

Equation 1 will be related to the square of the ion concentration ratio. For $RH = 100\%$,

$$\frac{k^-}{k^+} = 1.492 \text{ and } \frac{N^-}{N^+} = 2.226$$

The empirical equation was obtained under laboratory conditions whereas these measurements were obtained in the field, but from this the expectation would be twice the negative ion concentration than the positive ion concentration.

Electrical Charges on Mist and Clouds

All natural or artificially produced aerosols will have a charge, depending on the method by which they are produced.

Mist, or cloud, produced by the clustering of water vapour in a near saturated atmosphere, is formed in the presence of the natural potential gradient. Chalmers [2] reports work by Gunn on the measurement of charges on water vapour particles in non-raining clouds at an altitude of 1400m with diameters up to 0.01 μm , and found charges of $-2.0 \times 10^{-9} \text{ C/m}^3$, and $+1.3 \times 10^{-9} \text{ C/m}^3$ for particles greater than 10 μm . The cloud is electrically neutral and thus the charge of $+0.7 \times 10^{-9} \text{ C/m}^3$ remains for the remaining diameters. Chalmers notes that the average charge per droplet may well carry more than one electronic charge whereas others would carry less than one charge.

A charge of -2×10^{-9} C/m³ would, in the ion chamber, represent a total ion count of $12\,500 \times 10^6$ ions/m³, and this ion concentration would be over the entire mobility range for particle sizes up to 0.01 μ m. The ion chamber would detect the charge without differentiating between single or multiple charges on the particles. There is, however, considerable variability in the results of other workers reported by Chalmers who found lower values for the charges.

Webb and Gunn, Chalmers [4], found charges on droplets and ions in fog to be an average of -4×10^{-10} C/m³ for large droplets and $+14 \times 10^{-10}$ C/m³ on the ions, which corresponds to an average of less than one electronic charge per droplet.

The charges on rain drops, due to their falling through a potential σ are reportedly from $+3 \times 10^{-15}$ C/m³ up to -10^{-10} C/m³, and Chalmers [5] note the large variation of charges on the same sized drops which have fallen through the same potential gradient.

With the ion chamber, there was a wooden shield placed above the ion chamber so that rain would not fall directly upon the ion chamber, and especially to avoid rain drops falling directly onto the first plate, C1, which would lead to erroneous readings.

A further experiment has been conducted with the ion mobility scanner in an environmental chamber, which is more than 8 m³ and capable of temperature and humidity control and with metal walls which provide a Faraday screen. It was found that humidity levels up to 80% relative humidity did not produce any significant ions, but when the humidity sprays were activated, there was a dramatic increase in ion concentration. By reducing the relative humidity to about 27%, and then changing the controls to demand 90% relative humidity, a nearly linearly increasing relative humidity of 5.9% RH/minute was obtained over a period of 9 minutes during which time the humidity sprays were on continuously and the complete scan of positive and negative ion mobilities and their concomitant ion concentrations were obtained. Table 1 shows the results from which it can be seen that the water spray produced quite high ion concentrations, but the total spacecharge was low and negative with the ion concentrations being very nearly equal.

Table 1 Ion Concentrations and Ion Mobilities for Environmental Chamber Water Sprays

Collector Number	Mobility $\times 10^{-4} \text{ m}^2/\text{V sec}$	+Ve Ions $\times 10^6/\text{m}^3$	-Ve Ions $\times 10^6/\text{m}^3$	Spacecharges $\times 10^6/\text{m}^3$
1	2.88-1.0	4100	4930	-20
2	0.85-0.6	3110	3260	-150
3	0.54-0.4	3740	3920	-180
4	0.35-0.2	124	395	-271
5	0.18-0.1	19600	1990	-300
6	0.098-0.08	5530	5540	10
7	0.079-0.06	8180	8180	0
8	0.059-0.04	15600	15600	0
9	0.037-0.02	121	493	-484
10	0.019-0.01	110000	115600	-5200
11	0.0098-0.008	24000	24700	-500
12	0.0079-0.006	36000	37400	-800
13	0.0059-0.004	59000	62100	-2800

No great accuracy is claimed for these readings, but they do demonstrate the ion mobility spectrum of the water spray and show the expected increase in ion concentration for Collector No. 10, since this had been deduced from previous measurements with a more simple parallel plate ion chamber.

When the water sprays were switched off, the ion concentration began to decay immediately, and the decay half lives were found as shown in Table 2.

Table 2 Decay Half Lives for Water Vapour

Collector No.	Mobility Range $\times 10^{-4} \text{ m}^2$	-VE Ions $T_{1/2}$ secs.	+VE Ions $T_{1/2}$ secs.
1	2.77-1.0	57	23
10	0.019-0.01	498	684

Chalmers [6] identified the average life of an ion as:

Over land 50 sec
 Kew (Polluted) 20 sec
 Over sea 300 sec

There was no indication of the polarity of the ions or of the method of measurement.

It should be noted that with this multiple plate ion chamber, there is a filtering effect due to the previous plates, so that all ions of mobility higher than the mobility being measured are removed by collection before the air reaches the selected collector plate. This includes the first collector plate, C1, because this is preceded by an earth plate of 1cm which will limit the onset mobility at the leading edge of C1 to $2.77 \times 10^{-4} \text{ m}^2/\text{V}.\text{sec}$.

Ion Mobility

The induced current into an insulated metallic structure from an ion cloud has been studied [7] and depends upon the current density $J \text{ amp}/\text{m}^2$ of the ion cloud.

$$J = nekE \quad (2)$$

where n = ion concentration
 e = electronic charge
 k = ion mobility
 E = electric field

The current induced is given by:

$$I_{in} = \int_S n e k E \quad (3)$$

Where s is the surface area through which the ions enter the object. Hara et al [7] showed that this was practically independent of the wind velocity but highly subject to the leakage resistance to ground. The values used in these calculations included a value of spacecharge density of $1.2 \times 10^{-8} \text{ C/m}^3$ and ion mobility of $1.5 \times 10^{-4} \text{ m}^2/\text{v. sec.}$: these values were those typical of HV DC lines. This spacecharge density would reflect total ion concentration of about $75,000 \times 10^6 \text{ ions/m}^3$. These values are in agreement with those obtained by Bracken [8] except that the ion mobility, obtained from a least squares fit, was $1.6 \times 10^{-4} \text{ m}^2/\text{v. sec.}$ for negative ions and $1.7 \times 10^{-4} \text{ m}^2/\text{v. sec.}$ for positive ions. Values previously given by EPRI [9] were: negative ions $1.99 \times 10^{-4} \text{ m}^2/\text{v. sec.}$ positive ions $1.46 \times 10^{-4} \text{ m}^2/\text{v. sec.}$

These ion mobility values are those found in fair weather and little field work seems to have been done to evaluate ion concentrations with different ion mobilities.

The drift velocity of an ion, V_d , is proportional to the electric field intensity such that:

$$V_d = kE \quad (4)$$

where k is the constant of proportionality, or mobility, having dimensions of m/sec/v/m or $\text{m}^2/\text{v. sec.}$ This holds true providing that the energy imparted to the ions by the electric field is low compared with the thermal energy. This requires that (10), (11)

$$\frac{E}{p} \ll \frac{\sigma}{e} \quad (5)$$

where p is the gas pressure in torr ($1 \text{ mm Hg} = 1 \text{ torr}; 760 \text{ torr} = 1.013 \times 10^5 \text{ Pascals}$), σ is the ion/molecule collision cross section ($\approx 10^{-18} \text{ m}^2$) and e is the electronic charge. The criteria is $\frac{E}{p} \ll 6 \text{ v/m-torr}$, since at greater values there will be increasing ionisation from accelerated electrons (and at high values of E/p , acceleration of ions).

The ion mobility is not easily calculated, McDaniel [12] gives Langevin's

(1905) calculation for ion mobility where:

$$k = \frac{A}{\sqrt{\delta} (k-1)} \left(1 + \frac{M}{m}\right)^{1/2} \quad (6)$$

where δ is the gas density, K the gas dielectric constant, M is the mass of the gas molecule and m the mass of the ion. A is a function of the parameter b , where

$$b^2 = \frac{8 \pi p \gamma^2}{(k-1) e^2} \quad (7)$$

γ is the sum of the radii of the ion and the gas molecule, p = gas pressure, b^2 is a dimensionless temperature and McDaniel shows that;

$$k_e = \frac{0.75 e}{\gamma^2 \sqrt{\delta p \delta}} \left(1 + \frac{M}{m}\right)^{1/2} \quad (8)$$

being the elastic sphere limit when b is very large and:

$$k_p = \frac{0.5105}{\sqrt{\delta} (k-1)} \left(1 + \frac{M}{m}\right)^{1/2} \quad (9)$$

In the polarisation, or small ion limit, when $b = 0$.

He further shows that by quantum mechanical theory

$$k_q = \frac{35.9}{\sqrt{\alpha} M_p} \text{ cm}^2/\text{v. sec.} \quad (10)$$

where α is the polarisability of the gas and is measured in atomic units (a_0^3 , a_0 being the radius of the first Bohr orbit), and M_p is measured in units of the proton mass, with k_q referred to a constant gas number density ($2.69 \times 10^{19}/\text{cm}^3$). Equation (10) is identical with equation (9) and the two equations (8) and (9) could be considered to define the lower and upper bounds of the mobility.

The mobility shown in (9) is independent of the ion charge and this is explained by noting that the force on the ion due to an electric field is directly proportional to the charge, but that the momentum loss of the ion due to impact produced by the inverse fifth-power-electrostatic forces is also proportional to the charge, with a resultant cancelling of the effects.

The first Langevin equation is:

$$k = 0.815 \frac{e\lambda}{Mv} \left(1 + \frac{M}{m}\right)^{1/2} \quad (11)$$

which can conveniently be related to physical parameters. (See also (13)).

$$\lambda = \frac{1}{\pi(r_1 + r_2)^2 N} \quad (12)$$

where r_1 , r_2 are the ion and molecule radii, N is the gas molecular density number. The ion velocity can be estimated as:

$$v = \sqrt{\frac{2KT}{m}} \approx 1.128 \quad (13)$$

where the factor 1.128 is the increased value of the average velocity to the most probable velocity. Equation (13) is derived by making the kinetic energy equal to the thermal energy: $\frac{1}{2}mv_p^2 = KT$.

Computed values of k differ from experimental values and the discrepancies are due to the difficulty in determining λ , the mean free path of the ion between collisions with other gas molecules. Table 3 (14) shows ion mobilities of some ions of interest for a temperature of 273°C and 760 Torr ($2.69 \times 10^{19} \text{ cm}^{-3}$ gas atoms) gas pressure.

Table 3

Gas	$k \times 10^{-4} \text{ m}^2/\text{v}.\text{sec.}$	$k^+ \times 10^{-4} \text{ m}^2.\text{v}.\text{sec.}$
Air (dry)	2.1	1.36
Air (very dry)	2.5	1.8
N_2	-	1.8 (N_2^+) 3.1 (N_3^+) 2.4 (N_4^+)
O_2	2.6 (probably O_2^- or O_3^-)	2.2 (probably O_2^+)
CO	1.14	1.10
CO_2	0.98	0.84
H_2O (at 100°C)	0.95	1.1

There is a further method of calculating the ion mobility (15) (16), from Stokes' Law for spherical particles.

$$k = \frac{ne}{6\pi R\eta} \left(1 + \frac{c}{pR} \right) \quad (14)$$

where n is the number of basic charges, η is the coefficient of viscosity of the air ($\eta = 1.8 \times 10^{-5}$ Ns m^{-2} at 15°C) p is the atmospheric pressure in cm of mercury, R is the ion radius, C is a constant ≈ 0.00617 .

The factor in parenthesis is Cunningham's correction to Stokes' law, and becomes unity for $R \approx 10 \mu\text{m}$ but is large for small radii.

Table 4 shows the calculated radii from equation (14) for the values of mobility defined by the separate collector plates of the ion mobility scanner. These radii are larger than those given by McDaniel for N_2 or O_2 , as shown in Table 5 for the gases found in air [12].

The radii for the lower values of mobility will be those for ion clusters (where cluster is the term for positive ion) and ion attachment (for negative ions). McDaniel [17] notes that a cluster of 12 O_2 molecules about an O_2^+ ion would be stable, and that molecular clusters of up to 30 might be observed for gases of higher dielectric.

Figure 26 shows the graph of equation (13) for mobility versus ion radius. Together with this are a series of graphs for $N(\text{H}_2\text{O})$ molecules, where N is an integer using Langevin's original equation (equation 11) for 760 torr, 288°K and using N times the molecular mass. As noted by McDaniel this equation gives mobility values too high for small ions [i.e. $1(\text{H}_2\text{O})$], but the values for larger ions, commencing at $4(\text{H}_2\text{O})$, are close to those for Stokes' Law.

The graph for $N(\text{H}_2\text{O})$ shows the possible diameters for the given mobility values of the ion chamber. The arrows indicate the mobility values where high ion concentrations were found. The difficulty is to determine what the effective diameter of, say, $8(\text{H}_2\text{O})$ might be. For example, the diameter of H_2 is given as 2.74×10^{-8} cm, that for O_2 is 3.61×10^{-8} and H_2O is 4.60×10^{-8} cm [18]. Aerosol clusters of strings, circles and plates have been observed [19] and it would not be logical to expect water vapour clusters to form perfectly spherical shapes.

Table 4 Radii of Ion Calculated from Stokes' Law at 288°K, 760 Torr
(1.013×10^5 Pascal)

Collector No.	Mobility $\times 10^{-4}$, $\text{m}^2/\text{v. sec.}$	Radius $\times 10^{-8}$ cm, (Å)
1	2,77	3,13
	1,0	6,22
2	0,847	6,76
	0,6	8,03
3	0,541	8,46
	0,4	8,95
4	0,35	10,53
	0,2	13,9
5	0,186	14,48
	0,1	19,81
6	0,098	20,01
	0,08	22,18
7	0,078	22,33
	0,06	25,66
8	0,059	25,88
	0,04	31,54
9	0,037	32,81
	0,02	44,95
10	0,019	46,15
	0,01	64,28
11	0,0098	64,96
	0,008	72,9
12	0,0079	72,67
	0,006	83,91
13	0,0059	84,65
	0,004	103,9

Table 5

Values of mean velocity $\bar{V}$, molecular diameter D , mean free path λ and the collision frequency ν , calculated from the kinetic theory for gases, 15°C (288°K) and 760 mm Hg.

Gas	Molecular Weight	$\bar{V}$ m/sec	D 10^{-8} cm	λ 10^{-8} m	ν 10^9 collision/sec
N ₂	28,02	467	3,75	6,28	7,4
O ₂	32,00	437	3,61	6,79	6,4
CO ₂	44,60	372	4,59	4,19	8,8
H ₂ O	18,02	582	4,60	4,18	13,9

A curve fit has been obtained for scans 156 to 250, which cover two cycles of relative humidity variation and comprise observations covering nearly two days. The equation obtained is given by

$$I = \text{EXP} [A - B [\ln (1 - R)]] \quad (15)$$

where I = ion concentration cm^{-3} , R is the fractional relative humidity and A and B are constants. The results of the curve fits are shown in Table 6 and No. 5 and No. 10 do not show a fit as there seem not to be ions present. For No. 8 the curve fit is: $I = \text{EXP} (a + bR)$, but as can be seen in Figure 8 the ion concentration does not vary significantly. Two significant conditions arise: the first is where the variation of ion concentration is large, that is the ratio of $I_{\text{max}}/I_{\text{min}}$; and the second where the variation of ion concentration is not large.

The large variations are shown in Table 6 as:

Nos. 2, 4, 7, 9 and 12 and these maxima are shown in Figure 23. The average values for the coefficients for these five mobilities are $A = 5,09$, $B = 1,774$. For the minima, $A = 5,345$, $B = 0,8796$. The ion concentration varies rapidly as the relative humidity exceeds 90%, as can be seen in Table 7.

Table 6 Curve Fit for Positive Ion Concentration Versus Relative Humidity

Collector No. and Figure No.	$\text{cm}^2/\text{v}.\text{sec.}$	A	B	R^2	MSE	$I_{\text{max}}/I_{\text{min}}$
1	2.77-1.0	5.124	1.117	0.825	0.365	40
2	0.85-0.6	4.445	1.986	0.811	1.411	500
3	0.54-0.4	5.01	1.197	0.860	0.342	40
4	0.35-0.2	4.771	1.925	0.816	1.29	600
5	0.186-0.1	-	-	-	-	-
6	0.098-0.08	5.13	0.68	0.60	0.415	22
7	0.00-0.06	5.36	1.637	0.76	1.28	250
* 8	0.06-0.04	1.5	0.0051	0.856	-	6.6
9	0.04-0.02	5.27	1.69	0.717	1.64	500
10	0.02-0.01	-	-	-	-	-
11	0.01-0.008	5.64	0.774	0.636	0.482	14.3
12	0.008-0.006	5.55	1.63	0.806	0.912	250
13	0.006-0.004	5.52	0.63	0.707	0.24	6.7

Equation: $\text{Ions}/\text{cm}^3 = [A - B \{\ln(1-R)\}]$

* Equation: $\text{Ions}/\text{cm}^3 = \text{EXP} (A + B \cdot R)$

MSE = Mean Square Error from analysis of variance

R^2 = Correlation Coefficient

Table 7 Projected Ion Concentrations from Equation (15)
 R = Fractional Relative Humidity

R	Large $I_{\max}/I_{\min}$ Ions $\times 10^{12}$ ions/m ³	Low $I_{\max}/I_{\min}$ Ions $\times 10^{12}$ ions/m ³
1.0	-	-
0.99	567 827	12 034
0.98	166 031	6 540
0.95	32 677	2 921
0.90	9 554	1 587
0.80	2 793	663
0.70	1 361	604
0.60	817	469
0.30	302	286

From Table 7 it can be seen that at low relative humidities the ion concentration reaches that found for normal background without the influence of transmission lines. Where the large values of ion concentration are found defines the $N(H_2O)$ cluster whose effective radius gives rise to a certain ion mobility.

Knowing that Stokes' and Langevin's Laws are not particularly accurate except with very pure gases and ions, it is nevertheless possible to hazard a guess at the clusters which correspond to the large ion concentrations. The ion mobility for H_2 is $K^- = 9.5$, $K^+ = 1.1$, from Table 3. Thus, for $K = 0.85 - 0.6$, it is probably $2(H_2O)$. By projecting the mobility ranges onto Figure 26 the guess is made for the value of N . This is shown in Table 8.

Table 8 Possible H₂O Clusters

Collector No.	Mobility $\times 10^{-4}$ m ² /v.sec	Radius r 10^{-8} cm	N(H ₂ O)
2	0,85	6,76	2
	0,6	5,03	
4	0,35	10,53	3 or 4
	0,2	13,9	
7	0,08	22,33	4 or 5
	0,06	25,66	
9	0,07	32,87	6 or 7
	0,02	44,95	
12	0,008	72,67	8
	0,006	83,5	

Figure 27 shows the plot of the equation with the data for Figure 2 having an $I_{\max}/I_{\min}$ ratio of 500. Figure 28 shows that for the data of Figure 3 which has a very low ratio of 40. The ion ordinate is Napierian logarithms.

Conclusion

The ion mobility spectra for increasing relative humidity shows a shift to the lower ion mobilities as would be expected for positive ion clusters and negative ion attachment and also indicates the loss of light, high mobility ions. It is uncertain how many elementary charges an ion may carry, but it is safe to assume that at the higher mobilities they must be unit charges since the mobility is directly proportional to the electric charge.

Consequently there is confidence that Figure 26, the graph of Stokes' Law and the superimposed values for Langevin's equation for ions of N(H₂O) mass, shows the possible effective radii of such clusters.

The more valid equations of Langevin, and the quantum mechanical equations are most suitable for pure gases and for ions of the same gas or for positive ions of alkali ions such as Li, Na, K, Rb, Cs; good correlation between theory and experimental data has been obtained [20].

In these cases it is possible to determine the first Bohr orbit. The problem of determining this in a cluster are very great, and the clusters of H_2O are very much dependent on the dipole configuration. The results present have been obtained in air which contains nitrogen, oxygen, carbon dioxide plus other polluting gases, and these latter could also affect the water vapour clusters in the fog.

The ion concentration, being measured at near ground level (1.4m) shows that a significant corona power loss is due to ions departing from the transmission lines, and consequently equation (15) is proportional to the corona power loss. Most of the corona power loss is due to the kinetic energy given up to ionisation in the air volume immediately around the transmission line.

The mechanism with high relative humidity could be fog droplets attaching to the conductors, but this seems rather improbable since the conductors are at a temperature between $50^{\circ}C$ and $90^{\circ}C$. The very small water droplets are likely to vapourise as they approach the conductor due not only to the temperature but also to the electric potential gradient set up across the droplet.

Because these are field measurements there is considerable fluctuation in the parameters, and it is a disappointment that the negative ions did not show a regular pattern as did the positive ions. One facet which has not been fully investigated is the curious effect of the air pressure. Compare, for example, the marked reduction in ion concentration with reduction in air pressure as shown in Figures 2, 4, 7, 9, 12 where the I_{max}/I_{min} ratio was greatest in the earlier scans. Whereas there are small increases in ion concentration as shown in Figures 5 and 10, which are coincident with the reduced air pressure. Peek's Law [21], upon which corona power loss calculations are based, predicts an increase in ionisation with reduced pressure. This would correspond to the increased distance between molecular collisions. This effect is noted in equation 12 and consequently the mobility will be affected by the gas density N , and thus air pressure.

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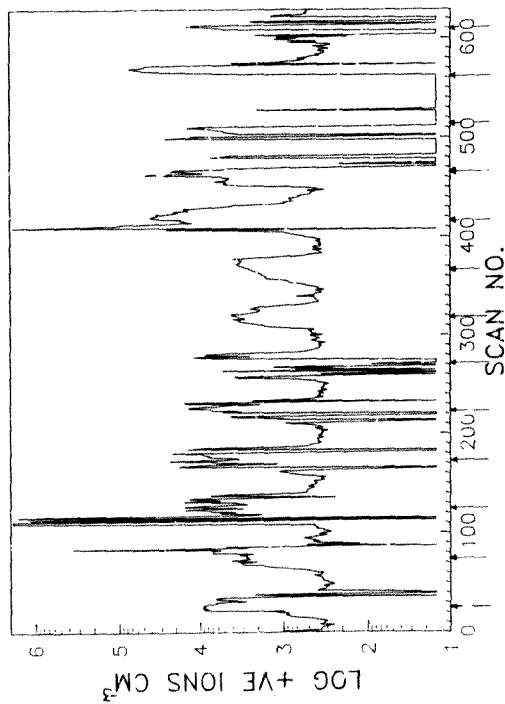


Figure 1
+ve ions: Mobility $2.77 - 1.00 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

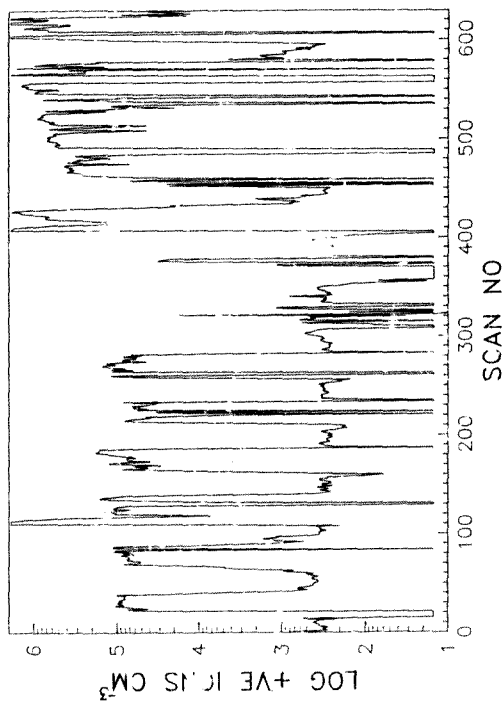


Figure 2
+ve ions: Mobility $0.847 \sim 0.60 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

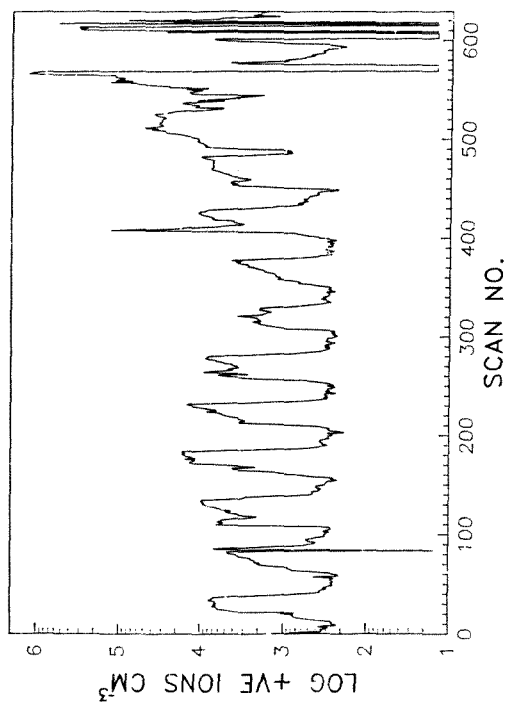


Figure 3
+ve ions: Mobility $0.54 - 0.4 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

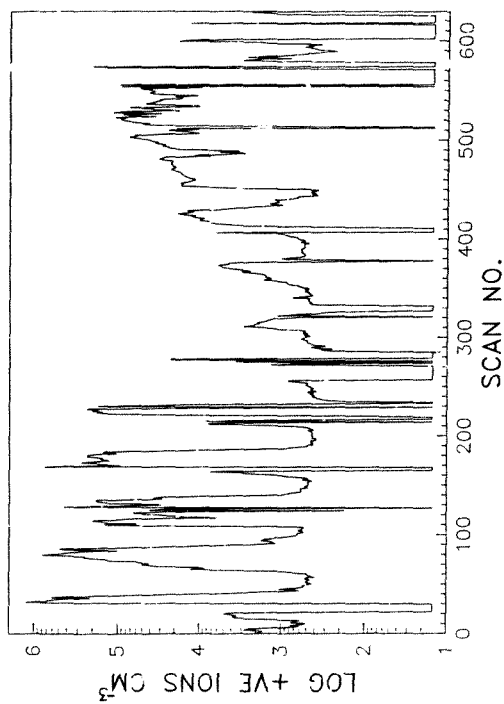


Figure 4
+ve ions: Mobility $0.35 - 0.2 \times 10^{-4} \text{ m}^2/\text{v.sec}$

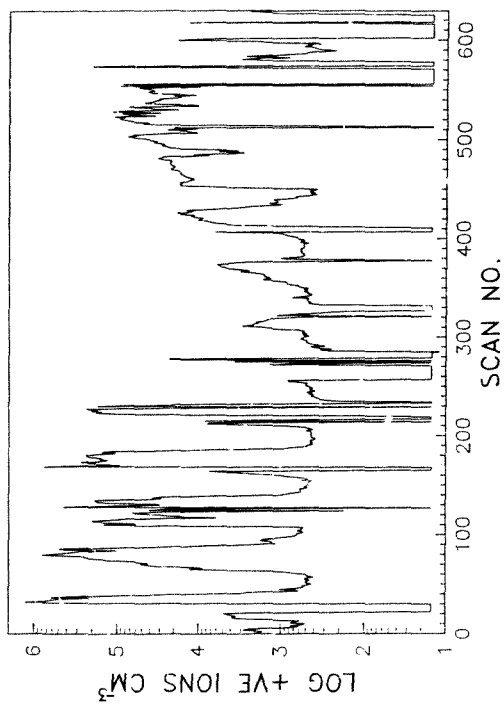


Figure 4
+ve ions: Mobility $0.35 - 0.2 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

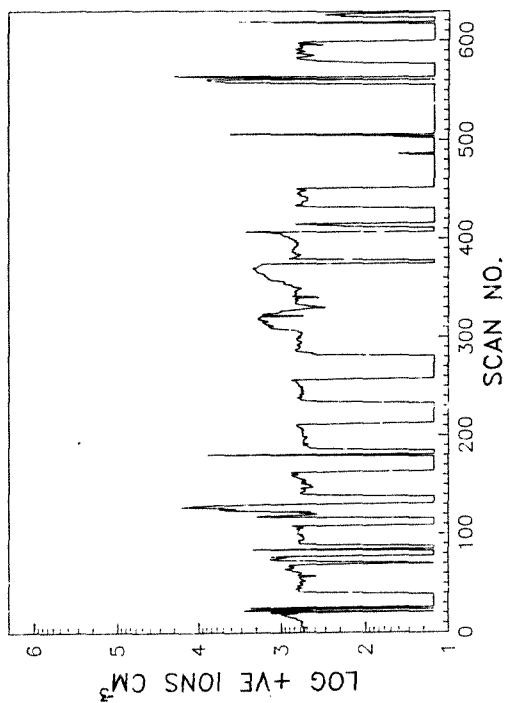


Figure 5

*ve ions: Mobility $0.186 - 0.1 \times 10^{-4} \text{ m}^2 \cdot \text{v} \cdot \text{sec}$

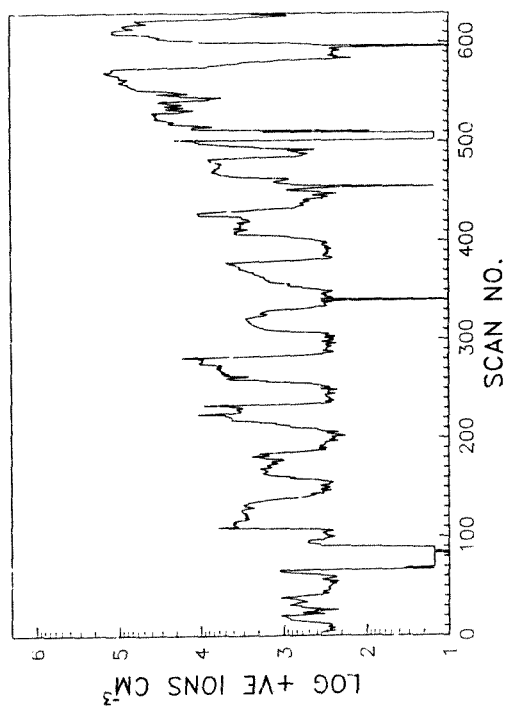


Figure 6
+ve ions: Mobility $0.098 \sim 0.08 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

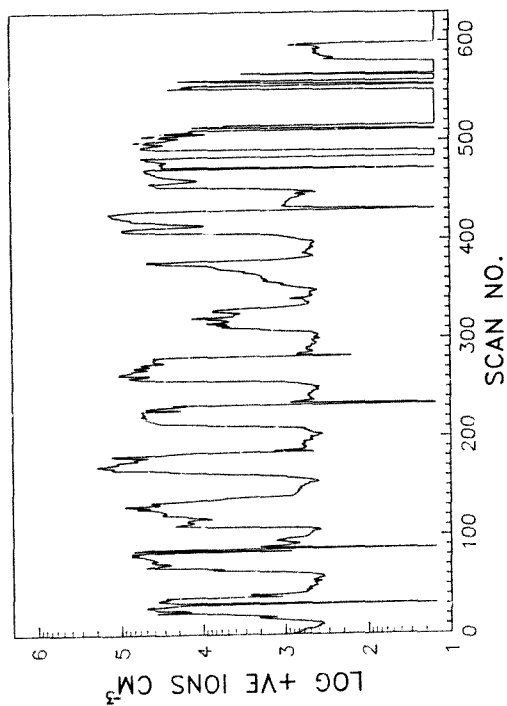


Figure 7

+ve ions: Mobility $0.079 - 0.06 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

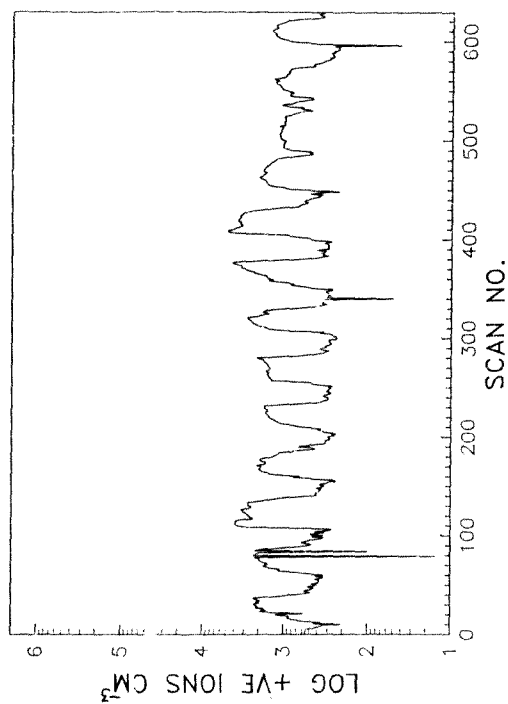


Figure 8
+ve ions: Mobility $0.059 - 0.04 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

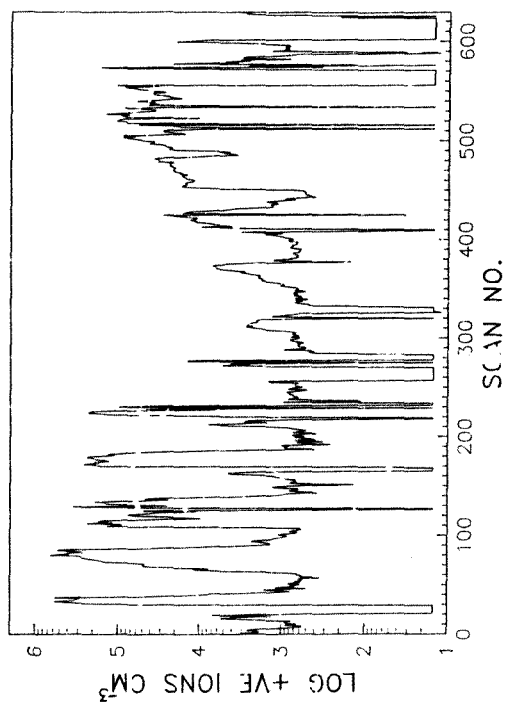


Figure 9
+ve ions: Mobility $0.037 - 0.02 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

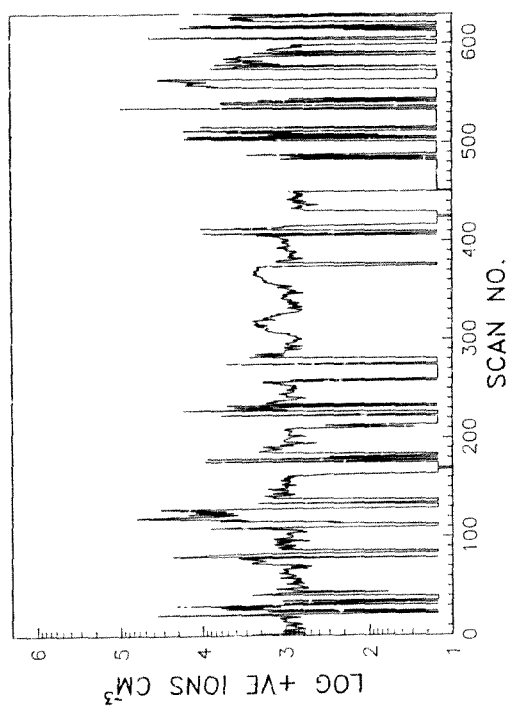


Figure 10
+ve ions: Mobility $0.019 - 0.01 \times 10^{-4} \text{ m}^2/\text{v.sec}$

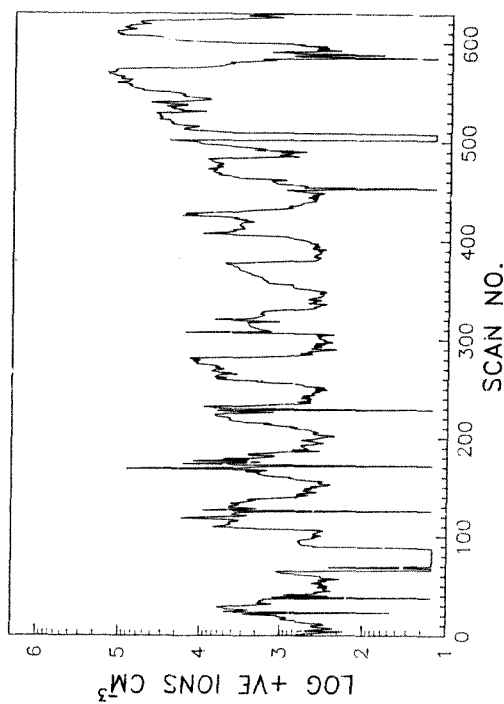


Figure 11
+ve ions: Mobility $0.0098 - 0.008 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

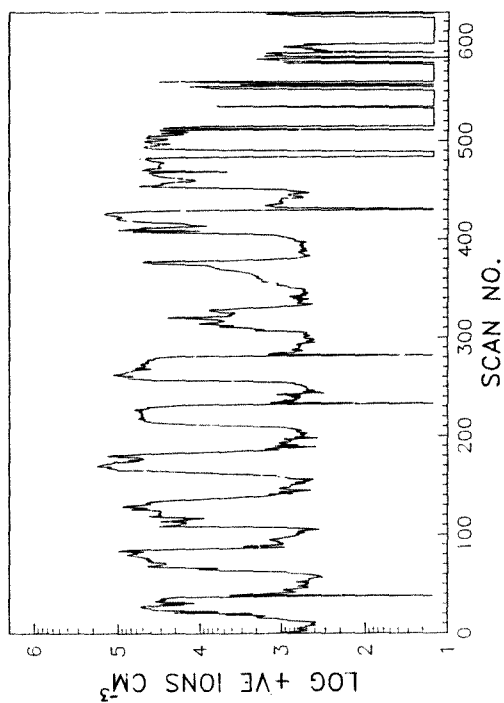


Figure 12

+ve ions: Mobility $0.0079 - 0.006 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

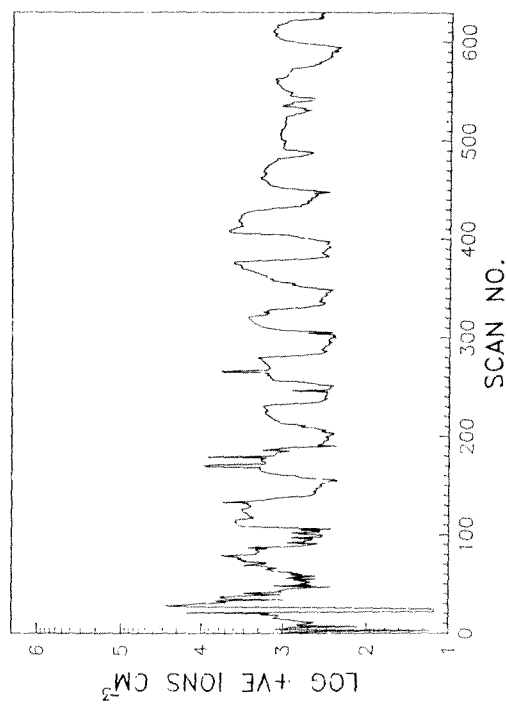


Figure 13
+ve ions: Mobility $0.0059 - 0.004 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

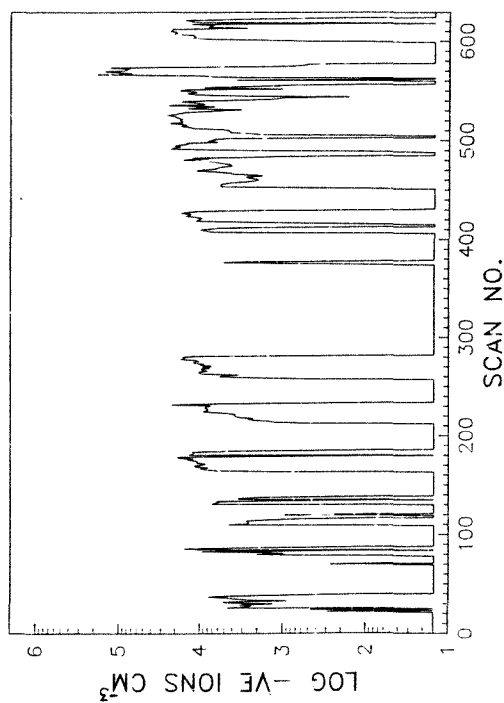


Figure 14
-ve ions: Mobility $0.186 - 0.1 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

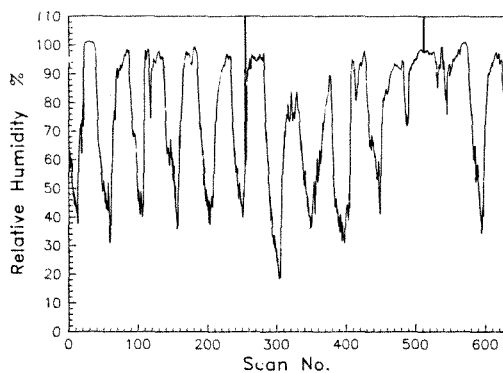


Figure 15
Relative Humidity

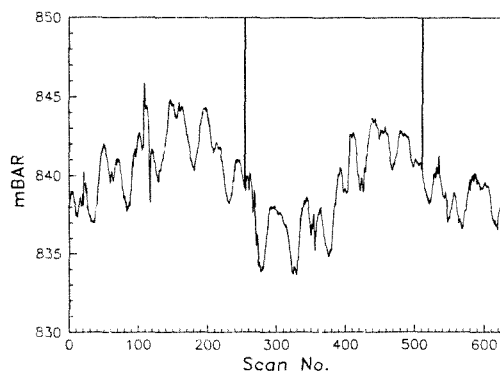


Figure 16
Air Pressure

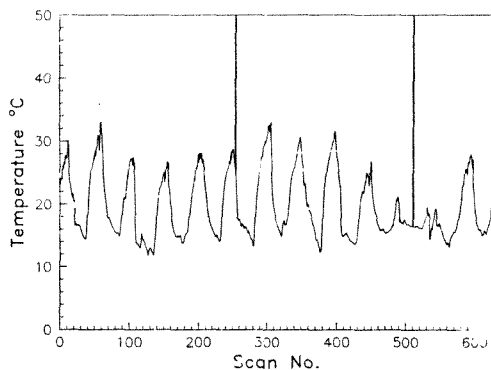


Figure 17
Temperature

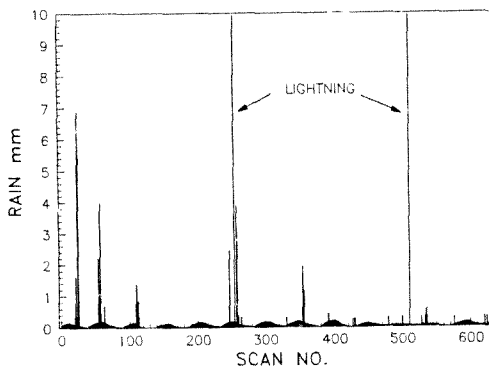


Figure 18
Rainfall

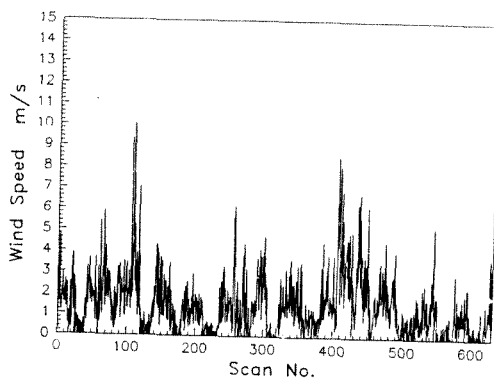


Figure 19
Windspeed

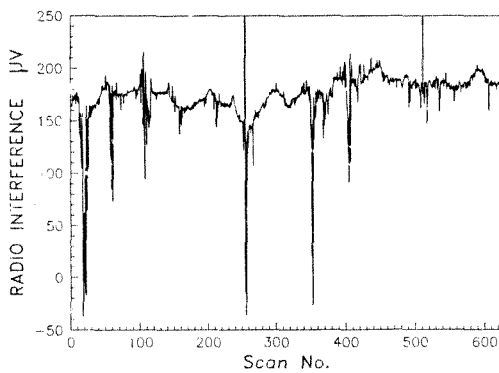


Figure 20
Radio Interference

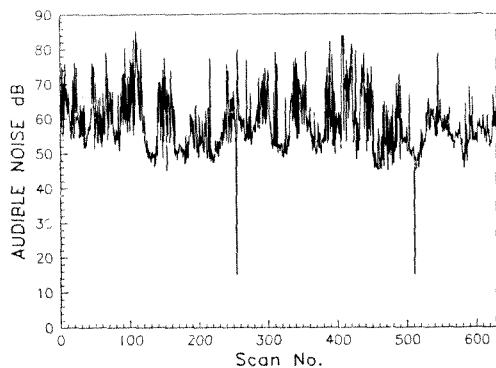


Figure 21
Audible Noise

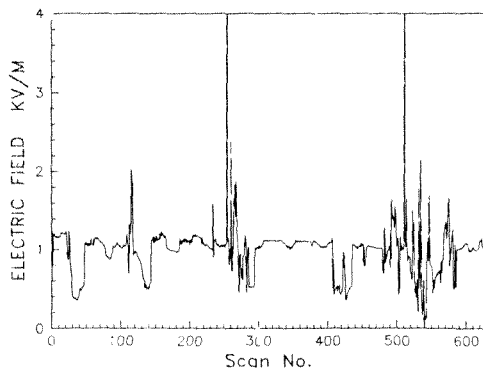


Figure 22
Electric Field

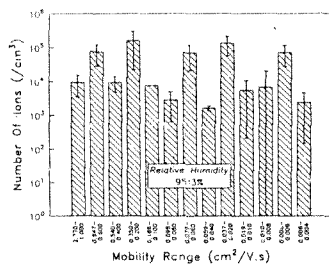


Figure 23
Mobility Spectrum: +ve ions. Soan 156 - 250

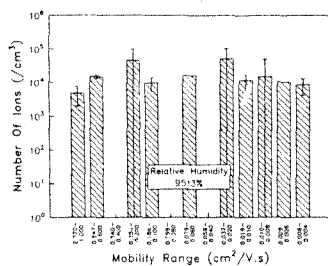


Figure 24
Mobility Spectrum: -ve ions. Soan 156 - 250

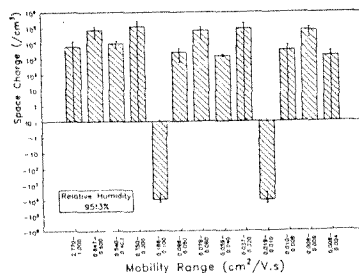


Figure 25
Mobility Spectrum: Spacecharge. Soan 156 - 250

MOBILITY FOR $N(H_2O)$ MOLECULES

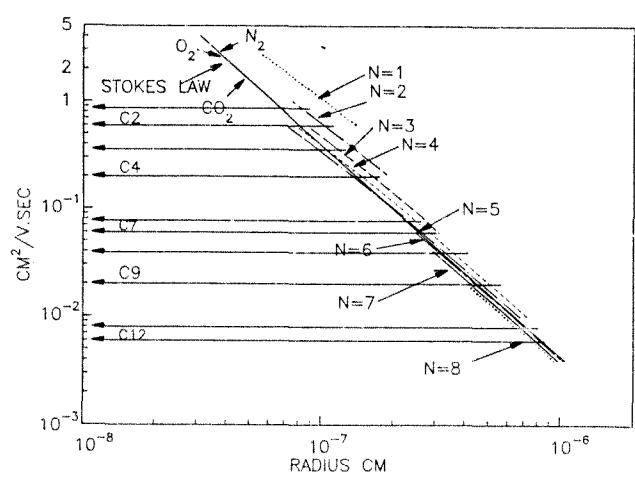


Figure 26
Stokes Law: Mobility versus Molecule Radius with Langevin's Law Computed
for $N(H_2O)$ molecules

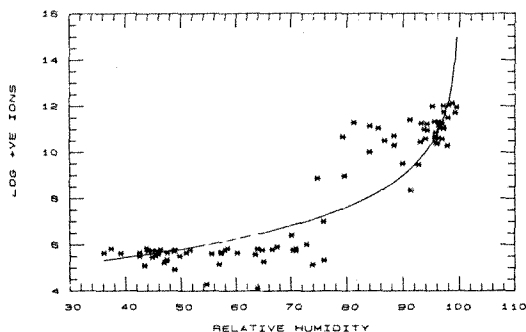


Figure 27

Curve Fit: Ions versus Relative Humidity: Mobility $0.85 - 0.6 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

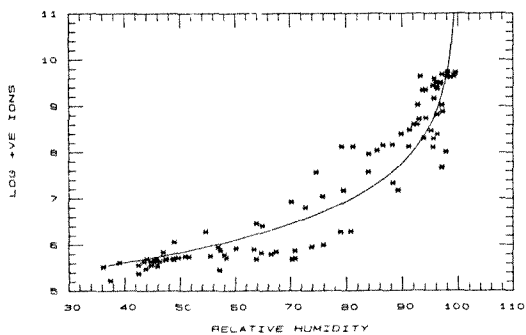


Figure 28

Curve Fit: Ions versus Relative Humidity: Mobility $0.54 - 0.4 \times 10^{-4} \text{ m}^2/\text{v}.\text{sec}$

APPENDIX A

ION MOBILITY SCANNING ION CHAMBER

Abstract: An aspirated ion chamber measuring from natural atmospheric ion levels of 400×10^6 ions/m³ to 1.6×10^{12} ions/m³ over a mobility range of 2.77 to 0.004×10^{-4} m²/V sec which has been proven for field use, is described.

Introduction

The ion current density in the vicinity of high voltage transmission lines is required to be known to be able to estimate the electric potential to which insulated persons or other objects which intercept the ion current can be elevated [1]. Additionally, the electric field in the presence of ion clouds from corona become distorted and it becomes necessary to know the ion density [2].

The usual method of measuring the ion current density, J amps/m², is by means of the Wilson plate method [3],[1] which measures the current flowing between a plate of known area and ground. The current density is given by [1], [2], [4].

$$J = pKE \quad (1)$$

where K is the ion mobility, E the electric field, p the space charge, $C_m/3$, which is the number of ions per unit volume, n , multiplied by the electronic charge, e . The assumption has been that ions of high mobility, where mobility refers to the proportionality constant, K m²/V sec, in relating the drift velocity of the ion in the electric field E , are the major contributors to the ion cloud charging effect. The usual value assigned to light negative ions is 1.8×10^{-4} m²/V sec, and 1.4×10^{-4} m²/V sec for positive ions [5]. However, it is clear that if the ion mobility is one order of magnitude smaller but the concomittant ion concentration is one order of magnitude greater, then the charging current density will be the same. The Wilson plate method requires that the ion mobility is known, but only estimates have been made [8]. Zaffanella [6] has described an aspirated ion chamber, identified as Model Beckett, where air is passed into a parallel plate ion chamber and the current through the ion chamber measures the ion concentration, n ;

$$n = \frac{I}{eWA} \text{ ions/m}^3 \quad (2)$$

where I is the current (A/m²), W is the air velocity (m/Sec) and A is the entrance area of the collection plates. Two collector plates of different dimensions are used to obtain ion concentrations of different mobilities, where;

$$K = \frac{Wd^2}{LV} \text{ m}^2/\text{V sec} \quad (3)$$

where d is the distance between the collector and anode plates, L the effective length of the collector plate, and V the potential applied to the anode.

When the anode plate is positive, the collector plate current is that due to positive ions repulsed from the positive anode. Conversely, negative ions are measured when the anode potential is negative.

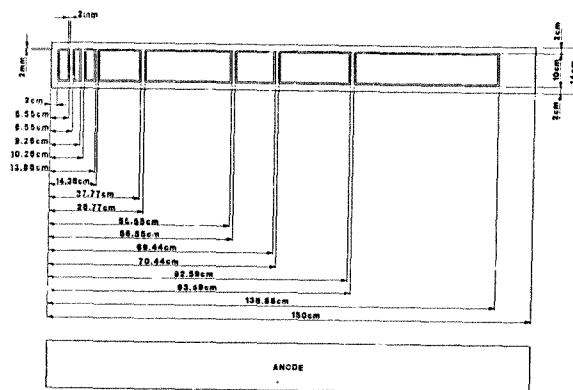
Zaffanella also notes a method of obtaining the ion mobility spectrum by using successive plates along a wind tunnel from an entrance slit. Early methods of determining ion mobility in laboratory conditions are given by Chalmers [7]. The ion chamber described here combines both methods to enable the ion concentration from natural levels of about 400×10^6 ions/ m^3 to a maximum of 1.6×10^{12} ions/ m^3 with a range of 13 mobilities from 2.77×10^{-4} $\text{m}^2/\text{V sec}$ to 0.004×10^{-4} $\text{m}^2/\text{V sec}$, and to measure the positive and the negative ion concentrations sequentially in a short interval of time so that they can be considered simultaneous.

Ion Chamber Construction

The collector plate is divided into a number of aluminium plates as shown in Figure 1. Each collector plate is held in place by Teflon beads and surrounded by an earthed guard plate. The aluminium anode plate extends parallel to the whole length of the multiple collector plates (1.5 M) with a distance of 1 cm between them. The electric field is thus clearly defined with the earthed guard plate ensuring that the electric field is linear and without edges which could produce concentrated fields which might produce secondary ionisation. The guard plate also interposes an earth between any insulation leakage path between the anode and the collector plates.

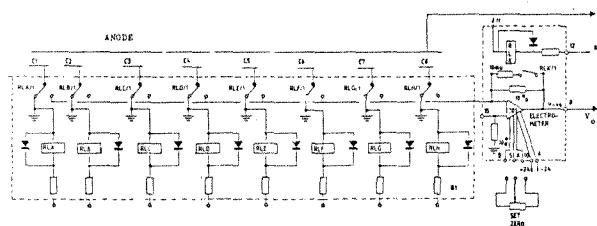
The ion mobility at the leading and trailing edge of each collector plate is given in Table 1 using equation (3). Using only 8 collector plates and applying 18 volts (+ve or -ve as required) to the anode the mobilities cover the range 2.77 to 0.04×10^{-4} $\text{m}^2/\text{V sec}$. By increasing the anode potential to

180V and using collectors 4 to 8 again, the mobility ranges of 0,038 to 3,004 $\times 10^{-4}$ $\text{m}^2/\text{V sec}$ are obtained.



Multiple Plate Ion Chamber

Figure 1



Ion Mobility Scanning Circuit

Figure 2

Table 1 Multiple Plate Ion Chamber Mobility Values
 $\times 10^{-4} \text{ m}^2/\text{Volt. Second}$

Collector Number	D1 (cm)	D2 (cm)	V Volts	K1 (at D1)	K2 (at D2)
1	2	5.55	18	2.77	1.0
2	6.55	9.26	18	0.85	0.60
3	10.26	13.88	18	0.54	0.40
4	14.38	27.77	18	0.39	0.20
5	28.77	55.55	18	0.19	0.10
6	56.55	69.44	18	0.098	0.080
7	70.44	92.59	18	0.079	0.060
8	93.59	138.88	18	0.059	0.040
9(4)	14.38	27.77	180	0.038	0.020
10(5)	28.77	55.55	180	0.0193	0.010
11(6)	56.55	69.44	180	9.8E-3	8.0E-3
12(7)	70.44	92.59	180	7.8E-3	6.0E-3
13(8)	93.59	138.88	180	6.65E-3	4.0E-3

The essential circuit is shown in Figure 2, where 8 relays are used to select one of 8 collectors, the remaining collectors being connected to earth. The collector selected also remains at earth potential and the current input to a Keithly model 301 electrometer module, with a feedback resistor of $10^{10} \Omega$, gives an output voltage proportional to the ion current due to those ions present within the selected collector mobility range.

It is important to note that the non-selected collectors up stream of the air stream entering the ion chamber provide a filtering effect by collecting the ions of higher mobility values up to that mobility value relating to the selected collector plate.

A logic circuit controlled by a data acquisition system controls the serial selection, C_1 to C_{13} of the collector plates. For each collector selected, the anode is first made positive for one minute, the positive ion concentration read at the end of this time then the anode is made negative and after one minute the negative ion concentration is read. Thus, the near simultaneous positive and negative ion concentrations for each mobility range in Table 1 are obtained. A complete scan of 13 positive and 13 negative ions is completed in 30 minutes, with climate and other parameters being measured twice in each complete scan after reading C_1 and C_6 .

The electrometer feedback resistor is $10^{10} \Omega$, with an output voltage linear to ± 10 volts corresponding to an input current of $\pm 10^{-9}$ amperes. Consequently the insulation of the collector selecting relays, RLA to RLH, is of great importance, and tests on 5 volt DIL relays showed that the insulation resistance was better than $10^{12} \Omega$ providing the surface of the insulation was clean and dry.

The connections to each collector, and the common connection to the electrometer input, are made with Teflon covered wire directly to the relay pins concerned since it was found that glass fibre bonded printed circuit boards exhibited leakage resistances less than 10^8 ohms with relative humidity of 70%. The relays are housed as shown in Figure 2 in a metal channel connected to the earth guard plate, and the channel is then sealed with a silicon sealing compound all along the edges and at the end of the channel where the electrometer input connector and the relay selection wires emerge. Not only does the metal channel seal the relays from the external atmosphere, but it also provides a Faraday shield which prevents the change in anode potential from positive to negative from inducing changes into the insulation of the relays and connecting wire which would take a long time (> 30 seconds) to reduce the induced current to the equivalent natural ion level.

Prior to changing the anode polarity, or selecting the next collector plate, the electrometer is de-sensitised by switching in a $10 \text{ M}\Omega$ feedback resistor by means of a relay, RLK, which has a very high leakage insulation. This relay is always operated first and remains on for 10 seconds during which time the selector relays are operated, so that the settling time of the electrometer circuit is very much shortened subsequent to any change.

Each set of collector plates provides two collecting surfaces, top and bottom, if the collectors are placed between two anode plates. Two sets of collector plates are used, interposed between 3 anode plates, so that four collecting surfaces are obtained. Thus, for the same ion concentration in the air stream a current four times greater is obtained, which greatly reduces the high values of resistance required.

For the ion chamber, the electrometer current of the two combined collectors of 10^{-9} amperes corresponds to an ion concentration of 1.6×10^{12} ions/m³. The ambient ion concentration of 16×10^6 ions/m³ corresponds to an electrometer current of 10^{-14} amperes.

Air Velocity

The air velocity, W m/sec, is held at 1 m/sec by means of a fan which draws air in at the far end of the ion chamber. The fan is a small D.C. five bladed fan and the fan speed is controlled by an infra-red emitting diode beam to a photo transistor being interrupted by the fan blades and the resulting pulses control the fan operating potential by use of a linear ratemeter. This ensures that the air speed is independent of power supply potentials in the field, and the air velocity is set against a calibrated hot wire air velocity meter which has been corrected for use at the present operating altitude of 1800 m.

Because the multiple collector plates and the anode plates are parallel, spaced 1 cm apart, and 1.5 m in length, the air flow between the plates is believed to be laminar.

Ambient Temperature

The Keithly electrometer (Model 301) has an input offset current of 10^{-14} amperes with a drift rate of 10^{-15} amperes/24 hours. The input offset current doubles every 5°C change in temperature. The input offset voltage is adjustable to zero and changes by 150 μV per °C.

To provide optimum stability with temperature change, the resistance between ground and the non-inverting input must be the same value as the feedback resistor between the inverting input and the output.

Previous measurements performed with $10^{11} \Omega$ resistors and using an input test current derived from a voltage source and a series $10^{11} \Omega$ resistor, the errors due to temperature variations of the electrometer module are shown in Table 2. Whilst the errors at low input currents are large with the temperature change from 10 to 40°C, they relate only to the low natural levels of ion concentrations. In the $10^{10} \Omega$ configuration used, 10^{-13} amperes relates to 156×10^6 ions/ μ^3 . The error would be of the order of $\pm 15\%$ with this temperature change. Thereafter, the error becomes negligible.

The electrometer and the associated electronics are housed in a hermetically sealed unit on the ion chamber and are not used in the field in direct sunlight.

Table 2 Temperature Stability of Electrometer Module Using $10^{11} \Omega$ Resistors.

Input Current Amperes	Output Error % Against Temperature		
	10°C	25°C	40°C
$+10^{-13}$	-2	-40	-150
-10^{-13}	+9	+50	+145
$+10^{-12}$	-2	-5	-16.5
-10^{-12}	+0.5	+4	+14
$+10^{-4}$	-0.8	-1.8	-3.9
-10^{-4}	-0.6	-0.6	-0.57
$+10^{-10}$	-0.56	-0.5	-2.3
-10^{-10}	-0.58	-1.27	-2

Calibration Tests

To obtain a source of known ion concentration is difficult. The electrometer operation is most satisfactorily calibrated against a known input current as was used in the temperature variation tests.

To obtain a field method of checking at least the first four collector plates, an alpha source is made from natural Thorium (90 Th^{232} , $\alpha = 3.98 \text{ MeV}$) on an aluminium plate which, when placed upon an anode, provides an input current equivalent to about $1000 \times 10^6 \text{ ions/m}^3$ at each collector C_1 , 2, 3 and 4. Both of the two sets of collector plates can be so checked in this manner.

Relative Humidity and Water Spray Tests

The ion chamber was tested in an environmental chamber capable of both variable temperature and relative humidity. With the relative humidity changed from 30% to 85%, there was no perceptible change in the ion concentrations for the 13 ion mobilities. Only when the water sprayers for the humidity control system operated was there any indication of increased ion concentrations. By setting the humidity demand from 30% to 90% it was possible to have the humidity sprayers on continuously for a period of more than 30 minutes with a near linear rate of change of humidity of 5.9%/minute. Figure 3 shows the resultant ion mobility spectra for positive ions. Figure 4 shows that for negative ions, and Figure 5 shows the space charge spectrum obtained by subtracting the negative ions from the positive ions. The space charge spectrum is practically zero over the range of ion mobilities available which confirms that fog or cloud is electrically neutral [9], although the ion concentrations at ion mobility $0.019\text{--}0.01 \times 10^{-4} \text{ m}^2/\text{V sec}$ is high.

By switching off the humidity sprayers, it was found that the ion concentration began to decrease immediately. Table 3 shows the decay half lives found which decayed exponentially over a wide range.

Table 3 Decay Half Lives for Water Vapour

Collector No.	Mobility $\text{m}^2/\text{V sec}$ $\times 10^4$	-ve ions	+ve ions
		$\tau^{1/2} \text{ secs}$	$\tau^{1/2} \text{ secs}$
1	2.77 - 1.0	57	23
10	0.019 - 0.01	498	684

Chalmers [10] identified the average life of ions as;

Overland	50 seconds
Kew (Polluted)	20 seconds
Oversea	300 seconds

but gave no indication of the polarity or the concentrations.

Field Results in Rain

The ion chamber was situated under 400 kV AC transmission lines. These were 3 sets of 3 phase lines, each phase is a 38 cm equilateral triangle bundle using 35,5 mm aluminium conductors. The phase to phase spacing is 10,8 m, with about 30 m spacing between centre wire to centre wire of each transmission line.

Figure 6 shows the rainfall over a period of time, being scan 150 to scan 170 and therefore covering about 10 hours. Figure 7 shows the positive ion spectrum for scan 158 which is when 2,6 mm of rain fell. Figure 8 shows the negative ion spectrum and Figure 9 the space charge.

From scan 159 onwards saturation occurred with ion concentrations greater than 2×10^{12} ions/m³ for certain ion mobilities. From scan 158 to scan 162 a total of 60 mm of rain fell. From a Bonneville Power Administration Computer Programme, the corona power loss for these three transmission lines would be about 170 kW/kM.

General

The ability of this ion mobility scanning ion chamber to operate in heavy rainfall has been shown. The only covering for the ion chamber was a flat wooden cover held over the ion chamber so that rain or sun would not fall directly into the entrance of the ion chamber.

The housing of the ion chamber is made from a proprietary aluminium alloy unit normally used in small sections for holding printed circuits. Lateral slots run the 1,5 m length and the anode and multiple collector plates are pushed into these slots. This has advantages since it holds the plates firmly and the plates, anode and collectors, can be easily removed for cleaning. During dry weather the plates collect dust particles and they require occasional cleaning.

Tests have been made with spraying water from an atomiser into the entrance slit. The 2 mm air gap between the collectors and the guard plate has proved difficult to bridge with water. An initial problem was the reduced insulation of the anode supports which absorbed water. This was corrected by using a varnish to stop the absorption of water.

An effect of intense ion clouds on the ion chamber is that ions of the high concentration still tend to be collected even when the anode potential is reversed. This is thought due to the reduction of the ion chamber electric field. To avoid reading this corrupt data, the data acquisition system rejects an electrometer output voltage of the wrong polarity and replaces it with an artificial value equivalent to 15×10^6 ions/m³. This effect is shown in Figure 8 especially.

Figure 10 shows the construction of one multiple collector plate with the cover over the relays and the wire emerging from this cover.

Figure 11 shows the ion chamber with the electrometer and associated electronics. The aspiration fan is housed in the right hand section which is hinged. When the fan compartment is opened, the connectors from the collectors to the electrometer are accessible, as are also the connectors for the relay control.

Acknowledgements

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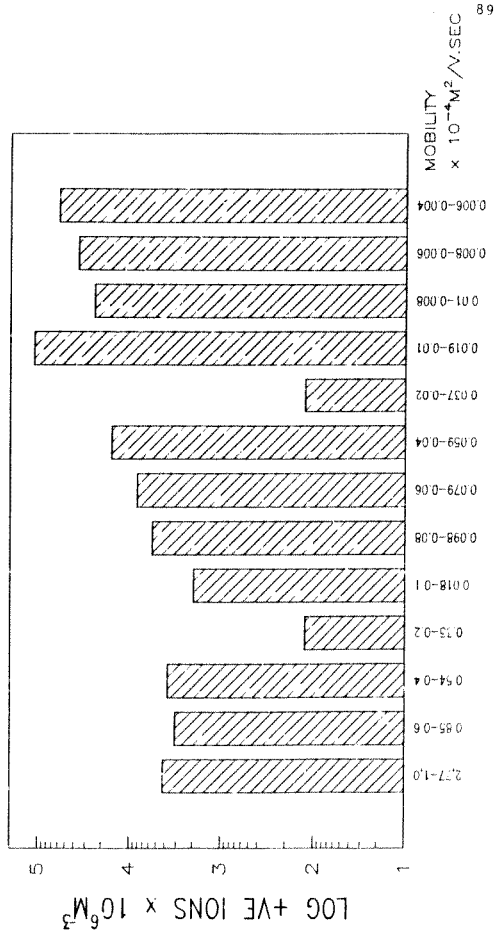
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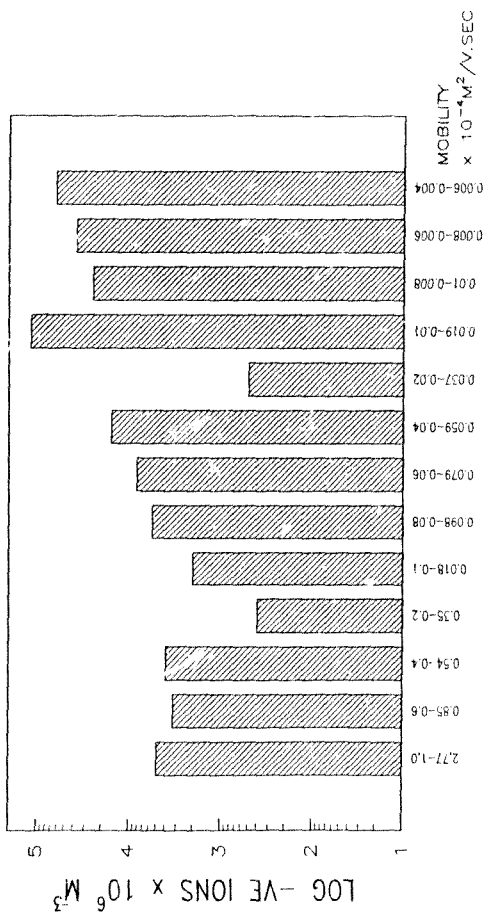
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WATER SPRAY



Positive Ion Mobility Spectrum
Figure 3

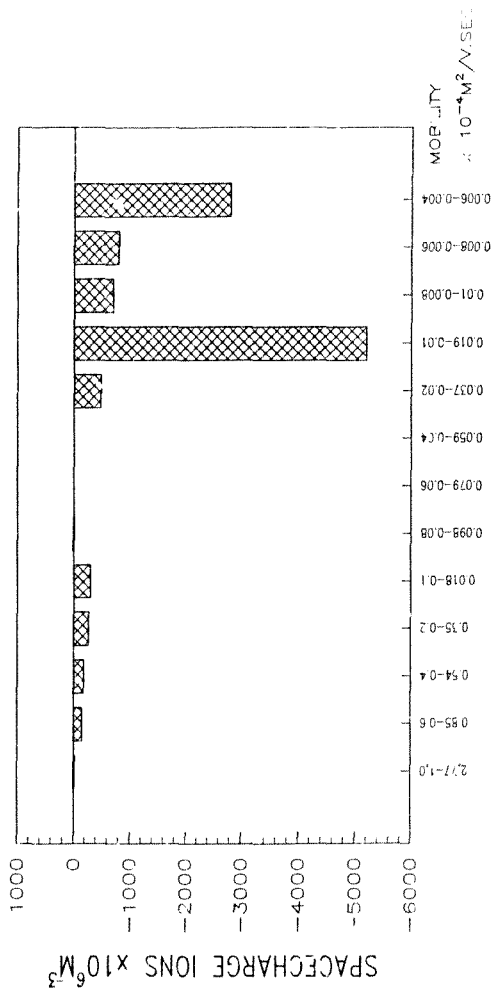
WATER SPRAY



Negative Ion Mobility Spectrum

Figure 4

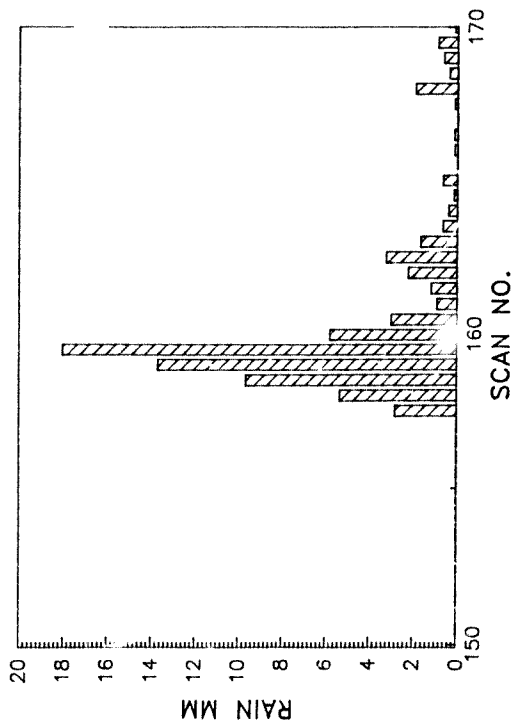
WATER SPRAY



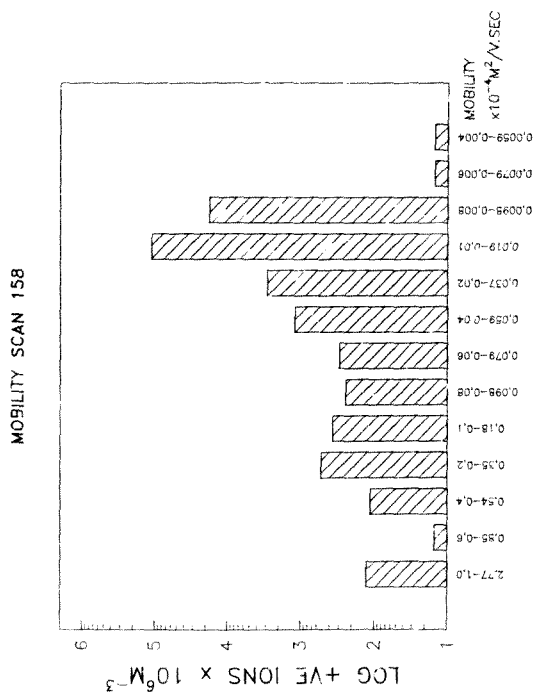
Space Charge Mobility Spectrum

Figure 5

29/10-3/11/87

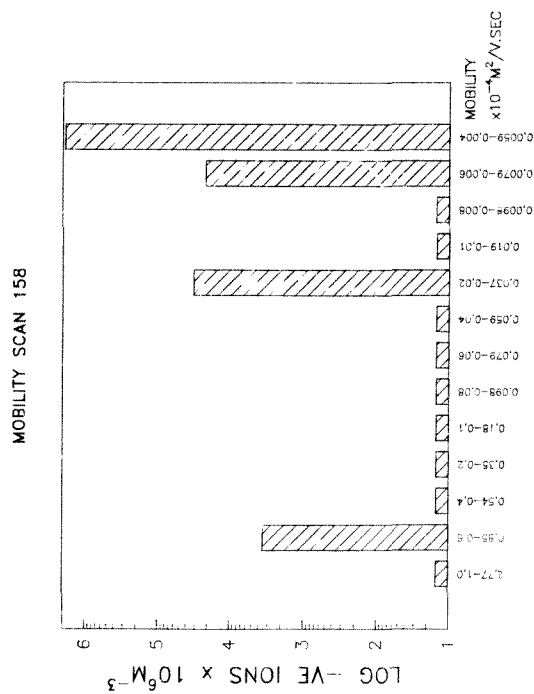


Rainfall
Figure 6



Positive Ion Mobility Spectrum

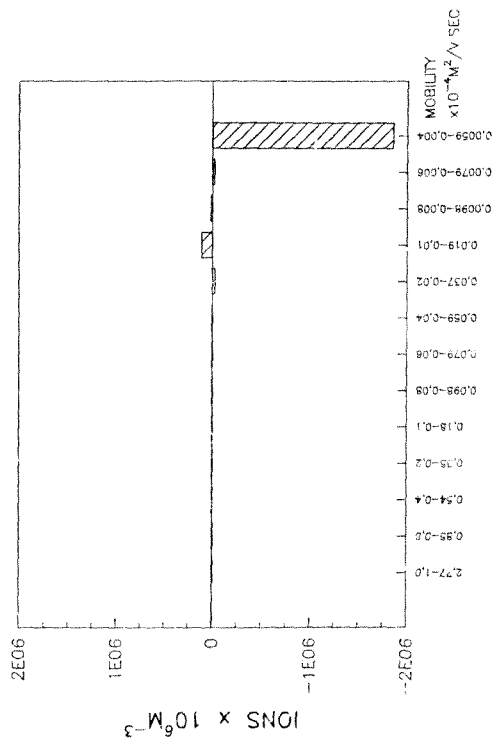
Figure 7



Negative Ion Mobility Spectrum

Figure 8

SPACECHARGE SCAN 158



Space Charge Mobility Spectrum
Figure 9

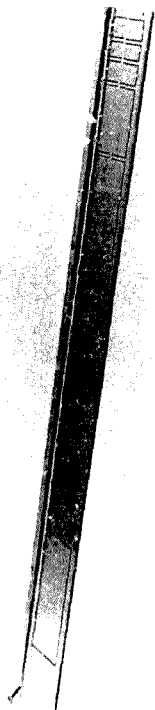


Figure 10

Multiple Collector Plates

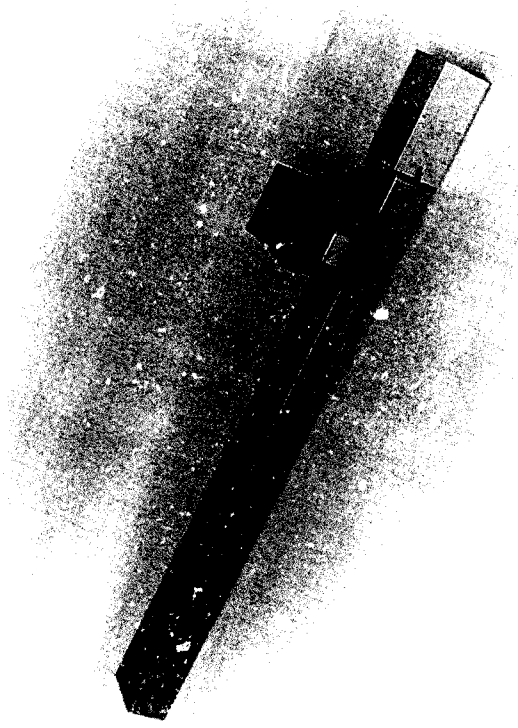


Figure 11
Ion Mobility Scanner

APPENDIX B

SPHERICAL PROBE FOR ELECTRIC FIELD MEASUREMENT

Abstract: The measurement of AC electric fields is necessary especially around irregular shaped objects at high potential since these cannot be easily calculated. The spherical probe described here is potential free due to the high insulation provided by an optical fibre, which also transmits the data to ground potential. Because the coin size batteries essential to power the probe have a finite life, and will produce errors if the battery voltage falls below a given level, a method has been developed to enable the battery voltage to be monitored via the optical fibre.

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Introduction

Feser and Pfaff [1] have described a small spherical probe of 40mm diameter comprising four quadrants in opposing pairs such that two orthogonal electric fields can be measured. Use is made of optical fibres to transmit the data from the sphere to the ground, and the high insulation resistance of the optical fibre ensures that the sphere is potential free in the electric field.

Pfaff [2] has further described a sphere which provides three orthogonal directions, using three pairs of quadrants, with a frequency response of 100 MHz.

These probes were designed to measure both the electric field and the impulse transients in pre-discharge and breakdown conditions during the impulse testing development of high voltage components used in power transmission lines.

The spherical probe described below is designed for the much more modest purpose of measuring the electric field around high voltage structures, especially irregular structures, with as little perturbation of the field as possible. These structures are those commonly found in high voltage switchyards such as conductor clamps, bus bar couplers, etc.

Another purpose for this probe was to measure electric fields around animal cages for biological and environmental purposes.

Spherical Probe

For a sphere divided into two hemispheres as shown in Figure 1, Pfaff [2] has shown that the current between the two hemispheres is an ideal current source, i_0 , flowing into an impedance comprising a resistor and a capacitor in parallel.

Where the ohmic coupling resistance is low, the voltage across the resistor will be:

$$V_m = \frac{\vec{A} \cdot \vec{R} \cdot d\vec{D}}{dt} = R \vec{A} \cdot \vec{D} \quad (1)$$

where D is the dielectric displacement, and A the area. In this case the bandwidth of the sensor is limited only by the stray capacitance C .

Where the coupling capacitor is the terminating component and the ohmic resistance is high, then the output voltage is given by:

$$V_m = \frac{A}{C} D = \epsilon \frac{A}{C} E \quad (2)$$

In both cases the magnitude of V_m is dependent on the direction of the area relative to the direction of the electric field. When the area subtends an angle of 90° to the electric field, the charge induced into the opposing quadrants will be equal and in phase and consequently $V_m = 0$.

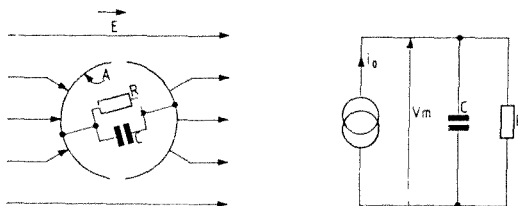


Figure 1

Principle of Capacitive Spherical Probe

- (a) Sphere in electric field
- (b) Equivalent circuit

Dono and Zaffanella [3] have derived the equation for the current between two hemispheres lying in the direction of the electric field as:

$$i_o = \frac{dq}{dt} = j\omega 3\pi r^2 \epsilon E \quad (3)$$

where D is the dielectric displacement, and A the area. In this case the bandwidth of the sensor is limited only by the stray capacitance C .

Where the coupling capacitor is the terminating component and the ohmic resistance is high, then the output voltage is given by:

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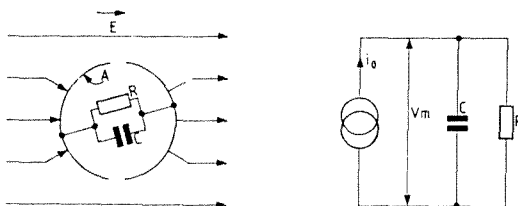


Figure 1

Principle of Capacitive Spherical Probe

- (a) Sphere in electric field
- (b) Equivalent circuit

Deno and Zaffanella [3] have derived the equation for the current between two hemispheres lying in the direction of the electric field as:

$$i_0 = \frac{dg}{dt} j\omega 3\pi R^2 \epsilon E \quad (3)$$

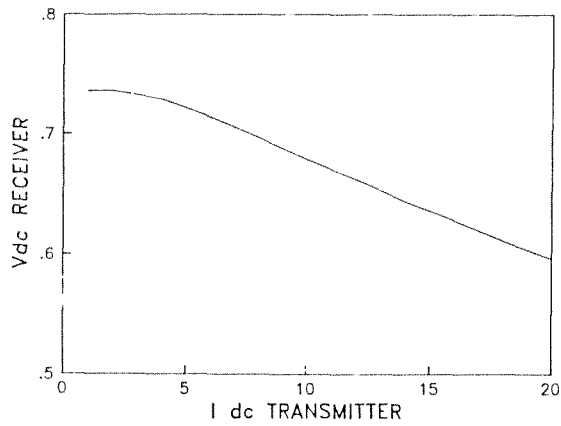


Figure 2

Transmitter and Receiver Characteristics

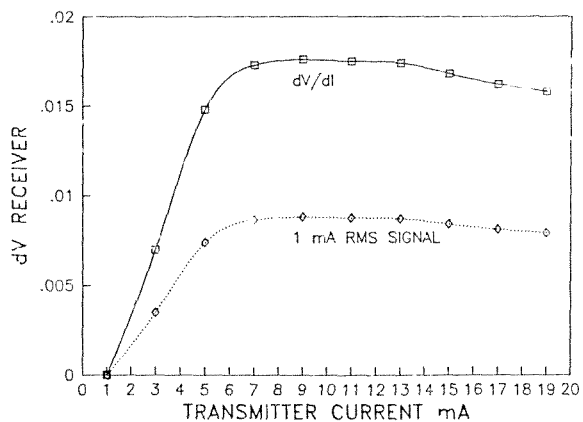


Figure 3

Forward Bias Characteristic : Transmitter and Receiver

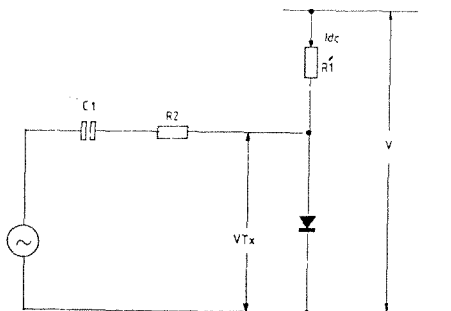


Figure 4
Equivalent Transmitter Circuit

When the terminating component is a capacitor, the potential derived across it is independent of the alternating frequency of the electric field, since:

$$V_m = \frac{j\omega 3\pi r^2 \epsilon_0 E}{j\omega C} \quad (4)$$

$$= \frac{3\pi r^2 \epsilon_0 E}{C}$$

Where ϵ_0 is the permittivity of free space.

The bandwidth will be limited by the physical constraints of the electronic measuring system and the bandwidth of the optical fibre data transmission system. For the purpose of measuring the electric fields from 50 or 60 Hz power systems, the upper bandwidth need only be sufficient to allow measurement of the highest expected harmonics: any bandwidth higher than the 20th harmonic is unnecessary unless fast transients are to be measured, and then the methods of Feser and Pfaff would be required.

It is important to note that the spherical probe is highly directional, with the maximum signal obtained when the two hemispheres are aligned with the electric field, and zero when they lie at right angles to it.

To transmit the data along an optical fibre, the most simple method is to use the analogue characteristics of the optical transmitter and receiver. The data is not required to be transmitted over a long distance and an optical fibre length of 10m is adequate. The optical transmitter is an infra-red emitting diode where the light output is proportional to the forward current in the diode. The optical receiver is also a linear analogue device where the output potential is as shown in Figure 2 which is the combined transmitter/receiver characteristic with a 10m optic fibre coupling. To transmit the AC voltage derived from the hemispheres it is necessary to forward bias the transmitter diode so that the maximum signal from the sensor remains within the linear part of the characteristic. Figure 3 shows the forward bias characteristic dV/dI , where dV is the change in receiver voltage for the concomitant transmitter current dI . The signal due to a 1 mA RMS current is also shown modulating the forward bias current. The equivalent circuit is shown in Figure 4, R_2 defines the AC current modulation amplitude from the hemisphere potential. C_1 provides a DC blocking path and must be large enough not to give attenuation at 50 Hz.

R_1 provides the forward bias current to the transmitter diode. The accuracy of the transmitted data is dependent upon the battery voltage, V , which provides both the forward bias current and also powers the electronic circuit. Should the voltage fall such that the forward bias current be reduced below 5 mA, then distortion of the potential due to the electric field will occur. Because of the small size of the probe the power supply is provided by two coin size lithium batteries giving a nominal 3 V each, but the total voltage on load falls rapidly to 5.5 volts until the end of life, about 185 mA/hours, when the battery potential, and hence the forward bias current, falls. With a battery voltage of 3.91 volts the error in reading the electric field is -5.2%, but when the battery voltage has fallen to 3.36 volts, the error in measuring the electric field is -21.7%. Consequently it is necessary to be able to monitor the probe battery voltage, especially when the maximum fields of 50 KV/m are being measured. The necessity of this is emphasized when it will be recalled that the probe will be switched on for periods of hours when equipotential plots of electric fields are being done. Figure 5 shows the effect of the discharging battery potential.

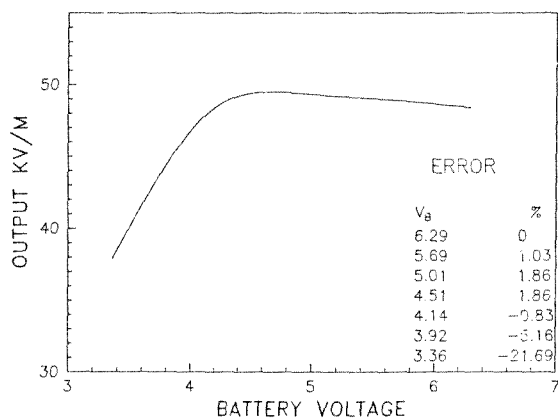


Figure 5

Variation of Output with Battery Voltage

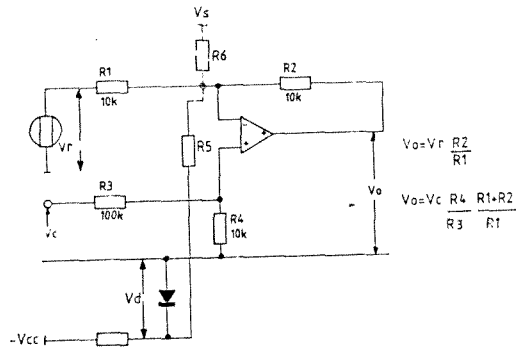


Figure 6
Electronic Solution to Equation 5

Probe Battery Voltage Monitoring

The overall transmitter/receiver characteristic being linear, as was shown in Figure 2, provides the method of measuring the battery potential. The DC potential at the receiver, V_r , will be related to the forward bias current, I_{do} , in the transmitter by:

$$V_r = A + B(I_{do}) \quad (5)$$

thus,

$$V_r = A + \frac{B(V - V_t)}{R_1}$$

where V_t is the forward biased potential across the transmitter diode, and V the battery voltage.

From this we obtain,

$$V = \frac{R'}{B} (V_r - A) + V_t \quad (6)$$

V_t changes by only 0,05 V for I_{dc} changing from 10 to 5 mA, and thus the probe battery voltage is directly proportional to the voltage at the optical receiver.

The circuit in Figure 5 shows the electronic solution to Equation 6. The unity gain amplifier ($R = R2$) gives an output of $-\frac{R'}{B} V_r$, and the input offset to the non-inverting input provides the constant value of $(\frac{R'}{B} A + V_t)$. Since the non-inverting input has a gain of 2, given by $(R1 + R2)/R1$, then the value for V_c , which must be adjustable to take account of differences in transmitter/receiver characteristics, and optical fibre attenuations, is given by:

$$V_c \cdot \frac{R4}{R3} \cdot \frac{R1 + R2}{R1} = V_o$$

or

$$2 V_c \cdot \frac{R4}{R3} = \frac{R'A}{B} + V_t \quad (7)$$

The phase inversion of V_r provides an output at V_o directly proportional to the probe battery potential and in the correct sense. The value of V is obtained directly by further DC amplification by the factor $R'/B = 50$. At this point the AC signal will be about 0,4 RMS with the battery potential output in the range 4-6 volts. The DC is eliminated by capacitive coupling and after further amplification an RMS to DC converter provides a second DC potential equal to the electric field in KV/m. The two potentials are displayed on a liquid crystal display, with a push button changing the KV/m scale to that of the battery potential.

The optical receiver output voltage is temperature sensitive. This is no doubt due to the optical input being a phototransistor with an open base. As a result, a temperature compensating circuit has to be included, as shown by the dotted lines in Figure 6.

The temperature characteristic is that expected from a forward biased diode, being KT/e , where K is Boltzmann's constant, T the absolute temperature and e the electronic charge, giving about 1.5×10^{-3} V/°C. Compensation is achieved by using a forward biased diode voltage as the temperature sensitive component and inputting a current into the summing amplifier in opposition to that from the optical receiver.

Over a temperature range of 10°C to 40°C, the sum of currents into the amplifier are required to be the same:

$$\frac{(V_r(T_0) - a_r \cdot T)}{R1} \cdot R2 = \frac{V_s R2}{R6} - \frac{(V_d(T_0) - a_d \cdot T)}{R5} \cdot R2$$

Where

$V_r(T_0)$ designates the receiver potential at 0°C

a_r = temperature coefficient of the receiver

a_d = temperature coefficient of the compensating diode

T = temperature °C

V_s = positive supply potential

V_d = compensating diode potential

$R5$ = resistor providing compensating current

$R6$ = resistor providing the offset bias from the diode potential

$R2$ is a common factor and can be eliminated thus:

$$\frac{V_r(T_0)}{R1} - \frac{a_r \cdot T}{R1} = \frac{V_s}{R6} - \frac{V_d(T_0)}{R5} + \frac{a_d \cdot T}{R5}$$

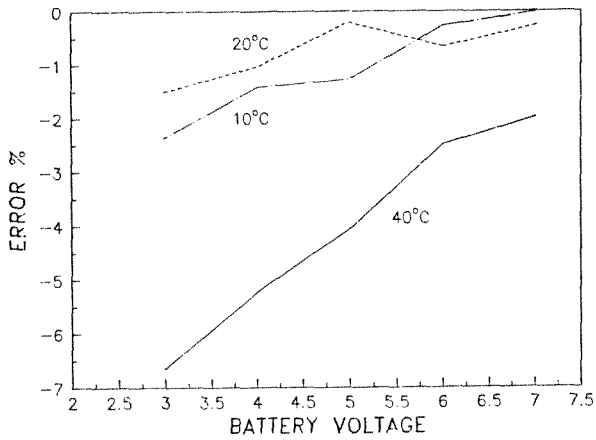


Figure 7

Error due to Ambient Temperature Change

Since at

$$T_o : \frac{V_r(T_o)}{R1} = \frac{V_s}{R6} - \frac{V_d(T_o)}{R5}$$

then,

$$\frac{a_r \cdot T}{R1} = \frac{a_d \cdot T}{R5}$$

From which

$$R5 = \frac{a_d}{a_r} \cdot R1$$

The term $V_s/R6$ is the offset current equal and opposite to the current from the diode voltage and $R5$ at temperature T_o . $R6$ is found from:

$$R6 = \frac{V_s}{V_d(T_o)} \cdot R5$$

The values for $R5$ and $R6$ are found after determining a_r and a_d and they are: $R5 = 11\ 751$ ohms, $R6 = 222\ 847$ ohms, and any DC offset discrepancy can be removed by suitable adjustment of V_o .

The errors in reading the battery voltage over the temperature range of 10°C to 40°C are shown in Figure 7, and the maximum error at $+40^\circ\text{C}$ is 5.5% at a battery potential of 4 volts. That is, it reads low in a safe operating condition when the batteries require replacement.

Calibration and Results

Since the current between the two hemispheres is proportional to the square of the radius of the sphere, it is not sufficient to rely upon calculation for the calibration.

The calibration was performed between parallel plates 2 a. by 1.5 m, placed 2 m apart, using a potential divider accurate to 2% at 100 kV R.M.S. The value of the capacitance, C , is 6.2 nF and Table 1 shows the calibration results.

Table 1 Calibration of Spherical Probe

Field KV/M	Reading KV/M	Error %
50	50,0	0
40	40,4	1
30	31,4	4,6
20	21,2	6
10	10,8	8
5	5,4	8
2,5	2,8	12
0,5	0,9	80

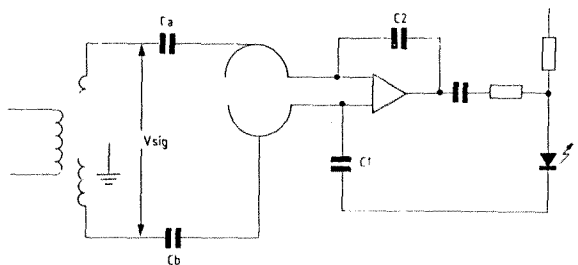


Figure 8
AC Field Meter Calibration

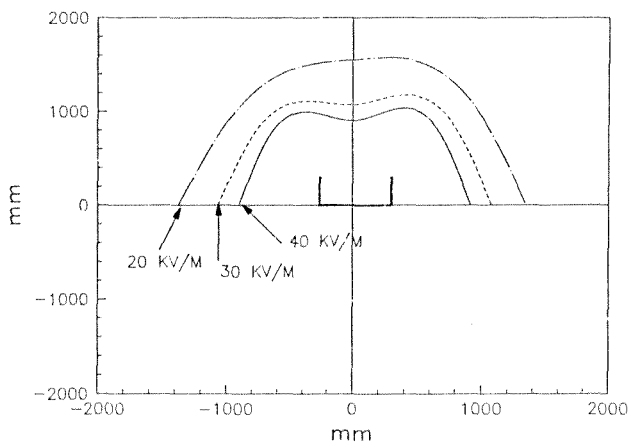


Figure 9

Equipotential Plot around Non-Linear Energised Object

There is a zero error due to low frequency AC noise currents in the amplifier. The minimum reading is 0,2 KV/m or less. Some of the error in Table 1 may be due to the potential divider.

Once the probe has been calibrated with the parallel plate, then a laboratory calibration can be simulated using a bi-phase AC voltage and two capacitors as shown in Figure 8.

The values of C_a and C_b are determined by adjusting them until the previously calibrated spherical probe reads 50 KV/m.

In a precision made sphere they could be calculated from:

$$V_o = -1/2 V_{sig} \cdot \frac{C_a}{C_2} - 1/2 V_{sig} \cdot \frac{C_b}{C_1}$$

Since $C_1 = C_2$ and $C_a = C_b$, with the output voltage into the transmitter being 0,7 V RMS equivalent to 50 KV/m, then, with $V_{sig} = 25$ V RMS (12,5 - 0 - 12,5);

$$C_a = \frac{V_o}{V_{sig}} \cdot C_2$$

$$= 180 \text{ pF}$$

In practice, the calibration capacitors will be different for each probe due to the difference in radius.

With the capacitor calibration, the maximum error at 6,25 KV/M was - 0,86%.

The frequency response is -2,2% at 10 KHz, and -20,4% at 20 KHz. Figure 9 shows the results of an equipotential plot at a constant height around an irregular structure comprising an aluminium rod of 8 mm diameter bent into a U shape of size 220 mm and base 560 mm. The probe is 62 mm diameter so that it is rather more than 10% of the U base, but the plot still gives reasonable resolution.

Conclusion

A small spherical probe has been described using simple methods to provide a potential free sensor in an electric field with an overall accuracy of better than 10%, and with the ability to measure the sensor battery potential, which is necessary to avoid errors in reading the electric field when the battery voltage has become low due to exhaustion of the battery.

The components used are low cost optical transmitters and receivers, being less than \$3 each, and the optic fibre link and connectors costing the most at \$200, inclusive of the optical connectors.

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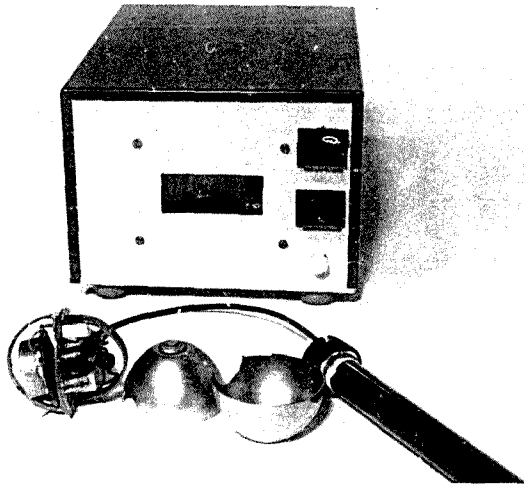


Figure 10
Spherical Probe

Author Cockbaine David Robinson

Name of thesis Measurement Of Ion Mobility Spectra For Rain And Relative Humidity Induced Ion Phenomena Under 400 Kvac Transmission Lines. 1988

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